Performance sensitivity of subsonic liquid hydrogen long-range tube-wing aircraft to technology developments

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Abstract

Liquid hydrogen (LH_2) may enable the decarbonisation of long-haul aviation. However, its low volumetric energy density and subsequent tank space and weight requirements will penalise an aircraft's specific energy consumption (SEC, MJ/tonne-km). We evaluate the impacts of developments in four technology areas – aerodynamics, structures, cryo-tank gravimetric index (η), and overall efficiency (η_o) – on the design-point performance of a large subsonic tube-wing LH_2 aircraft. We characterise the critical value of η, which must be exceeded to enable a given design range. For a design range of 14,000 km, η must exceed 0.52 today but only 0.35 with expected 2030 airframe and engine efficiency improvements. Using the most optimistic technology development estimates we observe that SEC could reduce by ~25% via improvements in η_o and aerodynamics and by 33% via improvements in all four areas. Developments in technologies to improve η_o and reduce drag are critical to enabling zero-carbon long-haul air travel.

Keywords

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

Nomenclature

BWB	Blended wing body	OEW	Operating empty weight
C_f	Skin friction coefficient	R	Aircraft range
FLOPS	Flight optimisation system	SEC	Specific energy consumption in MJ/tonne-km
GTOW	Gross take-off weight	SPK	Synthetic paraffin kerosene
h	Lower calorific value	T/W	Thrust to weight ratio
Jet-A	Conventional jet fuel	VLTA	Very large twin aisle
L/D	Lift to drag ratio	$W_{F,block}$	Block fuel weight
LH_2	Liquid hydrogen	$W_{F,total}$	Total fuel weight carried at mission start
LNG	Liquid natural gas	W_{final}	End of cruise aircraft weight
LNH_3	Liquid ammonia	$W_{initial}$	Initial cruise aircraft weight
LTA	Large twin aisle	W_p	Passenger payload weight
LTO	Landing and take-off	η	Gravimetric index
MTOW	Maximum take-off weight	ω	OEW and fuselage weight reduction factor
NASA	National Aeronautics and Space Administration	η_o	Overall efficiency
NO_x	Oxides of nitrogen	λ	Ratio of dry tank weight and cryogenic fuel weight

1. Introduction

The aviation industry forecasts that air transportation demand could double in the next two decades despite the effects of COVID-19 pandemic [1]. Aviation contributes to 3.5% of the net anthropogenic radiative forcing [2]. In a business-as-usual scenario considering the predicted demand, aviation's climate impacts might increase significantly [3,4]. In a bid to achieve climate neutral growth, the aviation industry anticipates that the use of advanced aircraft technologies and low-carbon alternative fuels together could contribute to 80% of the required efforts [5].

The National Aeronautics and Space Administration (NASA) initiated the concept of 'N+i' goals to reduce noise, fuel consumption, and landing and take-off (LTO) oxides of nitrogen (NO_x) emissions, and to improve aircraft performance [6], which encourage the use of advanced aircraft concepts/technologies and alternative fuels. These are expected to enter service in a fixed timeframe in future. 'N+i' nomenclature is used to define the sequence of improving aircraft generations, where N specifies the present generation and 'i' represents a specific future generation beyond N.

Long-haul aviation is a challenging sector to decarbonise [7–9]. Currently, only 50% blend of synthetic paraffin kerosene (SPK) from alcohol-to-jet, hydro-processed renewable jet, and Fischer Tropsch production pathways, and 10% blend of sugar-to-jet SPK, are approved alternative fuels for civil aviation [10–13]. In our previous study [7], we reviewed and quantitatively evaluated different aircraft propulsion technologies and energy vectors (batteries, fuel cells, solar electric and ion propulsion), and alternative fuels [methanol, ethanol, 100% SPK, liquid hydrogen (LH_2), liquid natural gas (LNG), and liquid ammonia (LNH_3)], to examine whether they could enable a typical long-range travel of a large twin aisle (LTA) tube-wing single decker aircraft using Breguet's range equation. This equation is a fundamental equation in aeronautics which predicts the aircraft performance metrics from the fuel type (calorific value), aircraft aerodynamics (lift to drag ratio [*L/D*]), η_o (propulsion) and aircraft weight (structures) [14]. We observed that under current technology projections there are only two alternatives to Jet-A fuel such as 100% SPK and LH_2 fuel. Both enable a typical long-range flight of 14,000 km (7,500 nautical miles) within the maximum take-off weight (MTOW) limit of a (baseline) present-day LTA tube-wing aircraft that seats 366 passengers.

LH_2 as an aircraft fuel is garnering interest because its gravimetric energy density is 2.78 times greater than Jet-A and its potential to emit zero carbon emissions in the use-phase [7]. However, the volumetric energy density of LH_2 is a quarter that of Jet-A, which poses challenges to LH_2 powered tube-wing aircraft design in terms of fuel storage. The aviation industry has initiated R&D and investments on cryogenic tank testing, fuel infrastructure, plans of fuel testing in aircraft, and conceptualizing aircraft design [15–18].

An aircraft could be powered by LH_2 via fuel cell systems, turbo-electric (hybrid shaft-powered), or thrust-powered gas turbine engines. Studies on fuel cell LH_2 powered aircraft [6,19,28–32,20–27] and LH_2 turbo-electric aircraft [33–35] suggest that both methods are feasible for only regional/short- to medium-range for a small- to mid-size aircraft even considering technology developments[7].

For a large LTA tube-wing LH_2 aircraft, the fuselage length could increase by approximately one-third of the baseline Jet-A aircraft fuselage length for accommodating this cryogenic fuel thereby penalizing the aircraft performance and specific energy consumption (SEC) [7,36–38]. The Breguet range equation shows that the aircraft performance depends on the type of fuel used and advancements in aircraft technology such as use of energy efficient engines and lighter materials and improved aerodynamics, and thus it could be employed to examine the effects of the above three advancements in aircraft technology, especially on the long-range LH_2 powered LTA aircraft performance such as its SEC.

Table 1. Different studies on LH_2 powered aircraft and the cryogenic tank gravimetric index used

Study	Application	Tank type	η
Multi-layer insulation system			
Cleansky 2 [36,39]	19 passengers with 500 km range	Integral	0.25
Cleansky 2 [36,39]	80 passengers with 1,000 km range	Integral	0.30
Cleansky 2 [36,39]	165 passengers with 2,000 km range	Integral	0.35
Cleansky 2 [36,39]	250 passengers with 7,000 km range	Integral	0.37
Cleansky 2 [36,39]	325 passengers with 10,000 km range	Integral	0.38
Woehler et al. [40]	421 passengers with 14,260 km range	Integral	0.52
Foam insulation			
Huete et al. [41,42]	232 passengers with 10,370 km range, 332 passengers with 8,890 km range, 388 passengers with 6,112 km range, and 720 passengers with 3,334 km range	Integral	0.45
Huete et al. [41]	232 passengers with 7,400 km range	Integral	0.3
Huete et al. [41]	232 passengers with 12,960 km range	Integral	0.85
Cryoplane [43,44]	All aircraft categories	Integral	-
Winnefeld et al. [45]	General application of cylindrical tanks	Non-integral	0.6 – 0.7
Brewer’s work summarised by Verstraete [46]	-	Non-integral	0.9
NACA/NASA [47,48]	High-altitude (20 km) reconnaissance aircraft	Integral	0.881 feasible
Delgado Gosálvez et al. [20]	19 passengers with 926 km range	Non-integral	0.5
Verstraete et al. [49]	32 passengers with range of 2,100 km	Integral	0.66 – 0.71
Gomez et al. [50]	197 passengers with 9,000 km range	Integral	0.74 – 0.83
Brewer’s work summarised by Gomez et al. and Verstraete [46,50,51]	400 passengers with 10,190 km range	Integral	0.84
Prewitz et al. [52]	108 passengers with 5,612 km	Integral	0.73 – 0.77
Quibén et al. [53]	158 passengers with 3,704 km	Integral	0.5
Prewitz et al. [52]	168 passengers with 6,852 km	Integral	0.74 – 0.78
Xisto et al. [54]	414 passengers with 13,890 km	Integral	0.70
Woehler et al. [40]	421 passengers with 14,260 km range	Integral	0.68
Beck et al. [55]	VLTA blended wing body aircraft for 531 passengers with 11,400 km range	Non-integral	0.77
Verstraete et al. [49]	550 passengers with 13,890 km range	Integral	0.76 – 0.79

LH_2 cryogenic tank weight is an important technology parameter which is reported in literature either as: (i) the gravimetric index, gravimetric efficiency, or gravimetric storage density (all denoted as η), defined as the ratio of cryogenic fuel weight to the sum of the dry tank weight and cryogenic fuel weight [36,45,46,49]; or (ii) the ratio of dry tank weight to cryogenic fuel weight (λ). The integral type of tank is part of the basic airframe structure. Thus, it should withstand fuselage bending, shear and axial stresses along with bearing fuel containment load. Non-integral tanks only carry the fuel, and they are mounted inside or outside the fuselage [49,56]. Therefore, with a non-integral tank type, the tank’s role is only to bear the loads resulting from the fuel containment such as internal tank pressure, aircraft acceleration, fuel weight, fuel sloshing because of vibrations and manoeuvres. Non-integral tank design is heavier than integral tanks [49,56]. The cryogenic tank weight is dependent on the type of the insulation system used in its design [56].

Different studies on LH_2 powered aircraft are summarised in Table 1 along with their tank gravimetric index. It can be observed from Table 1 that η is dependent on the type of insulation and it improves with increasing aircraft size or range. For example, foam based integral tanks are known to have higher η as compared to other tank types, especially for long-range travel [49]. A value of $\eta = 0.38$ was assumed for a double-wall evacuated tank with multi-layer insulation used for a large long-range aircraft by the Clean Sky 2 - FCH joint project [36,39]. Additionally, a recent study by Huete et al. [41] examined the effect of η on aircraft range. The authors found that for short range aircraft the effect of η improvement on range is not as significant as the sensitivity observed for long-range aircraft. The authors also found that for long-haul flights, improving η from 0.3 to 0.85 could increase the range from 7,400 km to 12,960 km, respectively. Thus, η is a critical technology parameter that will determines the feasibility of LH_2 powered aircraft. In our previous study [7], we used a nominal value of $\eta = 0.78$ for the foam based integral tank for the LH_2 aircraft using present-day single decker tube-wing aircraft technology, based on the study by Verstraete et al. [49] for long-range LTA aircraft. However, given the range of values listed in Table 1, there is a need to evaluate the effect of cryogenic tank technology parameter η i.e., impact of different insulation material and/or tank type, on the (energy) performance of long-range LH_2 powered LTA aircraft. Further details on some of the studies in Table 1 is included in SI § 1 (Table SI 1).

A study by Prewitz et al. [57] modelled the performance of a regional hydrogen aircraft (ATR-72) having a design range of 1,324 km for maximum payload of 7 metric tons. The authors evaluated that the critical value of η to enable economic operations was 0.33 – 0.35, while the value of η required to enable design target range was 0.19. Other studies on gas turbine engine LH_2 aircraft have focussed on both regional/small- to mid-size aircraft [30,31,63–65,52,53,57–62], and studies on long-range LH_2 aircraft [37,40,50,66–69] have modified the design performance characteristics of LH_2 aircraft in comparison with the baseline aircraft. The modifications to the long-range LH_2 aircraft were in terms of reduced range and/or payload combinations [40,50,67,69], reduced cruise altitude and cruise Mach [37,68], and the aircraft is partially powered by LH_2 (67% by LH_2 and 33% bio-kerosene) [66], compared to the baseline Jet-A aircraft.

Studies by Verstraete et al. [49], Verstraete [38], Brewer [51], Airbus Cryoplane [43], Clean Sky 2 - Fuel Cells and Hydrogen joint project [36,39], Troeltsch et al. [68], Proesmans et al. [37], and Huete et al. [41,42] have modelled long-range LH_2 powered LTA aircraft but have not conducted a detailed sensitivity analysis which evaluates the impact of uncertainties in technology improvements on the LH_2 aircraft design and energy performance. There is a need for a sensitivity analysis which quantitatively evaluates the potential technology improvements and outstanding uncertainties, in terms of the performance of long-range LTA aircraft powered by LH_2. Such an analysis would estimate the impact of uncertainties in technology improvements on the LH_2 aircraft design characteristics and energy performance, which directly impacts the direct operating costs, and life-cycle energy and emissions. Additionally, the use of advanced technologies could reduce the additional fuselage length resulting from LH_2 storage tanks and SEC. Lastly, this sensitivity analysis will enable to estimate the critical value of tank η for a long-range LTA aircraft for the present-day and futuristic aircraft technologies.

The aim of this work is to evaluate the effects of technology development on the performance of future subsonic LH_2 long-range LTA aircraft, and the objectives are to:

1. Perform a sensitivity analysis to evaluate the effects of identified technology parameters for enabling a LH_2 powered long-range travel with an LTA aircraft with low SEC, within the maximum take-off weight (MTOW) limit of a baseline present-day LTA aircraft,
2. Evaluate the critical value of cryogenic tank η for a long-range LTA aircraft, and

3. Identify the technology parameters that could cause a dramatic improvement in SEC of an LH_2 powered long-range LTA aircraft.

The methodology for this sensitivity analysis is detailed next in §2 followed by results and discussion in §3. Details omitted from the main text are included in the Supporting Information (SI).

2. Methodology

We use Breguet's range equation for the LH_2 aircraft performance evaluation towards the sensitivity analysis. The Airbus 350-1000 aircraft is used as a baseline, and it cruises at a typical Mach and altitude with required reserves. This aircraft is modified for the use of LH_2 where both gravimetric and volumetric energy density effects of this fuel are considered on the aircraft structure, propulsion, and aerodynamics. Breguet's range equation analysis for the design point LH_2 aircraft performance is established and detailed in our previous study [7] and is summarised in §2.1 – 2.2. The sensitivity parameters and their ranges are discussed in §2.3.

2.1 Breguet's range equation

Breguet's range equation, represented by equation 1 (adapted from source [14]) calculates the aircraft range from the *L/D*, aircraft weight, lower calorific value of the fuel, and η_{o}. The range, R, of an aircraft is given by,

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

where g is gravitational acceleration, h represents the gravimetric energy density or the lower calorific value of the fuel, and W_{final} and W_{initial} are the aircraft weights at the end and beginning of cruise, respectively. The Breguet range equation is employed to flight operations where flight speed, *L/D* and η_{o} are constant over the flight segment (example cruise) [14]. In our previous study [7], we conducted validation of Breguet's range equation at four validation points, where the aircraft range is predicted for two separate payload cases for both B767-300F and A320-200. The performance characteristics estimation employing the range equation for these four points are in agreement with the published data (according to the defined criteria in [7]).

2.2 Flight mission profile and iteration process

We selected the Airbus A350-1000 aircraft (Jet-A) as a sector-relevant baseline case and evaluate LH_2 for the same payload weight and design target range. For Jet-A baseline aircraft, the MTOW, OEW and $W_{\mathrm{F,total}}$ are known for a given passenger payload weight (W_{p}) (366 passenger-payload), and this information and other data of A350-1000 aircraft (Jet-A) can be found in our previous study [7]. For storing LH_2 fuel in the cryogenic tank systems, we assume an integral type of cryogenic tank with foam-based insulation and allow for the extension of the fuselage, recognising that this would represent a significant engineering undertaking. The methodology/equations for calculating the effects of poor volumetric energy density effects of LH_2 via fuselage extension can be found in our previous study [7]. The additional fuselage results in penalty on the aircraft performance through increased drag/wetted area and operating empty weight (OEW). The total fuel weight carried at mission start ($W_{\mathrm{F,total}}$) governs the volume requirement to store LH_2 fuel and thus OEW of the aircraft. The aircraft GTOW is the summation of W_{p}, $W_{\mathrm{F,total}}$, and OEW. We have set a constraint on the aircraft GTOW, and it should be less than or equal to the MTOW limit of 316 tonnes (metric) for the baseline aircraft (weight breakdown can be found in [7]). This MTOW constraint is employed in this work since we have not carried out detailed aircraft structural examination. Thus, the MTOW governs the design limit on $W_{\mathrm{F,total}}$ i.e., for LH_2, $W_{\mathrm{F,total}}$

is iterated and calculated such that the aircraft GTOW ≤ MTOW. For LH_2 fuel, the wing design (aspect ratio, span, and planform area) is unchanged from the baseline aircraft, and this is similar to the procedure employed in the Airbus Cryoplane study [70]. The detailed methodology (design process schematic and equations) for calculating the OEW and *L/D* of the LH_2 aircraft which accounts for the performance penalty due to installation of cryogenic tank (weight) and the resulting increase in fuselage length and associated increase in fuselage structural weight can be found in our previous study [7]. The cryogenic tank η, and OEW and fuselage weight reduction factor (ω) are absorbed in the equations for the estimation of OEW of the LH_2 aircraft. Additionally, the skin friction coefficient C_f is absorbed in the equation for the estimation of the drag coefficient (or *L/D* calculation).

Equation 1 calculates the distance or range travelled during cruise. We estimate the fuel consumed in non-cruise operations using the lost fuel factor, which varies for different fuels and is represented as a percentage of the GTOW [71,72]. We define block fuel consumption as the sum of the fuel consumed during cruise and non-cruise operations of a typical mission. For both Jet-A and LH_2, a value of 0.9 is maintained for the ratio of block fuel weight ($W_{\mathrm{F,block}}$) and $W_{\mathrm{F,total}}$, and it accounts for additional or reserve fuel, according to the study by Nickol et al. [73] for both blended wing body and tube-wing long-range LTA aircraft. The SEC (in MJ/tonne-km) is a pertinent performance parameter as it is an important service unit for airlines which helps in the estimation of the direct operating costs. We calculate SEC for both baseline and LH_2 aircraft calculated from the $W_{\mathrm{F,block}}$ [SEC = ($W_{\mathrm{F,block}}\ h$) / ($W_{\mathrm{p}}\ R$)].

The aircraft weight at the beginning of cruise [W_{initial} = (1 – lost fuel factor) x GTOW] is calculated using the lost fuel factor. The lost fuel factor for Jet-A and LH_2 is 2.2% and 1.4% respectively [71,72]. The estimation of $\eta_{o,LH2}$ (overall efficiency of the LH_2 aircraft) from the known $\eta_{\mathrm{o,Jet-A}}$ (overall efficiency of the baseline Jet-A aircraft) is detailed in resource [7]. The ratio $\eta_{o,LH2}$ / $\eta_{o,Jet-A}$ i.e., the ratio of overall efficiency of the LH_2 aircraft and baseline Jet-A aircraft is calculated to be 1.0314 in our previous study [7]. Therefore, knowing $\eta_{\mathrm{o,Jet-A}}$ of the baseline A350-1000 aircraft, the $\eta_{o,LH2}$ of the modified aircraft powered by this alternative fuel can be estimated. Additionally, 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. Lastly, h for Jet-A and LH_2 are taken to be 43.2 MJ/kg and 120 MJ/kg respectively [74]. Thus, all parameters (or the calculation process) of equation 1 are known and the aircraft range can be evaluated. In our previous study [7], we compared our long-range tube-wing LH_2 aircraft design and its performance characteristics with other studies, and these are in good agreement with each other (within ±5%, a criterion defined for low-order aircraft performance modelling [75,76]).

2.3 Sensitivity analysis

The effects of four technology parameters on the LH_2 aircraft performance are evaluated by simultaneously varying all four input parameters, using Breguet's range equation: η, C_f, η_o, and ω. The range for each of these four parameters applied in the sensitivity analysis are listed in Table 2. The ranges in Table 2 for four technology parameters are discussed further in this section.

The range for η (0.35 – 0.881) is based on multiple studies that model LH_2 aircraft for different range and passenger seating capacity, and these are included in Table 1 and this index is absorbed in equation which calculates the OEW of the LH_2 aircraft. A study by Sjöberg et al. [77] simulates a light weight LH_2 tank (3 m diameter and 4.7 m length) employing composite materials with η = 0.94 for a full tank, compared with a metallic tank having η = 0.71. Recent advances in stronger and low-weight composite materials have enabled LH_2 cryogenic tank η = 0.92 for manufactured tanks [78] for a small sized tank (length 2.4 m and diameter 1.2 m), that might improve in future. The tank design specifics and application for both tanks revealed above are not known completely from respective studies, and thus they are not listed in Table 1 and the maximum limit for the sensitivity analysis the remains unchanged (0.881). It is to be noted that in this study though the gravimetric index of the cryogenic tank is varied, it accounts for both weight and volume effects of LH_2 (see our previous study [7] for details).

The skin friction coefficient C_f enables the estimation of the aircraft *L/D*. For the present large transport jets the value of C_f is 0.003 [7,79,80]. For advanced/modern (N+2 and N+3 technology) large transport jets, C_f is projected to improve to 0.0025 [81], as futuristic aircraft could employ drag reducing devices/technologies. η_o of Jet-A powered present-day aircraft viz. A350-1000 is 0.4, and for future Jet-A aircraft engine this value is expected to increase to 0.455 [73] and 0.5 [82,83] for N+2 and N+3 technology (2050 timeframe) respectively. According to our previous study [7], $\eta_{o,LH2}$ / $\eta_{o,Jet-A}$ is 1.0314. Using this ratio, for the LH_2 powered A350-1000 (present-day) $\eta_{o,LH2}$ is calculated to be 0.413, and for the N+2 and N+3 technology LH_2 powered aircraft engine $\eta_{o,LH2}$ is calculated to be 0.464 and 0.516, respectively. In a futuristic aircraft design by Nickol et al. [73] using advanced technologies and materials for a large twin-aisle tube-wing aircraft, the fuselage weight (using stitched and resin-infused composite) and OEW of the Jet-A aircraft reduces by 15%. Thus, ω which is absorbed in the calculation of the OEW, varies from 0% (present technology) to 15% (N+2 and N+3 technology).

Table 2. Input ranges for different technology parameters for the sensitivity analysis

Input parameter	Minimum value	Maximum value	Reference
η	0.35	0.881	[36,47,48]
C_f	0.0025	0.003	[79–81]
η_o	0.4 for Jet-A 0.413 for LH_2 (calculated)	0.5 for Jet-A 0.516 for LH_2 (calculated)	[82,83]
ω	0%	15%	[73]

3. Results and discussion

The range of the baseline Jet-A aircraft is calculated to be 13,870 km (approximately 7,500 nautical miles), which is the target range for the LH_2 aircraft that has same MTOW limit of 316 tonnes (metric tonnes) at design point, as that of baseline Jet-A aircraft for the same passenger payload of 34,770 kg (366 passengers-payload) [7]. The following sections evaluate the sensitivity of LH_2 aircraft range, fuselage length, GTOW, and SEC to the range of possible values for η, C_f, η_o, and ω.

3.1 Aircraft range and critical value of η

Figure 1 shows the effect of η, C_f, η_o, and ω on the LH_2 aircraft range relative to the (present-day) baseline Jet-A aircraft. In summary, the LH_2 aircraft range matches that of the baseline aircraft for higher η, η_o, and ω and lower values of C_f. The different panels in Figure 1 represent different combinations of discrete values of η_o and C_f, and in each the relative range is shown for continuous values of η and ω for the ranges summarised in Table 2. For a given combination of η_o and C_f, we can determine the critical values of η and ω that would enable an LH_2 aircraft range on par with the baseline aircraft.

For today's values of $C_f = 0.003$ and $\eta_o = 0.413$ (plot a in Figure 1) and $\omega = 0$, η_{critical} can be observed to be 0.52. Alternatively, if LH_2 storage tank weight were greater, and $\eta = 0.38$, the relative aircraft range would be limited to 75% (i.e., 10,000 km) and no reasonable values of ω would enable the aircraft to match the baseline range. For the best-case improvements to $C_f = 0.0025$ and $\eta_o = 0.516$ (plot i in Figure 1), we observe that baseline aircraft range would be matched for $\eta > 0.38$ if $\omega = 0$, and $\eta > 0.35$ if $\omega > 2.5\%$. Adding future aircraft technology reference points to the discussion, the single-dot-dashed and two-dot-dashed line represent N+2 ($\omega = 15\%$, $C_f = 0.0025$ and $\eta_o = 0.464$) and N+3 ($\omega = 15\%$, $C_f = 0.0025$ and $\eta_o = 0.516$) technology, respectively. In SI § 2 (Figure SI 1) we show the effect of varying design target range and required η_{critical} for N+2 values of η_o and C_f at $\omega = 0$ and $\eta > 0.6$ is required for a design range of 20,000 km. Additionally, in SI § 2 (Figure SI 2) we show the effect of varying design target range and required ω_{critical} for N+2 values of η_o and C_f at $\eta = 0.35$ and $\omega > 11\%$ is required for a design range of 14,000 km.

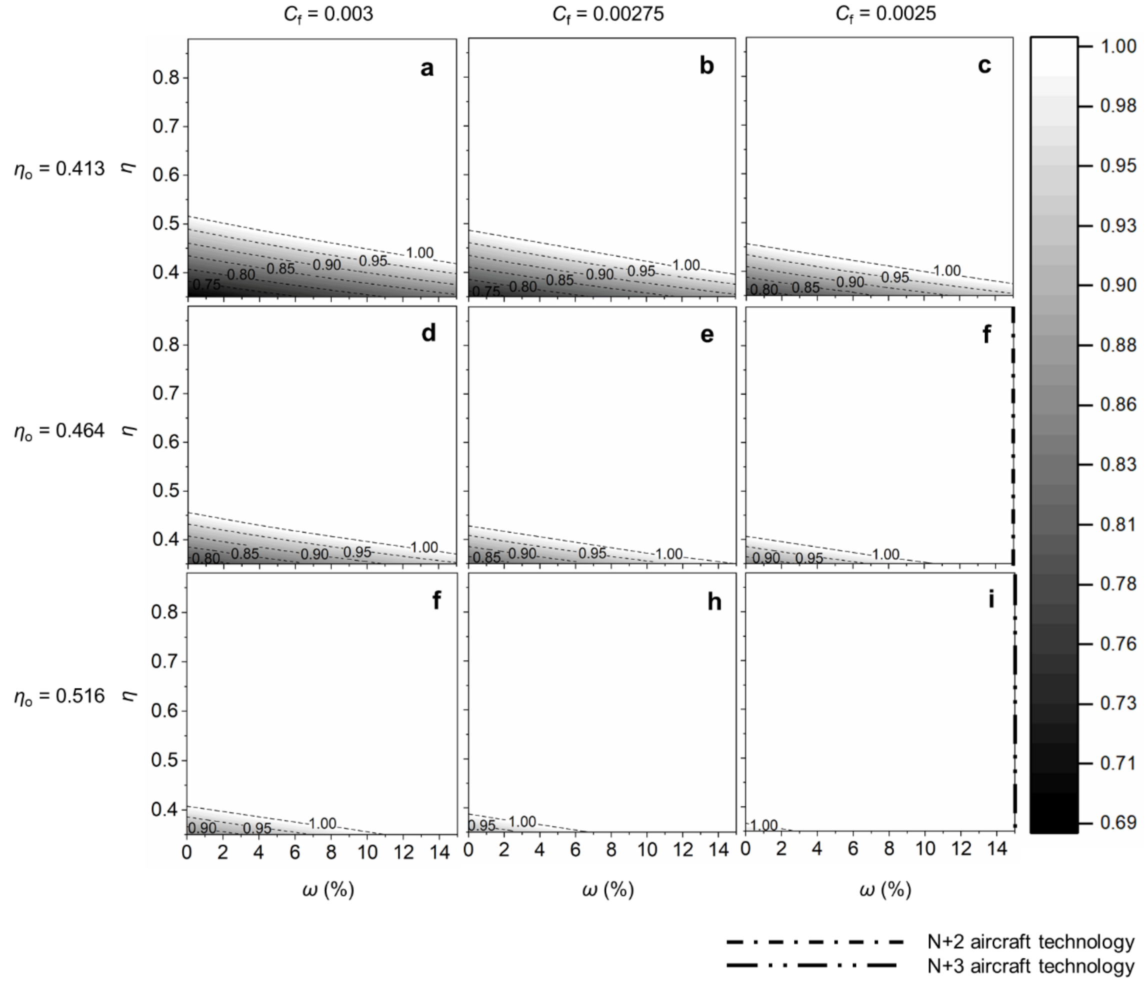

Figure 1. Effect of η, C_f, η_o, and ω on the LH_2 aircraft range relative to the (present-day) baseline (BL) Jet-A aircraft range

For the present-day aircraft technology, the critical value of η is 0.52 i.e., a minimum cryogenic tank η of 0.52 for enabling a (14,000 km) long-range LTA LH_2 aircraft (seating 366 passengers). Similarly, using N+2 and N+3 technology for the same payload and range combination, the (expected) critical value of $\eta < 0.35$ and $\eta \ll 0.35$, respectively, for a long-range LTA LH_2 aircraft.

3.2 Fuselage length extension

Figure 2 shows how the fuselage length is dependent on η and ω for different values of C_f and η_o. The relative increase in the LH_2 aircraft fuselage length is calculated with reference to the baseline Jet-A aircraft. In general, increasing η and/or ω would reduce the required additional fuselage length. However, for lower values of η and ω, the design range is not achieved (due to the MTOW constraint) and consequently the LH_2 aircraft fuselage length increases and peaks once the critical values of these two parameters are reached. Then as η and ω increase further, the fuselage length decreases due to reductions in the cryogenic tank weight and aircraft structural weight, respectively. As a result, the $W_{\text{F,total,LH2}}$ and associated OEW, and the aircraft GTOW reduce non-linearly with increasing η and/or ω

after the critical point. At a given higher η (beyond critical value), increasing ω reduces the LH_2 aircraft fuselage length (and associated drag) as the aircraft OEW reduces, which improves the energy consumption.

Additionally, LH_2 aircraft fuselage length can alternatively be represented in terms of the fineness ratio, which is defined as the ratio of fuselage length and fuselage diameter [84] and/or in terms of $W_{F,total,LH2}$. The trends of the effect of η, C_f, η_o, and ω on $W_{F,total,LH2}$ and fineness ratio are shown in Figure SI 3 and Figure SI 4 respectively (SI § 2). These trends are similar to the trends observed in Figure 2.

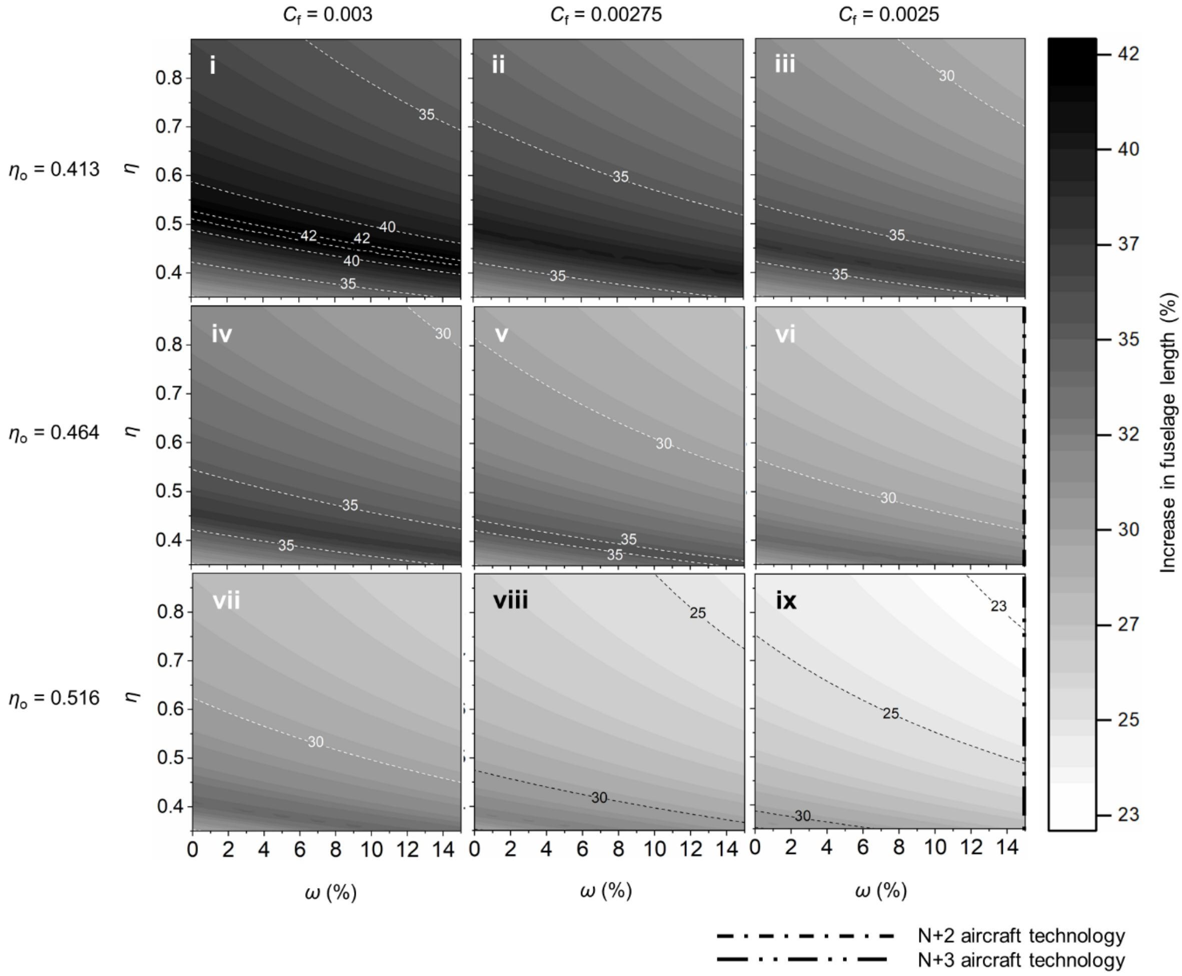

Figure 2. Effect of η, C_f, η_o, and ω on the percent increase in LH_2 aircraft fuselage length with reference to the (present-day) baseline Jet-A aircraft fuselage length

It can be observed from Figure 2 (with plot i in Figure 2 as a reference) that reducing C_f (from 0.003 to 0.0025) and/or increasing η_o (from 0.413 to 0.516) reduces the increase in the LH_2 aircraft fuselage length. Decreasing C_f reduces the drag coefficient (increases L/D), and/or increasing η_o improves the energy efficiency, thereby reducing the energy/fuel consumption or requirement and resultantly reducing the increase in the LH_2 aircraft fuselage length with reference to plot i in Figure 2. As a result, the LH_2 aircraft fuselage weight decreases with decreasing C_f and/or increasing η_o, and this can be observed from Figure SI 5 provided in SI § 2. For present-day aircraft technology at $\eta = 0.52$, we observe highest increase in LH_2 aircraft fuselage weight of 47%. Additionally, for N+2 and N+3 aircraft technology, we observe 10% - 15% and 6% - 10% increase (for different η) in LH_2 aircraft fuselage weight, respectively.

Within the range defined in this work for the four technology parameters, the maximum increase in the LH_2 aircraft fuselage length is observed to be 42.1% (at η_{critical} ridge in plot i in Figure 2). Additionally, N+2 aircraft technology leads to an increase in LH_2 aircraft fuselage length in the range of 27% - 33% (for different η). Lastly, the minimum increase in the LH_2 aircraft fuselage length is observed to be 22.5% (plot ix in Figure 2), where η, η_o, and ω have the maximum values and C_f has the minimum value i.e., N+3 aircraft technology with highest η ($\eta = 0.881$).

In the regime of η and ω combinations where the GTOW of the LH_2 aircraft equals MTOW, increasing ω reduces the aircraft structural weight, and therefore more LH_2 fuel quantity can be accommodated until the MTOW limit is reached. As a result, increasing ω increases the cryogenic tank weight in this regime. Increasing η and/or ω beyond their critical point reduces the cryogenic tank weight non-linearly (as $W_{\text{F,total,LH2}}$ decreases non-linearly from earlier discussion). These trends can be observed from Figure SI 6 provided in SI § 2. At a given higher η (beyond the critical value), increasing ω reduces the cryogenic tank weight as the aircraft gets lighter which improves the energy consumption. Additionally, reducing C_f and/or increasing η_o decreases the energy consumption/requirement (and $W_{\text{F,total,LH2}}$) and thus reduces the cryogenic tank weight. The lowest cryogenic tank weight is observed for both N+2 and N+3 aircraft technology at $\eta > 0.85$.

3.3 GTOW

Figure SI 7 provided in SI § 2 shows the effect of η, C_f, η_o, and ω on the ratio of OEW of the LH_2 aircraft (OEW_{LH2}) and the OEW of the (present-day) baseline (BL) Jet-A ($OEW_{\text{BL, Jet-A}}$) aircraft. We observe that increasing ω decreases LH_2 aircraft OEW, which is expected as per the definition of ω. As discussed earlier, increasing η reduces the cryogenic tank weight. Particularly, increasing η after the critical point reduces the cryogenic tank weight and LH_2 aircraft fuselage weight non-linearly. As a result, the LH_2 aircraft OEW reduces non-linearly with increasing η after the critical point. Additionally, reducing C_f and/or increasing η_o decreases the fuel/energy consumption and thus reduces the LH_2 aircraft fuselage weight and cryogenic tank weight, thereby reducing the LH_2 aircraft OEW. As expected, we observe lowest OEW_{LH2} at $\eta > 0.8$ for both N+2 and N+3 aircraft technology.

Figure 3 shows the effect of η, C_f, η_o, and ω on the ratio of GTOW of the LH_2 aircraft ($GTOW_{LH2}$) and the MTOW of the (present-day) baseline Jet-A ($MTOW_{\text{BL, Jet-A}}$) aircraft. The (dark) regime of η and ω combinations where the GTOW of the LH_2 aircraft equals MTOW (i.e., $GTOW_{LH2}/MTOW_{\text{BL, Jet-A}} = 1$) can be observed from Figure 3. After the critical point, increasing η reduces the LH_2 aircraft GTOW ($= W_p + OEW_{LH2} + W_{\text{F,total,LH2}}$) non-linearly as both LH_2 aircraft OEW and $W_{\text{F,total,LH2}}$ reduce non-linearly. At higher η beyond the critical value, increasing ω reduces the GTOW as the aircraft OEW reduces. Additionally, reducing C_f and/or increasing η_o decreases the fuel/energy consumption (and $W_{\text{F,total,LH2}}$ and the LH_2 aircraft OEW), and thus reduces LH_2 aircraft GTOW. For N+2 aircraft technology with $\eta > 0.8$, LH_2 aircraft GTOW reduces by approximately 30% compared to the baseline Jet-A aircraft. Within the range defined in this work for the four technology parameters, the maximum reduction in the LH_2 aircraft GTOW is observed to be 34% (plot x in Figure 3) compared to the baseline Jet-A aircraft, where η, η_o, and ω have the maximum values and C_f has the minimum value i.e., N+3 aircraft technology with $\eta > 0.8$.

The effect of the four technology parameters on the *L/D* performance can be observed from Figure SI 8 provided in SI § 2. Overall, the effect of C_f reduction on *L/D* performance is more pronounced than the effect of improvement in the other three technology parameters. The lift coefficient varies with the aircraft weight. Increasing η and/or ω reduce the GTOW or the aircraft weight (and lift coefficient) after critical point as discussed earlier, thereby reducing *L/D*. Additionally, reducing C_f reduces the zero-lift drag coefficient, thereby improving *L/D* performance. Similarly, increasing η_o

decreases the fuel/energy consumption (or reduces LH_2 fuselage length and the associated zero-lift drag), and thus improves the *L/D* performance.

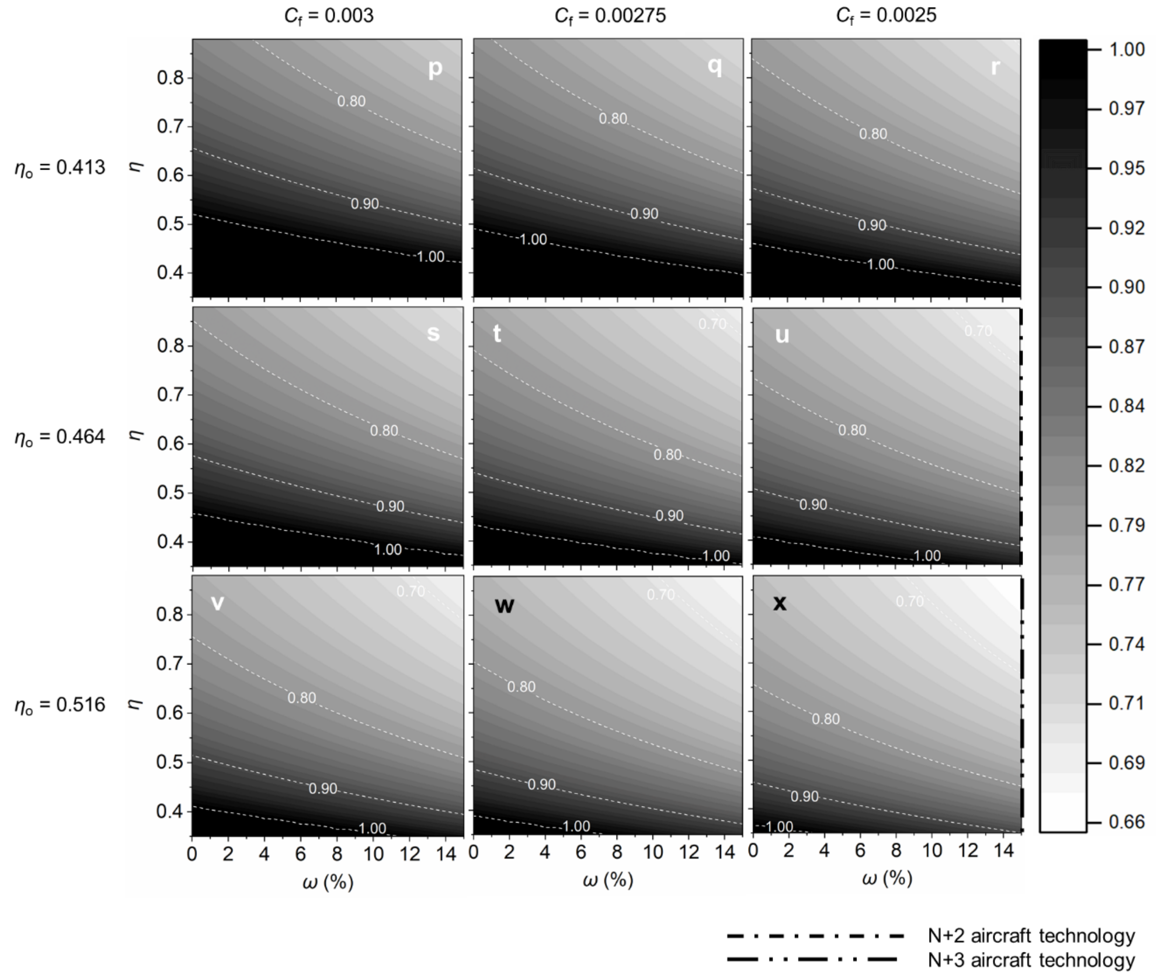

Figure 3. Effect of η, C_f, η_o, and ω on the ratio of the GTOW of the LH_2 aircraft ($GTOW_{LH2}$) and the MTOW of the (present-day) baseline Jet-A ($MTOW_{BL,\ Jet-A}$) aircraft

3.4 Specific Energy Consumption (SEC)

The impact of the four technology parameters on different aircraft aspects discussed above affect the aircraft's energy consumption. Figure 4 shows the effect of η, C_f, η_o, and ω on the ratio of SEC in MJ/tonne-km of the LH_2 aircraft (SEC_{LH2}) and SEC of the (present-day) baseline Jet-A ($SEC_{BL,Jet-A}$) aircraft. It can be observed from Figure 4 that as η increases, especially beyond the critical point (where design target range is met), LH_2 aircraft SEC decreases non-linearly due to the non-linear decrease in $W_{F,total,LH2}$ and OEW. Increasing ω reduces LH_2 aircraft weight and thus decrease the SEC, and this reduction is greater at higher η (beyond critical point). Additionally, reducing C_f and/or increasing η_o improves *L/D* and/or energy efficiency respectively, thereby reducing the LH_2 aircraft SEC. Within the range defined in this work for the four technology parameters, the maximum LH_2 aircraft SEC is observed to be 28.7% higher than the (present-day) baseline Jet-A aircraft (plot A in Figure 4, at low η with $C_f = 0.003$, $\eta_o = 0.413$ and $\omega = 0$). Additionally, for N+2 aircraft technology (with $\eta > 0.8$) the SEC reduction for the LH_2 aircraft is of the order of 25% compared to the (present-day) baseline Jet-A aircraft (plot F in Figure 4) (or ~6% increase in SEC compared to N+2 Jet-A aircraft [details in Table SI 2 in SI § 2]). Moreover, the N+3 technology (with $\eta > 0.8$) leads to a highest reduction in LH_2 aircraft SEC of approximately 33% than the (present-day) baseline Jet-A aircraft (plot I in Figure 4) (or ~6% increase in SEC compared to N+3 Jet-A aircraft [details in Table SI 2 in SI § 2]). This finding is similar to the findings of the study by Silberhorn et al. [64], which models the energy performance of LH_2 aircraft seating 261 passengers over 7,220 km using 2035 (N+3) aircraft technology. The energy consumption of this N+3 LH_2 aircraft decreases by 37.6% compared to present-day Jet-A aircraft.

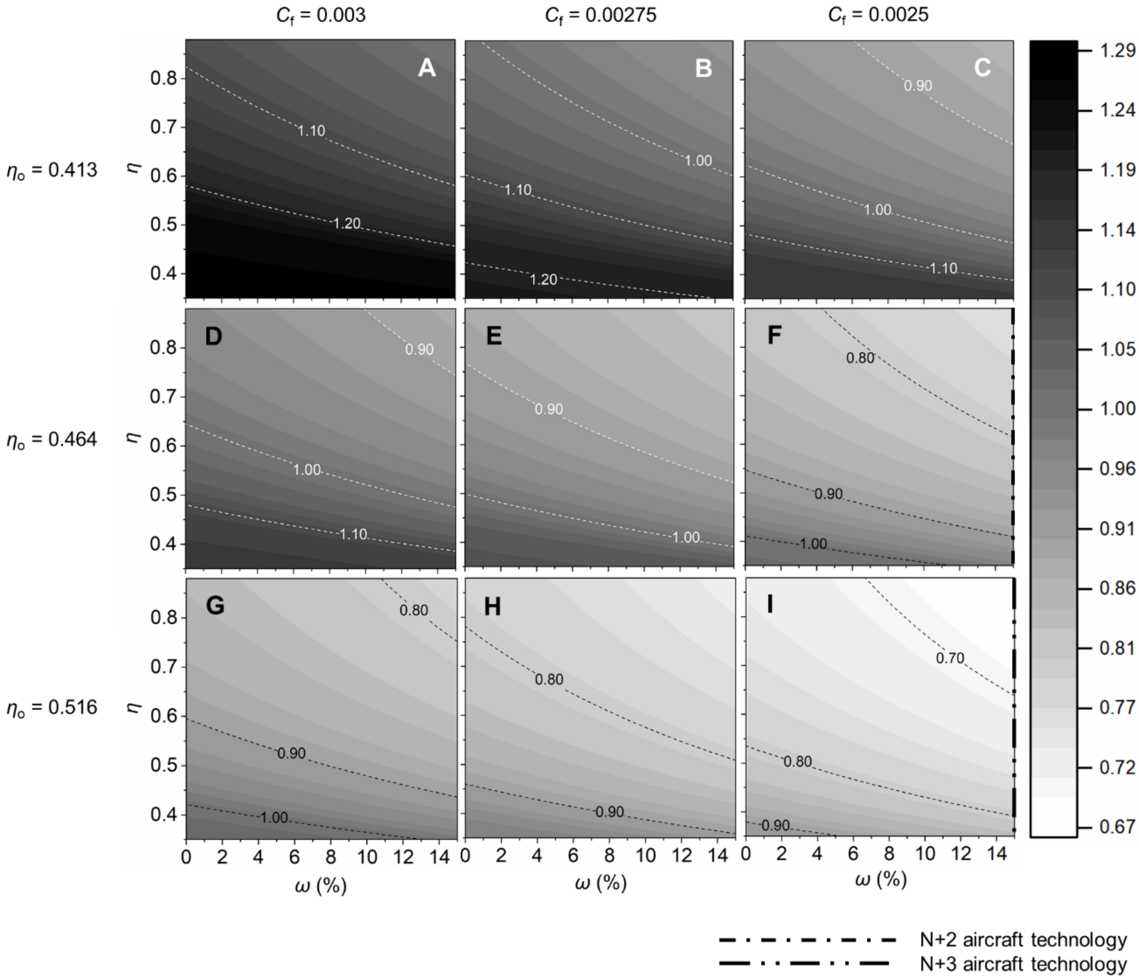

Figure 4. Effect of η, C_f, η_o, and ω on the ratio of SEC of the LH_2 aircraft (SEC_{LH2}) and SEC of the (present-day) baseline Jet-A ($SEC_{BL,\ Jet\text{-}A}$) aircraft

Figure 5 shows surface plots for comparing the effects of η, C_f, η_o, and ω on the ratio of SEC of the LH_2 aircraft and SEC of the (present-day) baseline Jet-A aircraft. Overall, we can clearly observe from Figure 5 that the effects of varying ω and/or η on LH_2 aircraft SEC are weaker than the effects observed for varying C_f and/or η_o. At higher values of η, increasing ω by 15% causes a significant reduction in LH_2 aircraft SEC compared to the effects observed at lower values of η. At higher values of η (beyond η = 0.7), LH_2 aircraft SEC is less sensitive to η variation. This ($\eta > 0.7$) is the typical regime observed for foam-based insulation tanks for long-range travel in large aircraft (from Table 1).

Referring to Figure 5 and using same plot names from Figure 4 (viz. plots A, C, G, and I), for a fixed C_f and η_o, and constant η, increasing ω by 15% causes a maximum reduction of LH_2 aircraft SEC by approximately 8%. Additionally, for a fixed C_f and η_o, and constant ω, increasing η from 0.35 to 0.881 causes a maximum reduction of LH_2 aircraft SEC by approximately 21%. For a constant η_o, reducing C_f from 0.003 to 0.0025 reduces LH_2 aircraft SEC by approximately 14% (moving from surface A to surface C). For a fixed C_f, increasing η_o from 0.413 to 0.516 (25% increase) reduces LH_2

aircraft SEC by approximately 22.5% (moving from surface A to surface G). Surface plot I in Figure 5 has highest and lowest values of η_o and C_f, respectively, used in this work, and it also includes the N+3 aircraft technology (not shown in Figure 5 but is shown in Figure 4). The lowest LH_2 aircraft SEC is found on surface plot I in Figure 5, at highest η and ω.

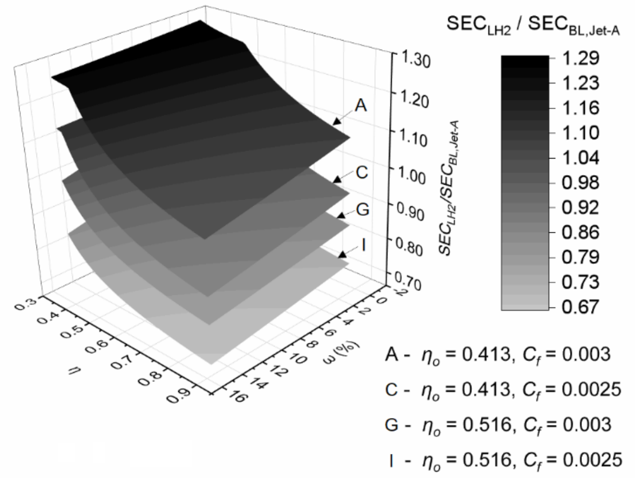

Figure 5. Surface plots for comparing the effects of η, C_f, η_o, and ω on the ratio of SEC of the LH_2 aircraft (SEC_{LH2}) and SEC of the (present-day) baseline Jet-A ($SEC_{BL, Jet\text{-}A}$) aircraft

3.5 Synthesis of results towards research objectives and guiding technology development

We observe via the sensitivity analysis that all four technology parameters – η_o, C_f, ω and η – impact the long-range LTA LH_2 aircraft performance. The aircraft design performance characteristics studied quantitatively (in §3.1 to 3.4) are the aircraft range, fuselage length extension for LH_2 storage, aircraft GTOW, and SEC and the sensitivity of technology parameters to it.

For the present-day aircraft technology, the critical value of η is 0.52 for a long-range LTA LH_2 aircraft. For N+2 and N+3 technology, the (expected) critical values of η are $\eta < 0.35$ and $\eta << 0.35$, respectively, for a long-range LTA LH_2 aircraft. Regardless of the aircraft technology, η should be maximised for reducing the SEC of the LH_2 aircraft. Lastly, it is observed that by increasing the target design range, the critical value of η also increases.

From the sensitivity analysis and discussion, it is clear that the technology parameters that provide reduction in LH_2 aircraft SEC, in decreasing order of impact, are η_o, C_f, ω and η. Ideally, all four technology parameters must be improved in future in order to enable a more energy efficient long-range travel with an LTA aircraft powered by LH_2 fuel. Particularly, η_o and C_f (or improved aerodynamics) provide a similar but significant order of reduction in LH_2 aircraft SEC, indicating that improving the overall efficiency and aircraft aerodynamics should be the priorities.

3.6 Discussion

Firstly, we observe that the LH_2 aircraft fuselage length increases significantly which could pose a challenge for LH_2 use in the conventional tube-wing airframe, since it could have stability and structural implications. The fineness ratio of the LH_2 aircraft modelled in our previous work [7] is (99.12/5.96 =) 16.63 (37.2% increase in fuselage length compared to the baseline Jet-A aircraft). From the sensitivity analysis in this work, the maximum and minimum fineness ratios are 17.23 (42.1% increase in fuselage length from baseline) and 14.85 (22.5% increase in fuselage length from baseline), respectively. Another challenge might be the compatibility of the significantly long tube-wing LH_2 aircraft with the present airport infrastructure for aircraft operations such as take-off, landing, and taxi.

Secondly, we observe that the LH_2 aircraft could have significantly lower GTOW (<34% reduction) and thus optimization is required for a lighter aircraft as the required thrust for maintaining the same thrust to weight (T/W) ratio reduces. This optimization would further decrease the SEC of the LH_2 aircraft.

Thirdly, from the sensitivity analysis we found that technology parameters that provide reduction in LH_2 aircraft SEC, in decreasing order of impact, are η_o, C_f, ω and η, and ideally all four technologies should be advanced. Also, it was observed that improving η_o and C_f (or improved aerodynamics) should be the priorities because they provide a similar but significant order of reduction in LH_2 aircraft SEC. Along these lines, the use of a blended wing body (BWB) aircraft architecture could be a promising solution for LH_2 use as it is expected to provide benefits in terms of significantly better integration of LH_2 storage due to its higher internal volume and highly improved aerodynamic (L/D) performance [36,85], compared to tube-wing aircraft.

LH_2 aircraft are attracting interest as: unlike fossil-derived Jet-A, LH_2 could be produced from renewable energy sources to lower life-cycle greenhouse-gas emissions, as further elaborated in SI § 3; LH_2 derived from renewable energy sources may reduce the sensitivity to volatile hydrocarbon fuel prices; and, LH_2 could be used for cooling of superconducting electrical machines and other onboard equipment, thus enabling further efficiency improvements. However, there are significant challenges in addition to those that we have considered in this study, including: the high energy required to liquify hydrogen as a result of ortho-para hydrogen conversion, but we note that technical developments may overcome this, e.g. [86],[87]; and, hydrogen boil off, which reduces the effective cryogenic tank gravimetric index [46,50,51] and has an indirect climate impact with a global warming potential over a 100-year time horizon of 11.6 ± 2.8 (one standard deviation) [88].

Furthermore, in our previous study [7] we conducted off-design performance (different range and payload combinations) of LH_2 aircraft and have included a qualitative discussion on important aspects such as: (a) impacts of fuel and life-cycle costs, (b) required modifications to aircraft and aviation sub-systems (infrastructure), and (c) impacts on airline decision-making and fleet planning.

3.7 Limitations

The current work is a low-order modelling of LH_2 aircraft performance characteristics using Breguet's range equation for the sensitivity analysis. The estimation of L/D ratio during cruise is done using the average aircraft cruise weight. Also, the wave drag is assumed to be negligible, and this is typically considered in the estimation of drag coefficient during a high-fidelity analysis. This examination is restricted only to the operational or use-phase of the aircraft and we do not consider life-cycle impacts. 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. The combustion of LH_2 fuel would release more water vapour at typical cruise altitude and could produce more contrails, and other non-CO_2 effects [22]. Moreover, aircraft stability and stress/structural evaluation are not conducted in this work (especially due to increase in fuselage length), and these could be important for LH_2 powered aircraft which is expected to have significantly greater fuselage length (~30% increase). The LH_2 aircraft could be significantly lighter (~30%) and thus optimization (airframe and engine) is necessary as this aircraft would have reduced thrust requirement for maintaining similar T/W as that of the baseline aircraft (or same aircraft class/type). The current study does not carry out rigorous aircraft design and optimization of LH_2 powered aircraft.

The other aircraft technology aspect that is important to the design of LH_2 powered long-range aircraft and the sensitivity analysis is the deck configuration or the fuselage diameter (single vs double deck). The volume of fuselage cryogenic fuel tank varies with the square of the diameter of the fuselage.

Therefore, large diameter (or equivalent diameter) fuselage similar to the Airbus A380 (double-decker very large twin aisle [VLTA]) can prevent large increases in fuselage length. This is also observed in the study by Verstraete [38] that uses FLOPS (flight optimisation system) software for aircraft performance modelling. The effect of fuselage diameter or cross-section is not investigated in the present work because this work is developed mostly using publicly available data. There is not a single aircraft in the present/past fleet that has full double-decker configuration in the LTA aircraft type which is the scope of this work.

4. Conclusion

Currently, the aviation industry is responsible for 3.5% of the net anthropogenic radiative forcing, and the use of advanced aircraft technology and low-carbon alternative fuels is the principal aviation industry's strategy to significantly mitigate climate impacts of aviation. This research performed a sensitivity analysis to evaluate the effects of four technology aspects – improved aerodynamics, use of lighter materials, cryogenic tank weight and improved overall efficiency – on the performance of subsonic LH_2 powered tube-wing LTA aircraft for 14,000 km range (or 7,500 nautical miles) seating 366 passengers at the design point, while considering the realistic gravimetric and volumetric energy density effects of LH_2 fuel on aircraft design within the MTOW limit of the baseline Jet-A LTA aircraft. We observe that the aircraft fuselage length increases significantly (~30%). This could pose challenges associated with the use of LH_2 in the conventional tube-wing architecture in terms of aircraft stability and structural design, and the compatibility of significantly long tube-wing LH_2 aircraft with the present airport infrastructure especially during aircraft operations such as LTO. We observe that for the present-day technology, the critical value of η is 0.52 for a long-range LTA LH_2 aircraft. For N+2 and N+3 technology, the (expected) critical values η are $\eta < 0.35$ and $\eta \ll 0.35$, respectively, for a long-range LTA LH_2 aircraft, but regardless of the aircraft technology used η should be maximised for reducing the SEC of the LH_2 aircraft. Additionally, we observe that by increasing the target design range, the critical value of η also increases. Moreover, we observe that improving the η_o and aircraft aerodynamics could contribute dramatically towards a more energy efficient LH_2 powered long-range aircraft compared to the present-day Jet-A aircraft. Lastly, using the most optimistic estimates for technology development, the SEC of the LH_2 tube-wing aircraft could be up to 33% lower than a present-day Jet-A aircraft, requiring at least 22% increase in fuselage length. Considering the above, the use of a BWB architecture could be a promising solution for LH_2 use as it is expected to provide benefits in terms of better integration of LH_2 storage due to its higher internal volume and highly improved aerodynamics (*L/D*) performance, compared to tube-wing aircraft. Lastly, the results of this work should inform further studies on the direct operating costs, and holistic/life-cycle energy and emissions (different production pathways). This will enable informed decision making towards the selection of alternative fuels and its production pathway, for a truly climate-neutral and cost-effective long-range air travel.

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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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