Data in brief: Performance sensitivity of subsonic liquid hydrogen long-range tube-wing aircraft to technology developments

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Abstract:

This is additional data to the main paper publication

Link to the main paper: https://www.sciencedirect.com/science/article/abs/pii/S0360319923038508

Nomenclature

BL	Baseline	SPK	Synthetic paraffin kerosene
BWB	Blended wing body	T/W	Thrust to weight ratio
C_f	Skin friction coefficient	$W_{F,total}$	Total fuel weight carried at mission start
FR	Fineness ratio	$W_{LH2\ tank}$	LH_2 cryogenic tank weight
GTOW	Gross take-off weight	η	Gravimetric index
LH_2	Liquid hydrogen	η_o	Overall efficiency
L/D	Lift to drag ratio	λ	Ratio of dry tank weight and cryogenic fuel weight
OEW	Operating empty weight	ω	OEW and fuselage weight reduction factor
PtL	Power-to-liquid		
SEC	Specific energy consumption		

SI 1. Tank gravimetric index

The cryogenic tank weight is typically reported as: (i) the gravimetric index, gravimetric efficiency, or gravimetric storage density (η), defined as the ratio of cryogenic fuel weight to the sum of the dry tank weight and cryogenic fuel weight [1–4]; or (ii) the ratio of dry tank weight and cryogenic fuel weight (λ). Table SI 1 shows different studies on liquid hydrogen (LH_2) powered aircraft with their tank gravimetric index. The integral type of tank is part of the basic airframe structure. Thus, it must 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 [1,5]. 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 [1,5]. It can be observed from Table SI 1 that tank η is dependent on the type of insulation and it improves with increasing aircraft size or range.

Table SI 1. Different studies on LH_2 powered aircraft with the tank gravimetric index

Study	Application	Tank type	Tank and insulation material	η	λ	Year, Ref.
			Multi-layer insulation			
Clean Sky 2 - Fuel Cells and Hydrogen joint project	19 passenger commuter aircraft with 500 km range	Integral	Double-wall evacuated tank with multi- layer insulation	0.25*	3**	2020 [2,6]
Clean Sky 2 - Fuel Cells and Hydrogen joint project	80 passenger regional aircraft with 1,000 km range	Integral	Double-wall evacuated tank with multi- layer insulation	0.30*	2.33**	2020 [2,6]
Clean Sky 2 - Fuel Cells and Hydrogen joint project	165 passenger (short-range) aircraft with 2,000 km range	Integral	Double-wall evacuated tank with multi- layer insulation	0.35*	1.86**	2020 [2,6]
Clean Sky 2 - Fuel Cells and Hydrogen joint project	250 passengers (medium-range) aircraft with 7,000 km range	Integral	Double-wall evacuated tank with multi- layer insulation	0.37*	1.70**	2020 [2,6]
Clean Sky 2 - Fuel Cells and Hydrogen joint project	325 passenger (long-range) aircraft with 10,000 km range	Integral	Double-wall evacuated tank with multi- layer insulation	0.38*	1.63**	2020 [2,6]
			Foam insulation			
Cryoplane	Different aircraft categories (regional to very large aircraft)	Integral	Stainless steel tank with polymer foam insultation	-	-	[7,8]
Winnefeld et al.	General application of cylindrical tanks	Non-integral	Aluminium alloy tank with polymer foam insultation	0.6 – 0.7*	0.667 – 0.429**	2018, [3]
Brewer (1991) summarized by Verstraete (2009)	-	Non-integral	Aluminium alloy tank with foam (polyurethane) insultation	0.9**	0.113*	1991, [4]

NACA/NASA	High-altitude (20 km) tube-wing reconnaissance aircraft	Integral	Stainless steel tank with plastic foam insulation	0.881 feasible (used 0.87)**	0.134 feasible (used 0.15)*	1955, [9,10]
Delgado Gosálvez et al. (Greenliner design)	19 passenger commuter aircraft with 926 km range	Non-integral	Aluminium alloy tank with foam insultation	0.5*	1**	2018, [11]
Verstrate et al.	Regional tube-wing aircraft for 32 passengers and range of 2,100 km	Integral	Aluminium alloy tank with foam (polyurethane) insultation	0.658 – 0.71*	0.52 – 0.408**	2010, [1]
Gomez et al.	Tube-wing aircraft for 197 passengers and range of 9,000 km	Integral	Aluminium alloy tank with polyurethane insultation	0.826 (rear tank) and 0.741 (forward tank)**	0.21 (rear tank) and 0.35 (forward tank)*	2019, [12]
Brewer (1991) summarized by Gomez et al. (2019) and Verstraete (2009)	Tube-wing aircraft for 400 passengers and range of 10,190 km	Integral	Aluminium alloy tank with foam (polyurethane) insultation	0.836**	0.196*	1991, [4,12,13]
Beck et al.	Very large twin aisle blended wing body aircraft with design range 11,400 km for 531 passengers)	Non-integral	Aluminium alloy tank with polymer foam insultation	0.77*	0.299**	2018, [14]
Verstrate et al.	Large tube-wing aircraft for 550 passengers and range of 13,890 km	Integral	Aluminium alloy tank with foam (polyurethane) insultation	0.764 – 0.791*	0.308 – 0.264**	2010, [1]

*Published values

**Calculated values

SI 2. Global sensitivity analysis – miscellaneous results

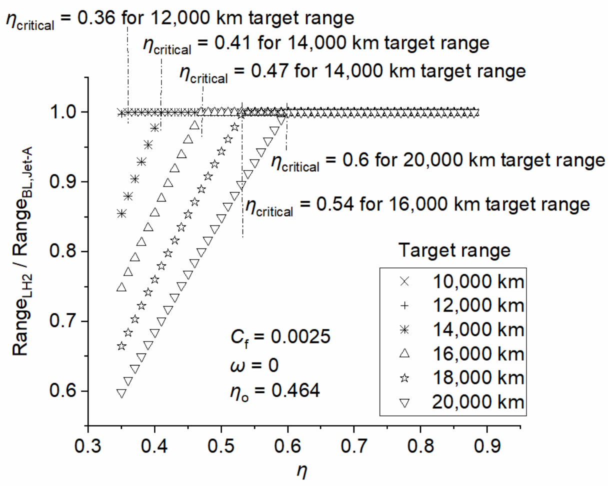

Figure SI 1. Effect of design target range on $\eta_{critical}$ of the LH_2 aircraft

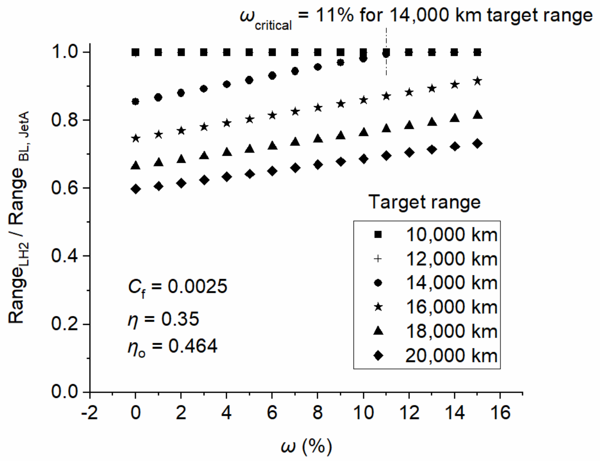

Figure SI 2. Effect of design target range on $\omega_{critical}$ of the LH_2 aircraft

Table SI 2. Performance characteristics of tube-wing LTA aircraft of different technologies for a design range of 13,870 km and carrying passenger payload of 34,770 kg

Aircraft/fuel	η	$W_{F,total}$ (kg)	Fuselage length (m)	OEW (kg)	η_o	L/D	GTOW (kg)	SEC (MJ/tonne-km)
Jet-A (A350)		126,101	72.25	155,129	0.40	18.63	316,000	10.17
N+2 Jet-A		89,256	72.25	131,859	0.45	19.74	255,886	7.20
N+3 Jet-A		79,791	72.25	131,859	0.50	19.55	246,420	6.43
LH_2 (A350)	0.88	49,226	98.51	175,532	0.41	15.88	259,528	11.02
N+2 LH_2	0.88	34,058	90.42	144,321	0.46	17.31	213,149	7.63
N+3 LH_2	0.88	30,433	88.48	143,155	0.52	17.33	208,358	6.82

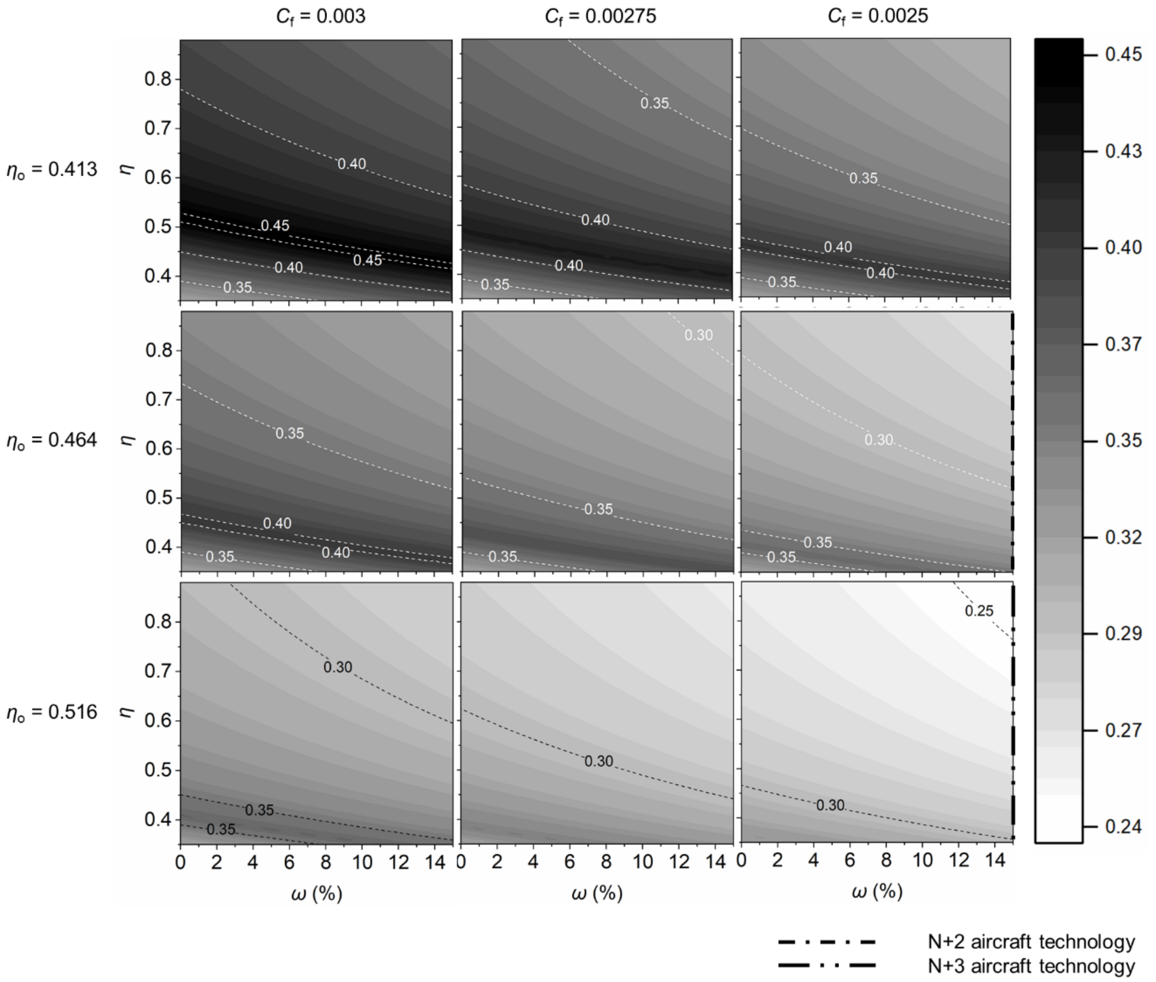

Figure SI 3. Effect of gravimetric index (*η*), skin friction coefficient (*C_f*), overall efficiency (*η_o*), and operating empty weight (OEW) and fuselage weight reduction factor (*ω*) on the ratio of the total LH_2 fuel weight carried at mission start ($W_{F,total,LH2}$) and (present-day) baseline (BL) Jet-A total fuel weight carried at mission start ($W_{F,total,BL\ Jet\text{-}A}$)

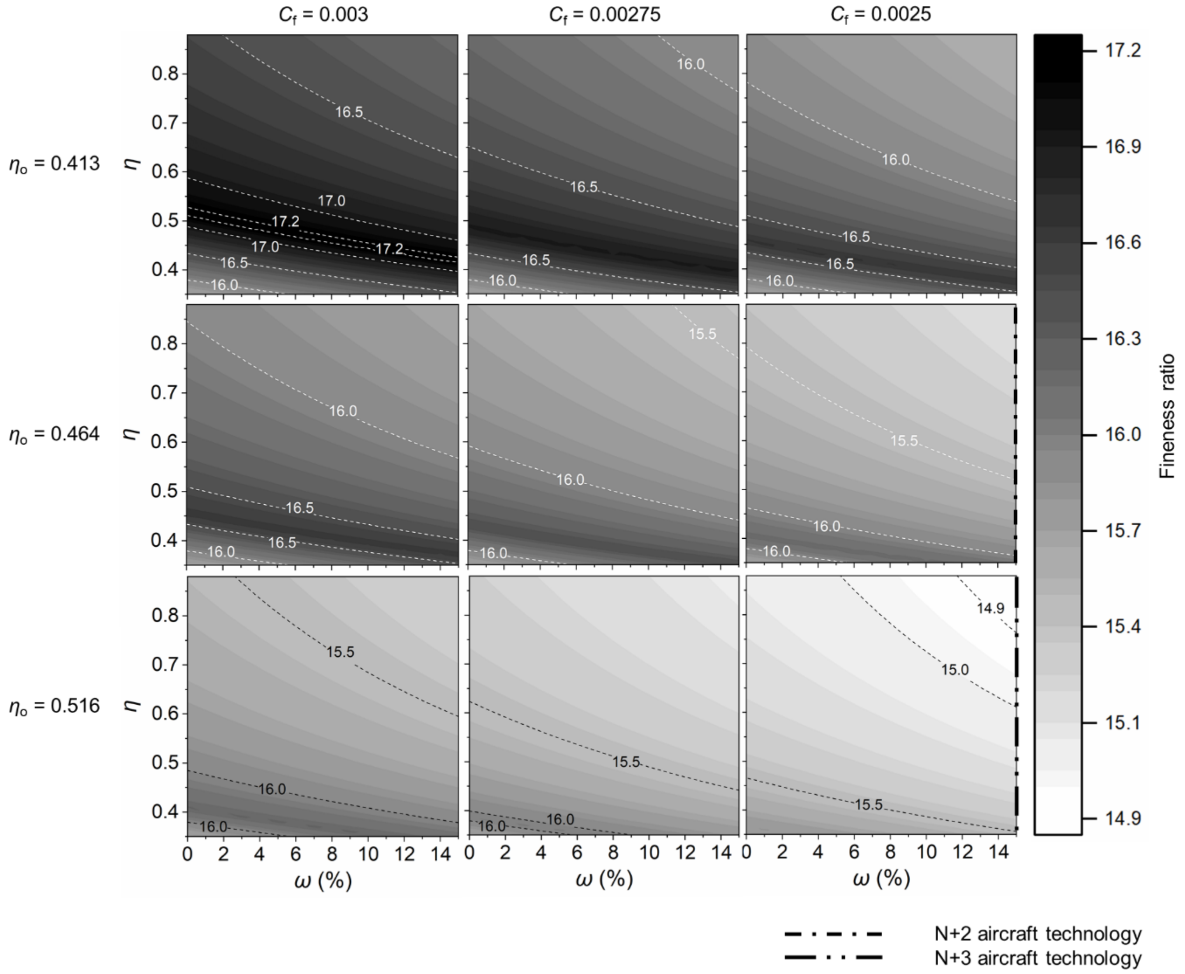

Figure SI 4. Effect of η, C_f, η_o, and ω on the fuselage fineness ratio of the LH_2 aircraft

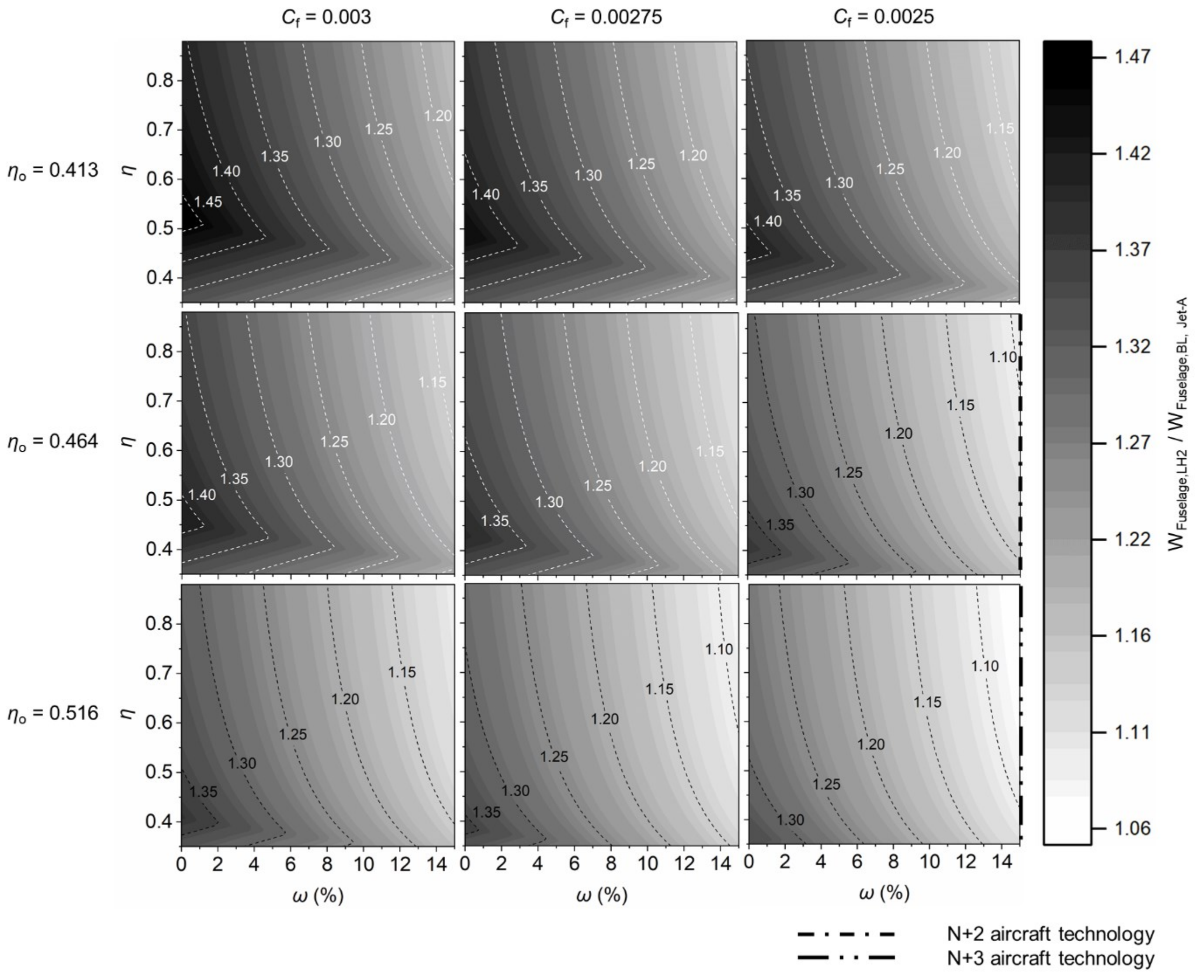

Figure SI 5. Effect of η, C_f, η_o, and ω on the ratio of LH_2 aircraft fuselage weight ($W_{Fuselage,LH2}$) and (present-day) baseline (BL) Jet-A aircraft fuselage weight ($W_{Fuselage,BL,Jet\text{-}A}$)

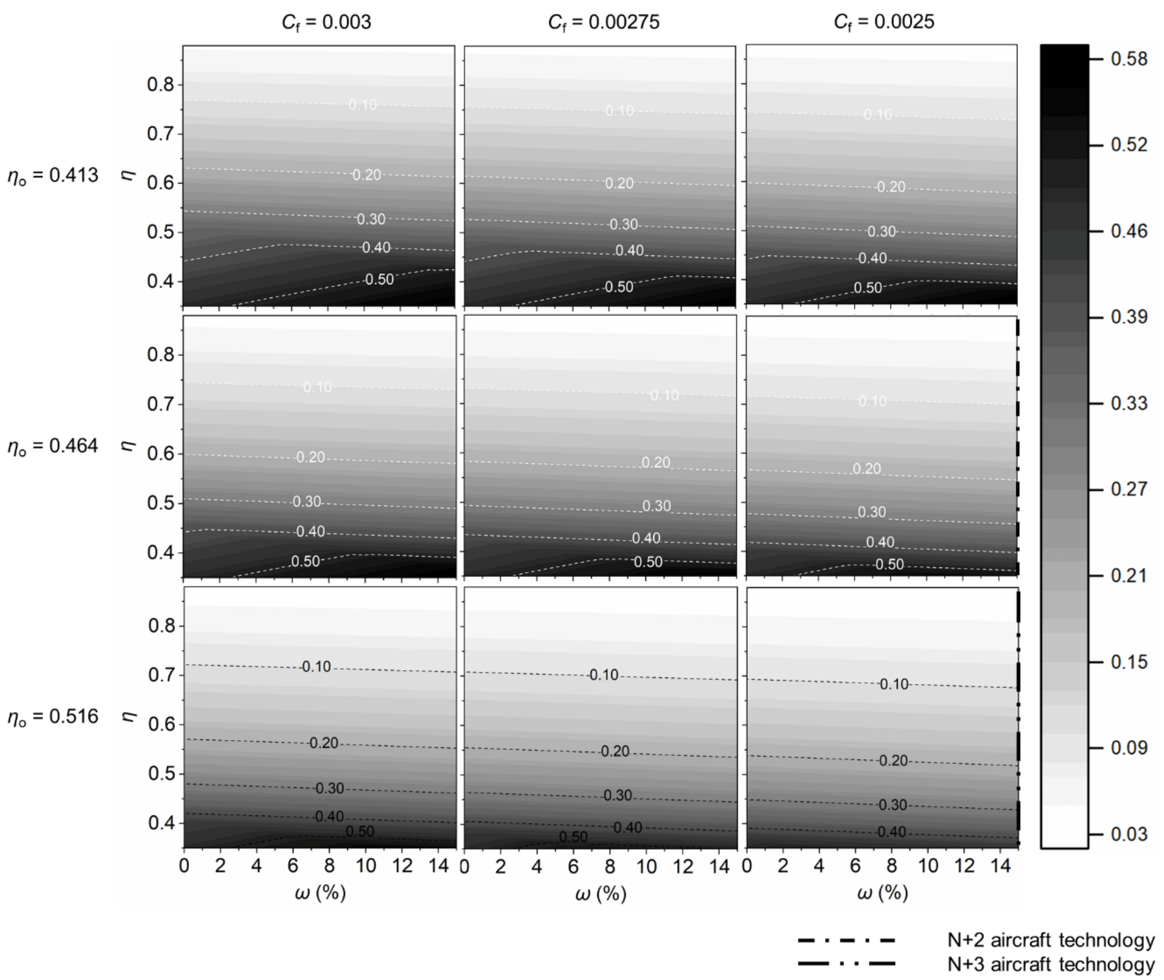

Figure SI 6. Effect of η, C_f, η_o, and ω on the ratio of the LH_2 cryogenic tank weight ($W_{LH2\ tank}$) and (present-day) baseline (BL) Jet-A aircraft OEW ($OEW_{BL,\ Jet\text{-}A}$)

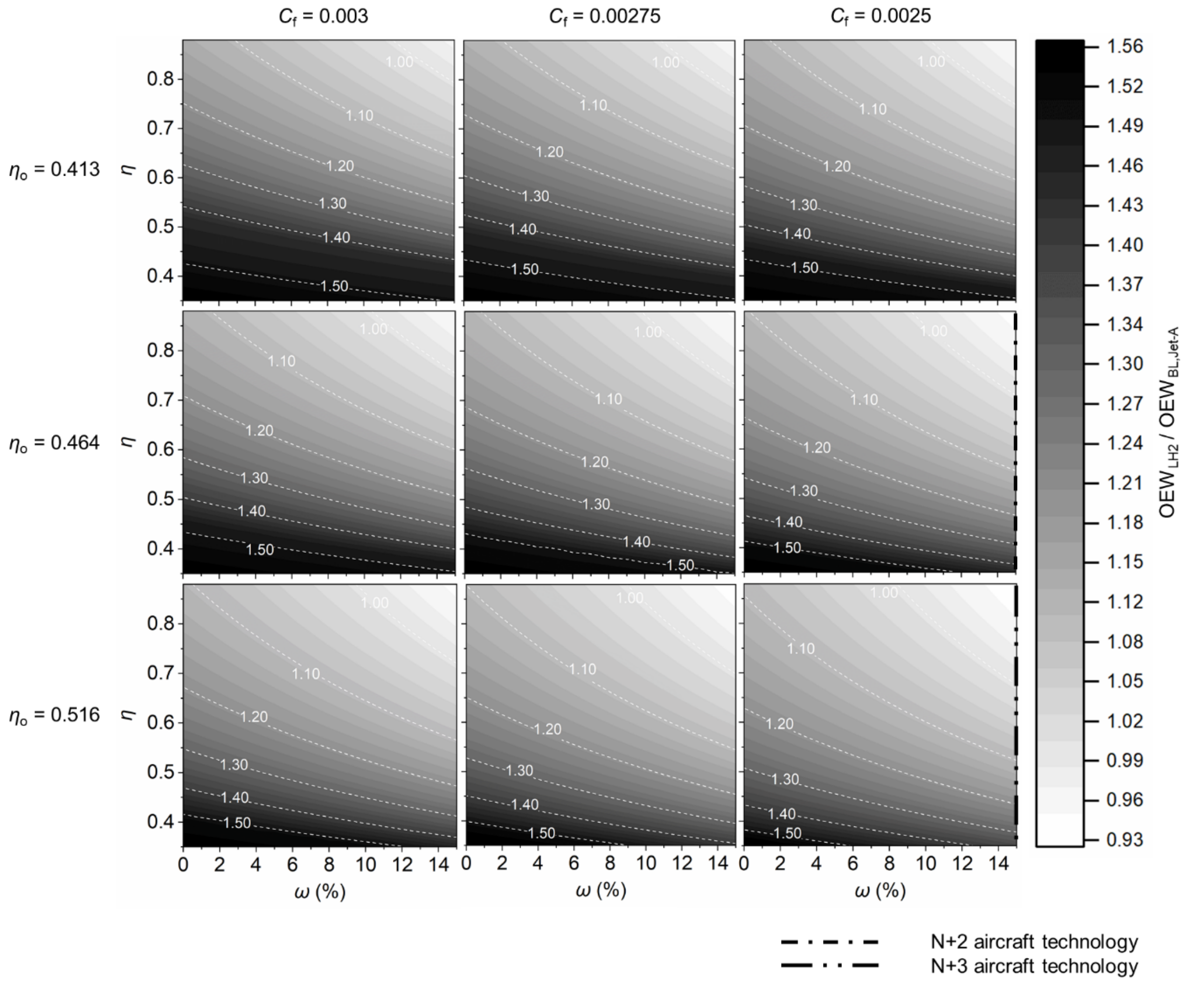

Figure SI 7. Effect of η, C_f, η_o, and ω on the ratio of OEW of LH_2 aircraft (OEW_{LH2}) and OEW of (present-day) baseline (BL) Jet-A ($OEW_{BL,\ Jet-A}$) aircraft

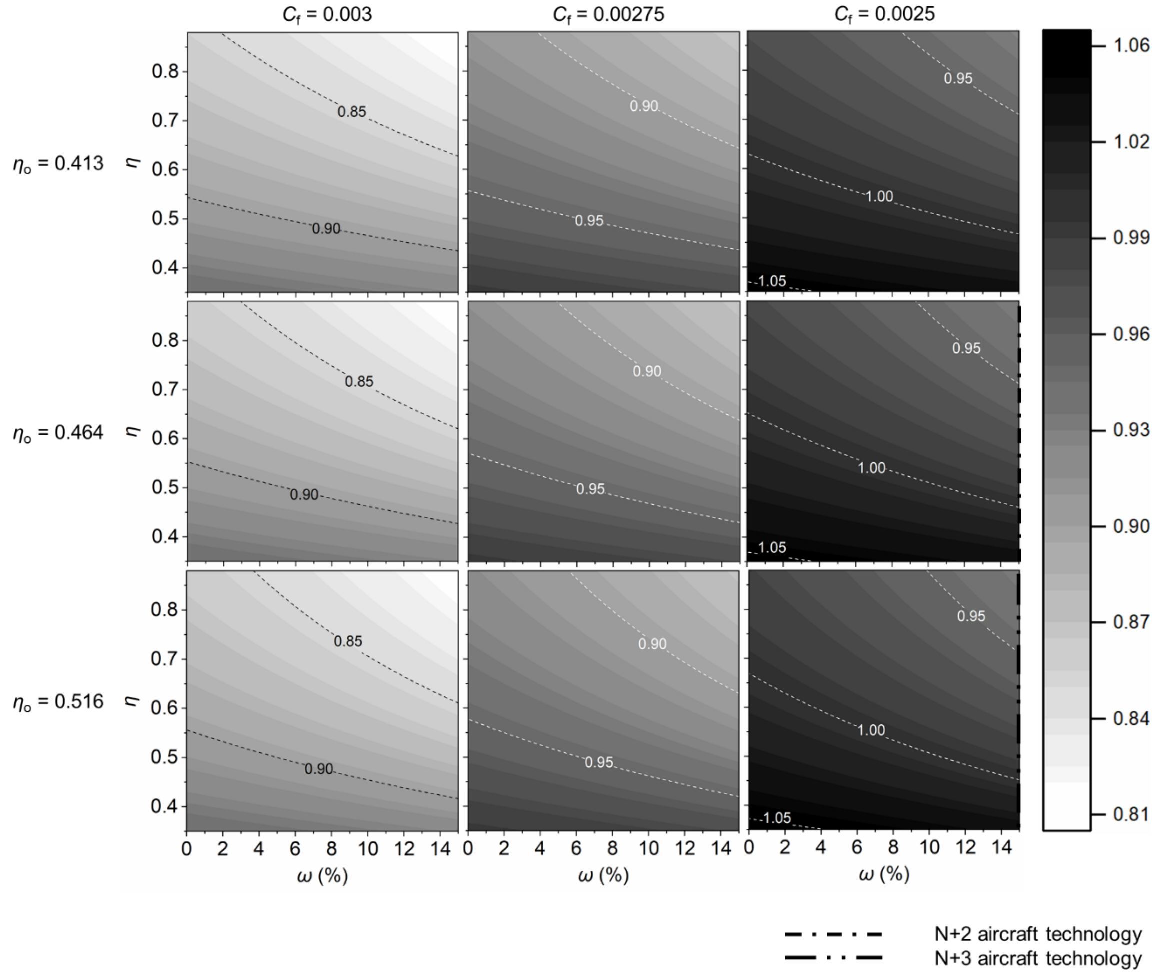

Figure SI 8. Effect of η, C_f, η_o, and ω on the ratio of LH_2 aircraft lift to drag ratio $(L/D)_{LH2}$ and (present-day) baseline (BL) Jet-A aircraft lift to drag ratio $(L/D)_{BL,\ Jet\text{-}A}$

SI 3. Detailed author comments

SI 3.1 Aircraft length

The fuselage fineness ratio (FR = length/diameter) of Boeing 777-300 ER is (73.9/6.2 =) 11.92, and that of both Boeing 777-200 LR and ER is 10.27 (= 63.7/6.2) [15,16]. The FR of Boeing 787-10, 787-9 and 787-8 are 11.7 (= 67.48/5.77), 10.75 (= 62/5.77) and 9.69 (= 55.91/5.77) respectively [17] [16]. The FR of the baseline A350-1000 Jet-A aircraft is known to be 12.12 [16]. The FR of the LH_2 aircraft modelled in our previous study [16] is (99.12/5.96 =) 16.63 (37.2% increase in fuselage length compared to the baseline Jet-A aircraft). From the global sensitivity analysis, the maximum and minimum FR is 17.23 (42.1% increase in fuselage length from baseline) and 14.85 (22.5% increase in fuselage length from baseline), respectively. The DC-8 Super 60 is an interesting case since it has a slender fuselage and FR of 14.95 (= 55.75/3.73) [16,18]. Finally, the FR of Concorde is 16.7 [19]. The Concorde is an exception to the above list of FR since it was a supersonic aircraft, having special aerodynamic needs relative to the sub-sonic civil aircraft. High FR or slender fuselage enables greater cruise Mach number flights because the drag divergence number increases [16,20].

LH_2 aircraft having longer fuselage poses several challenges [16]. These aircraft might need a complete engineering design and development for improving the structural strength to support a longer fuselage (for avoiding longitudinal fuselage failure). The longer fuselage especially with an unchanged diameter (high FR) might increase fuselage bending and related stresses. Also, fuselage length increase could move the location of aircraft's centre of gravity. As a result, an evaluation would be required for checking the criteria for landing gear positioning and an assessment on the necessary landing and take-off speeds for preventing tail-strikes. From a design perspective, a longer fuselage could be unsafe considering flight dynamics, and to provide stability the control surfaces and empennage should be recalibrated/redesigned.

Additionally, on an absolute scale, longer fuselage might require longer field length at landing and take-off and could have an effect on operations at the airport, turning radius, operations at the airport [16]. Thus, there could be compatibility issues of the significantly longer aircraft, with current airport infrastructure. The above aspects need to be considered while designing and/or planning of future airport if such significantly longer LH_2 aircraft (relative to present-day aircraft) are to be operated.

SI 3.2 Optimization of aircraft

In this study and previous study [16], it was/is assumed that the thrust production for alternative fuels (including LH_2) and Jet-A remains unchanged. It is observed in § 3 of the main document that the gross take-off weight (GTOW) of the LH_2 aircraft decreases by up to 34% (maximum GTOW reduction), and therefore its thrust/weight ratio (*T/W*) will be higher as compared with the baseline Jet-A aircraft. The optimization of the LH_2 aircraft is required accounting significant reduction in GTOW, thereby reducing the thrust requirement and thus the energy consumption. For a LH_2 powered aircraft, as per studies by Nojoumi [21] and Dincer [22], the thrust requirement decreases and causing the engine to become smaller in size causing weight reduction. The thrust requirement reduction decreases engine weight and related reduction in fuel weight, which further decreases the GTOW [16]. Thus, for LH_2 aircraft where there is significant reduction in GTOW, optimization is required for maintaining similar *T/W* of the baseline aircraft.

SI 3.3 Other future technologies for enabling LH_2 aircraft

The present aircraft structures (tube-wing) are designed to store Jet-A (type) fuel which fuel the gas turbine engines, and this combination only allows a limited retrofitting of alternative energy vectors such as LH_2 [3]. Novel and unconventional aircraft design architecture like the blended wing body (BWB) aircraft enables a more flexible integration of cryogenic hydrogen tanks [3]. This is because the BWB aircraft has lesser wetted area to volume ratio compared to the tube-wing aircraft [23]. In other words, BWB aircraft has higher internal volume and better *L/D* compared to the conventional tube-wing aircraft. In the global sensitivity analysis, it was observed that improving the aerodynamics was one of the two technology aspect that can enable a successful and energy efficient large long-range LH_2 aircraft. Therefore, BWB is a promising and new aircraft architecture is expected to provide benefits in terms of better *L/D* performance, and LH_2 storage due to its higher internal volume, compared to tube-wing aircraft.

According to the Clean Sky 2 - Fuel Cells and Hydrogen joint project report [2], "*LH_2 is technically feasible but less suitable for evolutionary long-range aircraft designs from an economic perspective*". PtL fuel might be a more cost-effective decarbonization solution with an evolutionary tube-wing long-range large aircraft [2]. Innovative and novel aircraft architecture like BWB could change that for the use of LH_2 in large long-range flight but may be after 2040 (service entry) [2]. Revolutionary designs like BWB that enable significantly better integration of the LH_2 storage and have improved aerodynamics, and could be an effective solution for the decarbonization of future large long-range air transportation [2]. The limitation of such radically novel/unconventional aircraft is that they have an uncertain and long commercialization process [2]. Additionally, these require extended testing for ensuring the aircraft's aerodynamic stability in different flight conditions and for optimizing cabin design, manufacturing, and operations [2].

SI 3.4 Embodied emissions and energy

The cost of LH_2 and other alternative fuels depend on the pathway and/or feedstocks with which they are manufactured [16]. Another aspect of the operational cost is the incentive of operating the aircraft with clean alternative fuels like LH_2 that release zero carbon. The production pathway of the alternative fuels should be less carbon intense, and this would enable aviation's decarbonisation in a true sense.

As per the Clean Sky 2 - Fuel Cells and Hydrogen joint project report [2], instead of LH_2, power-to-liquid (PtL) fuel [similar to synthetic paraffin kerosene (SPK) fuel properties] could cost less and offer a decarbonization solution to be used on an evolutionary tube-wing long-range aircraft. It is to be noted that hydrogen is an intermediate product in the PtL fuel manufacturing process (via electrolysis of water using the power generated from renewable energy) [16]. Accounting the conversion losses in the PtL fuel manufacturing (from hydrogen) and considering that LH_2 powered tube-wing aircraft using future technology could be 33% more energy efficient (known from the global sensitivity analysis) compared to the present day tube-wing Jet-A aircraft, the LH_2 aircraft powered by hydrogen manufactured from the renewable electricity might be more sustainable on life-cycle basis compared to PtL.

More information:

First author's other research work can be found in [16,24–53].

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