

Airliner Conceptual Designs for the Application of Alternative Fuels

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This paper investigates the application of alternative fuels in tube-and-wing aircraft configurations. Potential alternative fuel choices include biofuel, liquid hydrogen, liquefied natural gas and ammonia. A comprehensive mission range starting from 2000 nautical miles to 8500 nautical miles is explored, designed and analysed using GENUS, an in-house built multidisciplinary design analysis and optimisation platform. This paper aims to give a comprehensive study of different alternative fuel options and capacity combinations over different mission ranges. The different gradients of these trends demonstrate the additional benefits of using alternative fuels. The objectives of this study are 1) to determine how different fuel properties affect the designs and performance of aircraft; 2) to quantify the reduction of greenhouse gas (GHG) emissions by utilising alternative fuel. The results show cryogenic fuel, which requires fuselage fuel tanks and/or external fuel tanks, will noticeably increase energy consumption due to drag and weight penalties. Yet, the high specific energy density properties of liquid hydrogen (LH₂) will offset the penalties and result in a reduction in specific energy consumption (MJ/pax/nm), especially in a high capacity long range mission. A 20.8% and 13.7% reduction in specific energy consumption is calculated between the use of kerosene based jet fuel and LH₂ for a 400 and 800 pax design with an 8500 nm mission range respectively. In addition, the use of LH₂ and biofuel can significantly reduce life cycle GHG emissions if the fuel is produced through sustainable pathways.

Nomenclature

$\alpha(C)$	=	Constant angle of attack
$\gamma(C)$	=	Constant flight path
$a(C)$	=	Constant acceleration
DOF	=	Degree of freedom

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<i>GHG</i>	=	greenhouse gas
<i>H(C)</i>	=	Constant altitude
<i>IATA</i>	=	International Air Transport Association
<i>ICAO</i>	=	International Civil Aviation Organisation
<i>LCA</i>	=	Life cycle analysis
<i>LH₂</i>	=	Liquid hydrogen
<i>LNG</i>	=	Liquefied natural gas
<i>LSGRG2</i>	=	Large scale generalised reduced gradient 2
<i>Ma(C)</i>	=	Constant Mach number
<i>Ma(L)</i>	=	Linear Mach number
<i>MDAO</i>	=	Multidisciplinary design analysis and optimisation
<i>MTOM</i>	=	Maximum take-off mass
<i>NH₃</i>	=	Ammonia
<i>P_d(C)</i>	=	Constant dynamic pressure
<i>TAW</i>	=	Tube-and-Wing
<i>TO</i>	=	Take-off
<i>T_t(C)</i>	=	Constant throttle
<i>v(C)</i>	=	Constant velocity
<i>V_v(C)</i>	=	Constant vertical velocity

I. Introduction

ALTERNATIVE fuels have come to the interest of many in the commercial aviation industry. Especially with the vision of achieving Net Zero emissions by 2050. International Civil Aviation Organisation (ICAO), International Air Transport Association (IATA) and United Kingdom Sustainable Aviation have set their vision and technical road maps on how to achieve Net Zero, in which the application of alternative fuel plays a major role [1–6]. The use of alternative fuels can help achieve Net Zero by reducing direct emissions during flight and/or indirect emissions during fuel production.

Potential alternative fuel candidates include biofuel, synthetic fuel, liquid hydrogen (LH₂), liquefied natural gas (LNG) and ammonia (NH₃). Among these fuels, biofuel and synthetic fuel share much the same properties, such as density, specific energy density and volumetric energy density, to existing kerosene-based jet fuel. They are also known as drop-in fuel which can be adapted to current aircraft fleets with little to no modifications [7]. However, most of the other alternative fuel candidates have rather different physical properties, like density and boiling temperature, in which

some of them need to be used as a cryogenic fuel, including LH_2 and LNG. Therefore changes to existing aircraft are required, including but not limited to type of fuel tanks and fuel tank location and packaging [8–10].

Some alternative fuels show potential improvements in performance in addition to reducing greenhouse gas (GHG) emissions [11]. Take LH_2 as an example, it is a much lighter fuel compared to CJF. Some studies propose that it will be more suitable to use LH_2 for long range missions [8, 12–15]. However, there is a limited number of research investigating how the application of alternative fuels directly affects the designs of the aircraft and provides a fair performance comparison between designs with alternative fuels.

On the other hand, commercial aircraft have adopted the Tube-and-Wing (TAW) configuration since the beginning of the Jet age back in the 1940s [16]. The TAW configuration consists of a circular cross-section fuselage with wings attached in the middle lower part of the fuselage and stabiliser devices attached at the rear of the aircraft [17]. This is a simple and effective design where passengers and payload are concentrated in the fuselage. In addition, circular cross-section fuselage is optimised for pressurisation and location of exit doors, which make it safe and comfortable for passengers. Furthermore fuel is stored in integral wing tanks and additional centre tanks. However, integral wing tanks are not suitable for cryogenic fuel mostly because of the insufficient volume for insulation. Therefore, specifically designed cryogenic fuel tank is used as external wing tanks or fuselage fuel tank [9, 11]. There is also a rising interest in using conformal tanks for cryogenic fuels for commercial aircraft which is more commonly seen in military aircraft.

The aim of this paper is to explore the application of alternative fuels in conventional TAW configurations for different mission ranges to 1) determine how different fuel properties will affect the designs and performance of aircraft, 2) quantify the reduction of GHG emission by utilising alternative fuels. This will be evaluated in different emissions criteria counting total fuel consumption, life cycle emissions and specific fuel consumption [18].

II. Design methodology

The design analysis is conducted using GENUS [19], a multidisciplinary design analysis and optimisation (MDAO) platform. GENUS can model and analyse a wide range of designs from conventional TAW to box wing, high aspect ratio wing and blended wing body. There are a number of case studies of aircraft designs using GENUS [19–24].

GENUS consists of multiple parametric design modules where the user can input or modify different values to calculate different designs. These modules include geometry and packaging, mission, propulsion, mass breakdown, aerodynamics, performance and stability. In addition, it also consists of some extra modules like cost and emission.

A. Geometry and packaging

The geometry module allows the user to model their aircraft by defining body components and lifting surfaces. Body components refer to the fuselage, engine nacelle and external tanks if relevant. Meanwhile, wings, horizontal tail, vertical tail and canard are assigned as lifting surfaces. This allows a very flexible aircraft modelling thus making

it possible to represent both conventional and unconventional aircraft designs. Figure 1 exhibits an example of a conventional aircraft modelled by GENUS.

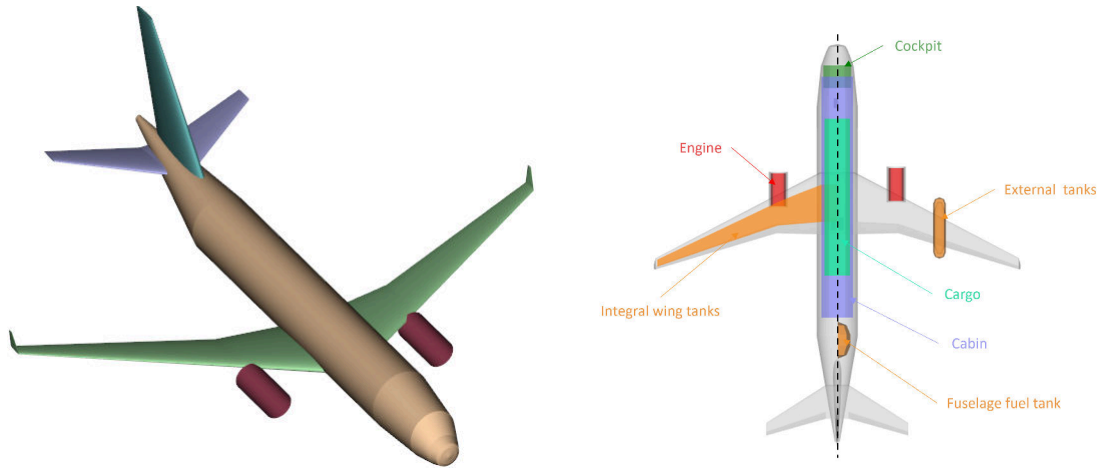


Fig. 1 Geometry generated by GENUS

Apart from the external geometry, GENUS is capable of modelling essential components inside the aircraft using a packaging module. This includes the cabin, cockpit, fuel tanks and cargo container, presented in Figure 1. Firstly, modelling these internal components can ensure the sizing of the aircraft is done correctly and has sufficient space for the designed payload, passenger capacity and fuel tank volume. This can also make sure there is no intercession between internal components and interference with the external surface. Secondly, modelling of these internal components allows a more accurate calculation of the centre of gravity (CG) position, which is calculated in mass breakdown modules and analysed in stability and control modules.

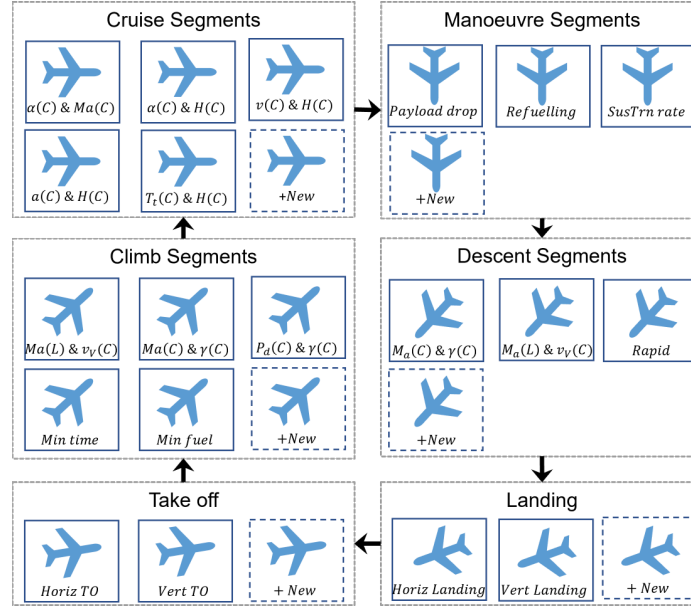
B. Mission and performance

Mission requirements can be defined in the mission module. Table 1 listed a range of payload and mission ranges which are employed to consider a range of market sectors. Exploring the whole design space can truly identify the advantages and disadvantages of the application of alternative fuels and how they respond and behave respecting different missions.

Specific missions can further break down into different flight segments including take-off, climb, cruise, descend, loiter, landing and more. These segments can be freely arranged and composed to simulate different flight profiles, displayed in figure 2. The entire mission is split into a collection of single instances of flight points. These points will be analysed to see if they will fulfil the mission requirement within the performance module. Results of the calculation will be generated through the output of this module with the errors between the results and target values.

Table 1 Mission requirement

Requirement	Value	notes
Passengers	200, 400, 800	single class with seat: 30" (P) $\times$ 17" (W) Three different passenger capacities
Range(nm)	2000 ~ 8500	increments of 500 nautical miles maximum range with maximum payload
Altitude (m)	12,000	assuming constant cruise altitude
Cruise speed (Mach)	0.8	assuming constant cruise speed
Take-off requirement (m)	2500	4C aerodrome or above @ standard sea level & temperature
Landing requirement (m)	1800	4C aerodrome or above @ standard sea level & temperature

**Fig. 2 Mission segment combinations**

C. Propulsion and emissions

NASA EngineSim model [25] is used in the propulsion module. This permits a high flexibility in engine modelling and generates rubber engines based on different design parameters, such as engine type, geometry, materials and so forth. Available thrust and specific fuel consumption (SFC) will be calculated at different flight conditions.

To simulate the application of alternative fuels, different alternative fuel properties are set within GENUS based on different literature reviews [26–29], listed in Table 2. GENUS can subsequently calculate the required fuel and determine if the design can satisfy the assigned mission. In addition, a simple emission model is constructed with preset GHG emission factors collected from various research papers [7, 11, 30–33]. It calculates the CO_2 emission of each flight by the fuel type and the amount of fuel used. Indirect CO_2 emissions from production, transportation and distribution can also be estimated.

Table 2 Alternative fuel properties

Fuel	Density (kg/m^3)	Volumetric energy density (MJ/L)	Specific energy density (MJ/kg)	Boiling point (K)
Kerosene [11, 30]	808	34.9	43.2	423.15
Biofuel [7, 11, 30]	870	33.9	38.9	588.15
LH ₂ [11, 31, 34]	70.8	8.49	120	20
LNG [11, 35]	430	22	48	113
Ammonia [11, 31– 33]	730	12	22.5	239.81

D. Mass breakdown

The mass breakdown module is capable of empirical methods incorporating Daniel Raymer [36], Denis Howe [37] and the Cranfield mass prediction method [38, 39]. Despite being three separated methods, they all share the similar approach by estimating an initial MTOM of the aircraft and verified with the calculated one. Once the result is converged, the components mass will be assigned based on the MTOM, which will later be used in the packaging module to predict the centre of gravity and inertia load distribution.

With the application of new technologies and design, such as cryogenic fuselage and/or external tanks, additional calculations and considerations are needed. Physical methods are used to estimation the structure and insulation weight of different cryogenic fuel tank based on the temperature and pressure requirement [40].

E. Aerodynamics

GENUS provides three different algorithms to calculate aerodynamic performance, DATCOM [41, 42], PANAIR [43] and AVL [44]. Each of these methods has its advantages and disadvantages. DATCOM is a robust aerodynamic solver which can provide a rapid and economical calculation on the aerodynamics of the design. However, DATCOM has limitations in analysing novel configurations, such as twin vertical tails. PANAIR uses the panel method which allows a more accurate aerodynamic prediction on the actual surfaces. This includes novel and arbitrary geometries and interfering flows between the wings and fuselage. Yet, since it is a higher order panel method, it requires higher computational power and a longer calculation time. Moreover, it can only calculate symmetric designs [45]. Last but not least, AVL uses a vortex-lattice model which is suitable for design mainly consisting of lifting surfaces. AVL is also capable of modelling fuselage and nacelles, that said, AVL is unable to predict aerodynamic performance properly if the fuselage has an influence on the aerodynamic load, such as a lifting body design [44].

For this research, DATCOM is used because of its fast and robust calculation which make it suitable to process a high number of data points and optimisation. Moreover, DATCOM is capable to capture potential wave drag at transonic speed. In order to compensate for novel aircraft components, such as external wing tanks, additional drag estimation method is used[].

F. Stability

The stability and control module uses the centre of gravity and moments of inertia of each main components calculated in the mass breakdown module, such as fuselage, wing, cabin, cargo and so on. Similarly, the aerodynamic centre position calculated in the aerodynamic modules to evaluate the stability characteristics and trim abilities of the aircraft. This includes static margin, longitudinal and lateral stability. This is evaluated throughout the whole mission envelope with different flight conditions, speeds, altitudes and angle of attacks. DATCOM is used in this module to provide a 6 DOF analysis to determine if the design is stable or not [41].

G. Validation

Validations of GENUS calculations are conducted in order to make sure generated results accurately reflect existing aircraft. Three trendlines in Figure 3 are generated through GENUS optimisation while scatter points represent different existing aircraft models. These points, maximum range with maximum payload, are collected from the payload-range diagram in the aircraft characteristic airport and maintenance planning published by different aircraft manufacturers [47–53]. This point in the payload range diagram aligns with the optimised results in GENUS. Close approximations between existing aircraft, shown as scatter points, and calculated results, are shown as trendlines. This indicates results produced by GENUS are accurately modelled and represented existing designs.

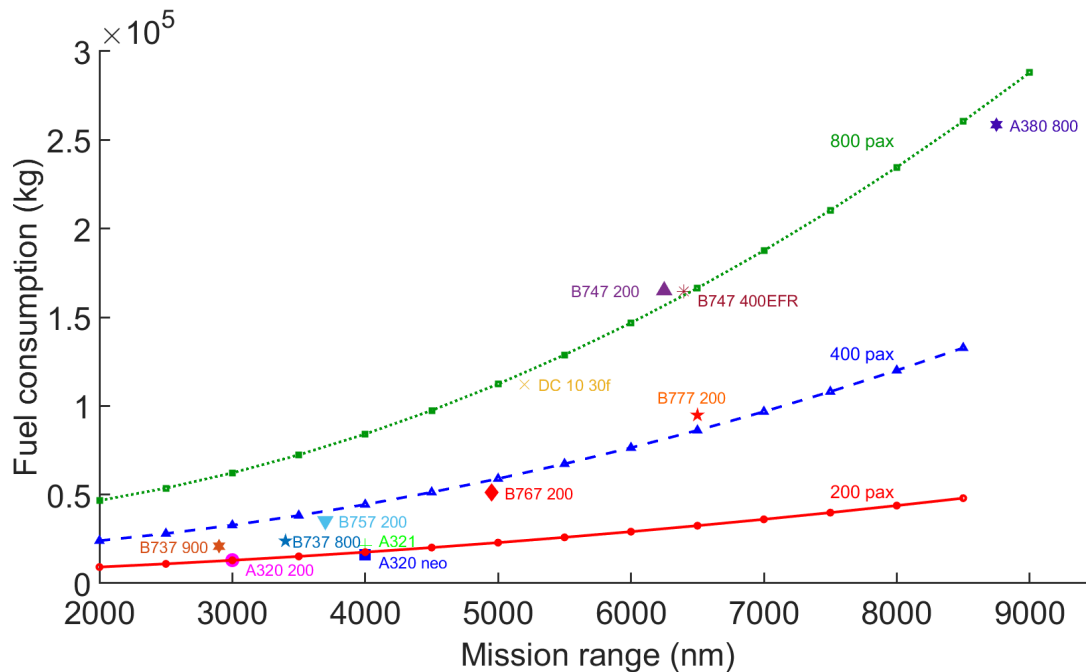


Fig. 3 GENUS validation with existing aircraft

H. Optimisation

GENUS is not only an aircraft analysis platform but also an aircraft design platform which includes a built-in optimisation capability. GENUS has a genetic algorithm and a large scale generalised reduced gradient 2 (LSGRG2) algorithm. The upper and lower limits can be applied to selected input values as design variables while the objective function can be chosen from the output. Design constraints can also be set through the output list with the three different constraint options, greater than zero, equal to zero and less than zero. Once the objective, variables and constraints are set, a multidisciplinary design optimisation can be performed and return with an optimum design.

In order to explore the performance of alternative fuels in different capacities and mission ranges, optimisation is performed at each point over the mission range and is presented in figure 4. The graph shows a trendline formed by optimised designs at each point. The trendline also exhibits a progressive change of the designs over the increase of the mission range.

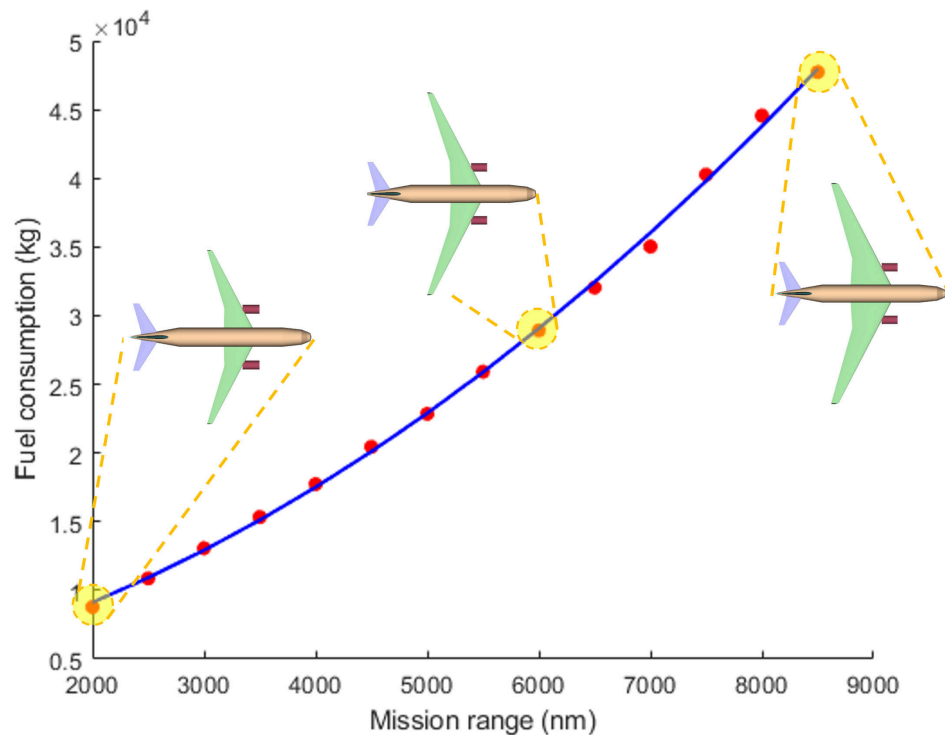


Fig. 4 Optimised TAW designs with kerosene-based jet fuel for 200 passengers capacity over different mission ranges

III. Ranges vs alternative fuel candidates

A. Geometry and packaging

The geometry and packaging of each design are being modified and optimised based on different mission ranges and fuel selections. One of the driving factors for the changes in the geometry is the fuel tank volume. The required fuel tank volume changes based on the mission requirement and on top of that different fuel candidates have different fuel tank requirements. Conventional integral wing tanks are not suitable for cryogenic fuels such as LH₂ or LNG, therefore capsule shaped fuselage fuel tanks or external tanks are added to the design.

1. Jet A fuel and drop-in fuel

Since the early days of the Jet age in the 1940s, kerosene-based jet fuel is already one of dominating fuels in the market. The conventional Tube-and-wing configuration has been designed around kerosene-based fuel, namely having integral wing tanks. Meanwhile, drop-in fuel refers to any fuel that can either be blended with or directly replace current Jet-A fuel without the need to modify the fuel system or the design of aircraft[7]. Biofuel fuel and synthetic-kerosene are two examples of drop-in fuels. As mentioned previously and illustrated in Figure 1, the geometry and packaging of kerosene-based fuelled designs, where all the payloads are within the fuselage while fuel tanks are mainly distributed over the wings. Furthermore, Figure 5 demonstrate a scenario where required fuel increased due to increase in mission range. As a result, an increase in integral wing tank volume will lead to an increase in wing size as illustrated in the figure. These three cases are designed and optimised based on the mission requirement using GENUS.

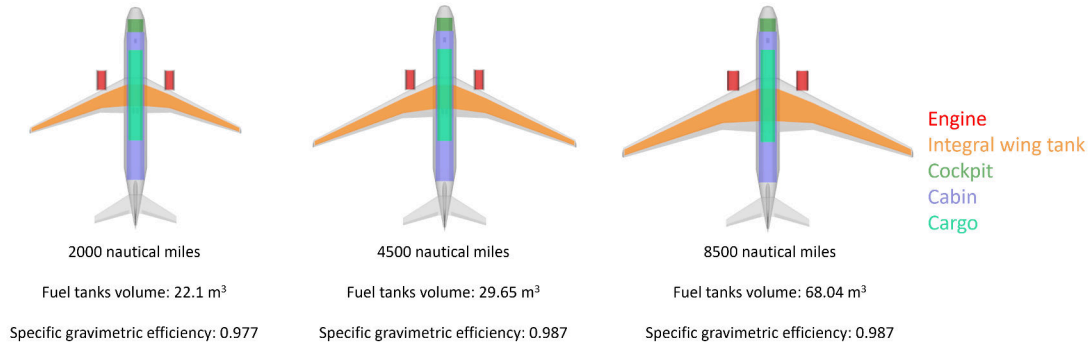


Fig. 5 Geometry and packaging demonstration of designs of drop-in fuels over different mission ranges

2. Cryogenic fuel

Cryogenic refers to the study of materials at low temperatures, normally ranging from 0 K to around 123 K[54]. Liquid hydrogen and liquefied natural gas are two examples of cryogenic fuels. One major difference between cryogenic fuels and jet-A fuel is the fuel tank requirement. Unlike Jet-A or drop-in fuel, cryogenic fuel cannot be stored inside the integral wing tank due to insufficient volume for insulation. Therefore, cryogenic fuels are designed to be stored within

fuselage fuel tanks or external tanks which is presented in Figure 6. There are different design constraints for these new fuel tanks, especially fuselage fuel tanks. The fuselage fuel tank in Figure 6 is fitted by extending the length of the fuselage so as to keep the designed capacity. The main constraint of this approach is the tail scraping angle and storage of main landing gears. There are other approaches such as reducing the number of passengers to increase the fuel tank volume which will be explained in section V.

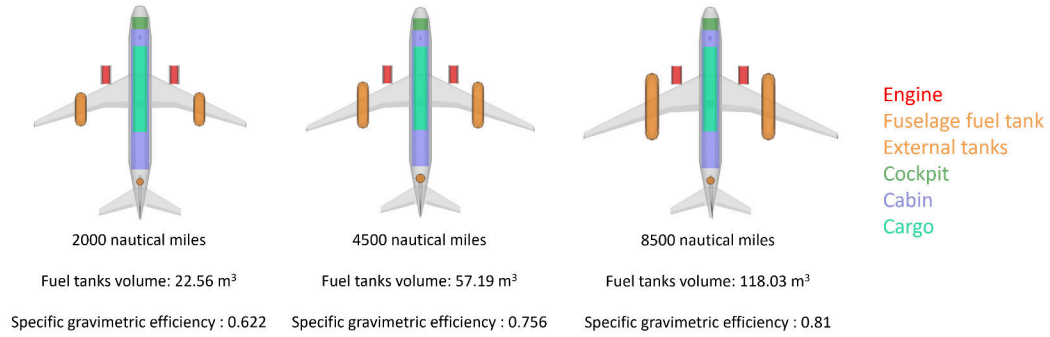


Fig. 6 Geometry and packaging demonstration of designs for cryogenic fuels over different mission ranges

IV. Fuel tank configuration trade-off

For different fuel tank configurations, there are different trade-offs between fuel tank volume, weight and drag. Each aspect is analysed between different fuel tank configurations with given fuel tank volume requirements. It is assumed that only one fuel tank configuration is chosen and subjected to changes in the following analysis.

A. Fuel tank volume

For the three tank configurations, each has different constraints over the fuel tank volume. The volume of integral wing tanks is heavily constrained by the size of the wing, which makes it inflexible, especially when scaling down. As a consequence, the fuel tank will not be fully optimised when the required fuel is low. However, the fuselage fuel tank struggles to scale up due to the physical limitation of tail scraping angle, main landing gears length and lateral stability. Meanwhile, the external tanks have the least restraints with them attached under the wing. The main constraint is the clearance under the wing and the potential striking at rotate.

B. Weight

Figure 7 and 8 show how the mass of the fuel tanks and operational empty weight (OEM) change as the volume of the fuel tanks increases. Both the weight of fuselage fuel tanks and external tanks increase very linearly while the weight of the integral wing tanks do not have a significantly change. This is because integral wing tanks are integrated into the wing and it is codependent to the wings. Thus it is very difficult to separate the weight of the integral wing

tanks without considering the wing. Therefore, OEM can provide a more complete analysis. The increase in OEM for both fuselage fuel tank and external tank configurations remains very linear while the integral wing tank configuration increases exponentially. This is mainly because of the increase in the wing area as the tank volume increases.

C. Drag

Figure 9 shows the increase in drag as the volume of fuel tanks increases. Both trends from fuselage fuel tanks and external tanks are linear and share similar gradients. The additional drag from these two tank configurations is mainly form drag. Both fuselage fuel tanks and external tanks will increase the total wetted area, which directly increases the total form drag. Coincidentally, the shape of external tanks will be capsule shaped, which has a low coefficient of drag, which will be beneficial to minimise the additional drag penalty. On the other hand, despite the increase in total wing area, the drag of the integral wing tank configuration decreases. The scale-up of the wings leads to an increase in aspect ratio and a longer wing span. This helps reduce lift-induced drag and hence leads to a reduction in drag. The increase in fuel tank volume in other tank configurations is also limited by other factors, such as tail scraping, clearance for external tanks and so on. As the required fuel tank increases, it is more difficult to scale up fuselage fuel tanks or external tanks while making sure the aircraft configuration is feasible. Therefore, it is logical to combine more than one tank configuration instead of just relying on one.

In addition, wing loading increases as a result of increases in MTOM. However, the increases in the integral wing tank configuration are not linear as wing area also increases as tank volume goes up, as demonstrated in Figure 10. The changes in wing loading effectively deviate the flight condition from optimum. This further suggested a wing resizing or modifying the flight condition should be conducted to allow the aircraft to operate more efficiently.

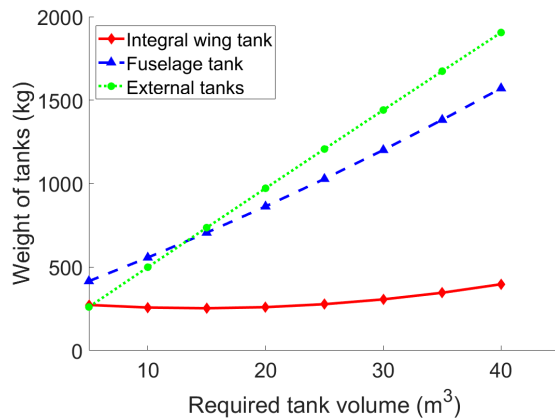


Fig. 7 Fuel tank weight of different configurations

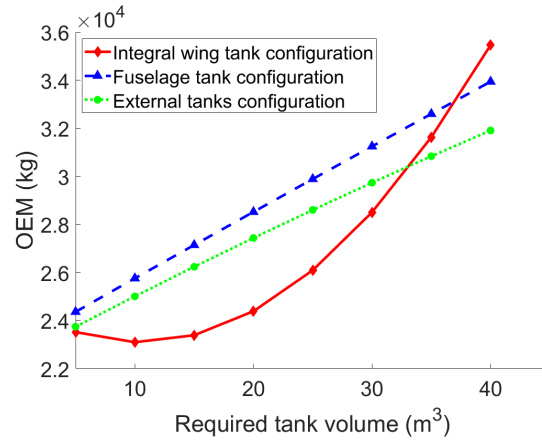


Fig. 8 OEM of different tank configurations

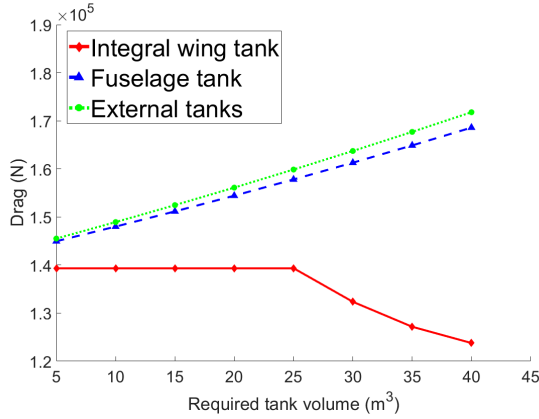


Fig. 9 Drag from different fuel tank configurations

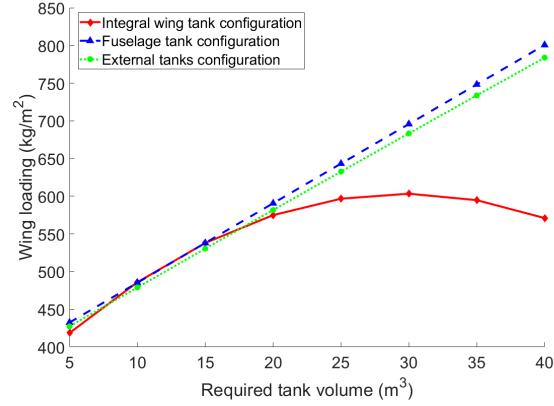


Fig. 10 Wing loading of different fuel tank configurations

V. Fuselage fuel tanks and stability trade-off

As mentioned in previous sections, there are a few design constraints for the fuselage fuel tanks, especially the location of the tanks. One of the most popular designs is having a front and aft tank as shown in Figure 11. This layout allows better longitudinal stability control however this design has an additional weight penalty for creating a catwalk to get access to the cockpit, as demonstrated in Figure 12. Therefore some propose the idea of having a single aft tank. This raises a concern of lateral stability as the mass of the fuel and fuel tank is now located at the rear of the aircraft, this will shift the centre of gravity backwards and lead to an unstable aircraft. To investigate where the limit to the tank size is, a trade-off study is performed. Without modifying the exterior of the aircraft, the volume of the fuselage fuel tank can be increased by reducing the number of passengers and converting them into fuel tanks as illustrated in Figure 13.

The calculation shows that the stability depends on the weight and the centre of gravity position of the fuel system. The results also implied that if the total mass of the passengers and payload is higher than that of the fuel system, the aircraft will still remain stable. There are some exceptions when the passengers' payload and fuel systems are at a similar weight, then it will more depend on the CG position. Stability is easier to achieve for fuel with a low density such as LH₂ or LNG.

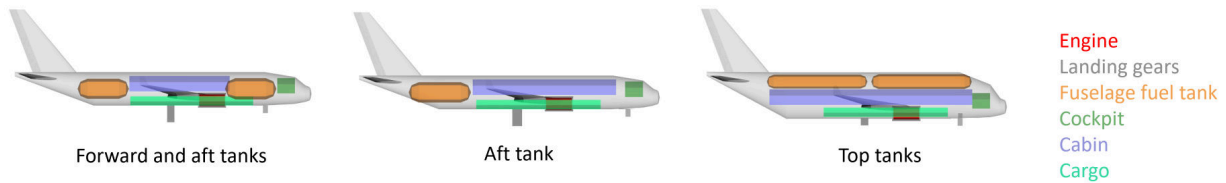


Fig. 11 Different fuselage fuel tank layouts

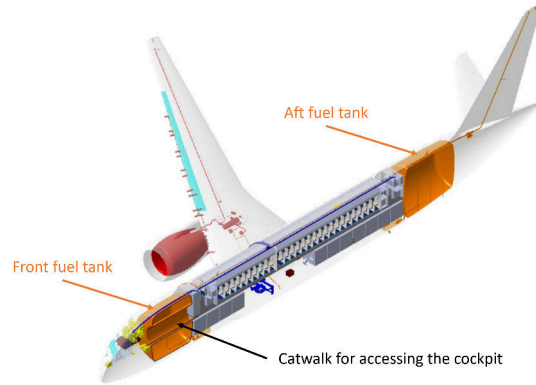


Fig. 12 Cross section view of front and aft tanks design

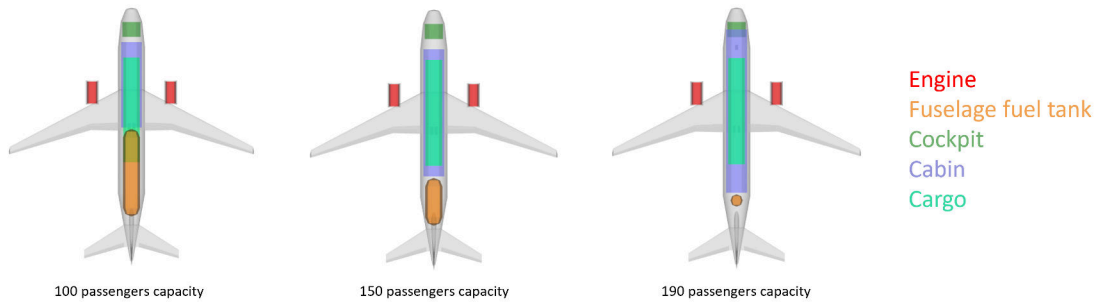


Fig. 13 Stability trade-off study

Capacity (pax)	100	110	120	130	140	150	160	170	180	190
Payload (kg)	8300	9130	9960	10790	11620	12450	13280	14110	14940	15770
Fuel system – Kerosene (kg)	50103.3	43958.5	40885.5	34738.4	28604	25543.9	19423.7	13303.4	10409.5	2726.48
Stability	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Stable
Fuel system – LH ₂ (kg)	10792.6	9521.2	8885.49	7614.08	6342.66	5706.96	4435.55	3863.27	2528.44	1116.8
Stability	Unstable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

Table 3 Longitudinal stability test

Figure 14 to 17 illustrate the centre of gravity and mass of the cabin and fuel tank. It also shows the centre of gravity position when the aircraft has a full and empty fuel tank which both need to be in front of the neutral point, indicated by the vertical line, to become stable. By comparing Figure 14 and Figure 15, it is clear to see the difference in fuel system weight and MTOM cg position. A heavy fuel system effectively drags the MTOM towards to rear end of the aircraft and makes it unstable. In the case of LH₂, the weight of the fuel is significantly less and hence the MTOM cg is much farther forward, even half of the cabin has been traded up for fuel.

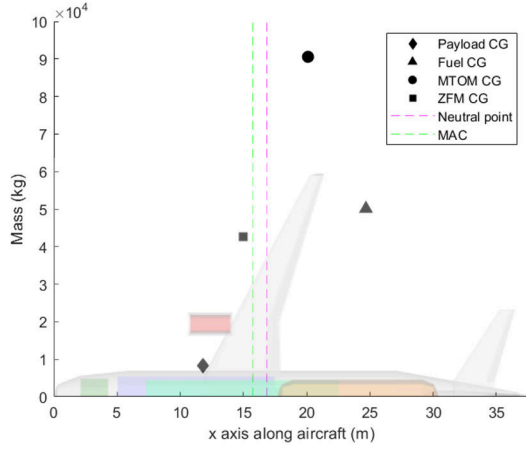


Fig. 14 cg position of 100 pax design with kerosene based jet fuel

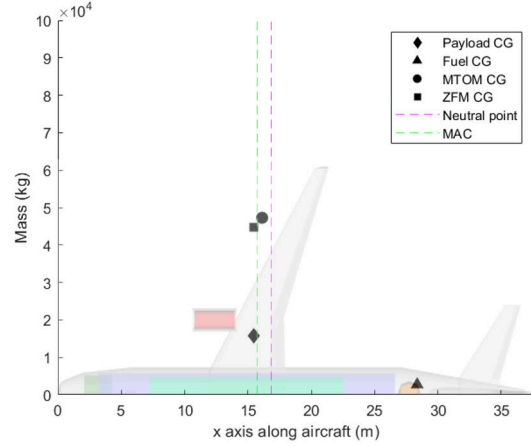


Fig. 15 cg position of 190 pax design with kerosene based jet fuel

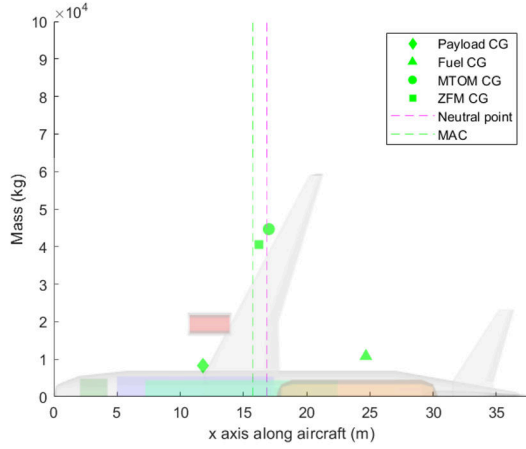


Fig. 16 cg position of 100 pax design with LH₂

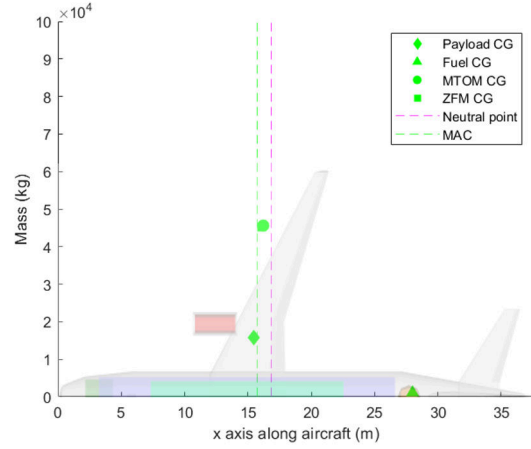


Fig. 17 cg position of 190 pax design with LH₂

VI. Results

After substituting all these different potential fuels in the TAW designs. The total energy consumption, total in-flight emission and total life cycle emission are calculated and presented as follows.

A. Emission

1. Total energy consumption

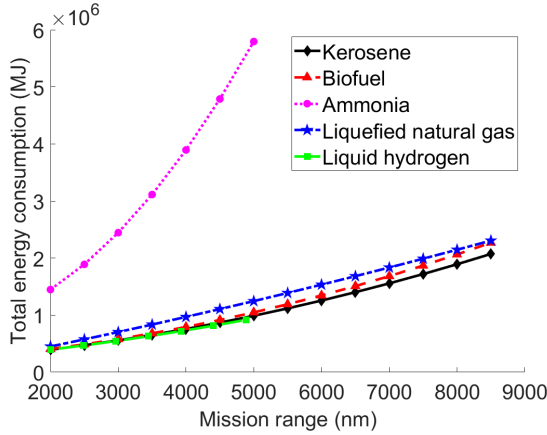
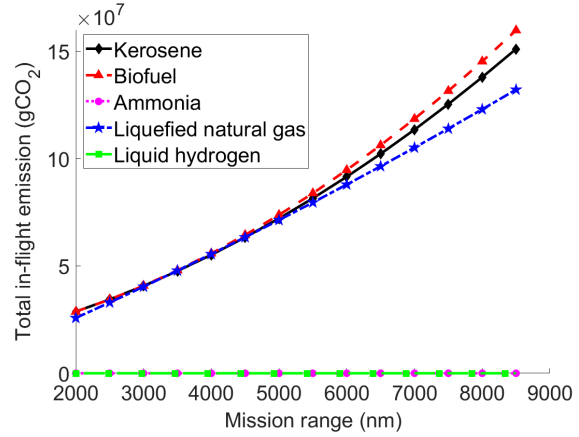
Figure 18 shows the total energy consumption of designs with the application of different alternative fuels. NH₃ has the most standout energy consumption compared to other fuels. Its high energy consumption is a direct consequence of the weight and drag penalties from fuselage and external fuel tanks. This is because of the properties of NH₃ with high density and low energy density. Even when LNG shares a similar trend of properties, the energy consumption is still noticeably higher than the remaining fuel options.

Table 4 Emission factors

Fuel	Well-to-Wing emission (gCO ₂ /MJ)	Combustion (gCO ₂ /MJ)	Total emissions (gCO ₂ /MJ)
Kerosene	12.25	73.2	85.45
Biofuel	-63.1 ~ 83.7	70.4	7.3 ~ 154.1
LH ₂	8.6 ~ 221.65	0	8.6 ~ 221.65
LNG	42.1	57.29	99.39
NH ₃	50.57 ~ 114.19	0	50.57 ~ 114.19

2. Total in-flight emissions

Total in-flight emission is calculated based on the GHG emitted during combustion. The emission factor, a coefficient which converts activity data into GHG emissions, of combustion is listed in Table 4. Figure 19 displays the in-flight emission where kerosene, biofuel and LNG shared a very similar level of emission in which biofuel has a slightly higher emission compared to the other two. On the other hand, LH₂ and NH₃ do not emit any CO₂ in flight.

**Fig. 18 Total energy consumption of TAW configuration****Fig. 19 Total in-flight emissions**

3. Total LCA emissions

For the total emissions from the life cycle assessment (LCA), fuel production is also taken into consideration and the results are demonstrated in the following Figure 20 and 21. Emission factor during fuel production varies based on different assumptions and production methods, which can significantly affect the results. Figure 20 demonstrates an idealistic estimation which is based on the most sustainable production method possible. Yet, Figure 21 exhibits realistic estimation which is based on the current technological level and industry practice. It is clear that nearly all the alternative fuel candidates show the potential to achieve a better overall GHG emission compared to conventional kerosene-based jet fuel. Having said that, given current fuel production pathways, the use of alternative fuels will not provide any improvement in a sustainability perspective.

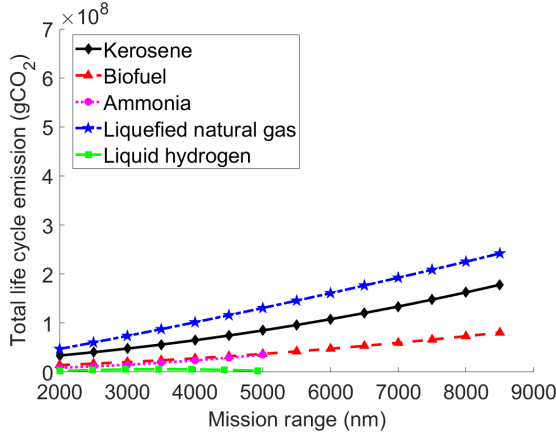


Fig. 20 Idealistic estimation of total life cycle emission for TAW configuration

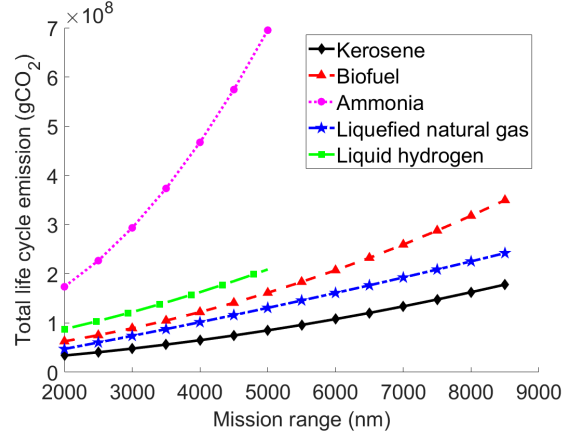


Fig. 21 Realistic estimation of total life cycle emission for TAW configuration

B. Performance enhancement

One of the questions which asked the most in the application of alternative fuel is the additional benefits from different fuel properties. For instance, LH₂ has a lower density which will potentially offer a more beneficial long range mission. In order to provide a fair comparison to determine if the application of alternative fuels will bring in additional performance benefits, specific energy consumption (MJ/pax/nm) is used to compare designs with different capacities, mission range and fuel used.

Figure 22, 23 and 24 show the changes in the megajoule per passenger per nautical miles of three different capacities over the same set of mission ranges. There are no significant advantages to the application of alternative fuels in the 200 capacity. In fact, both NH₃ and LH₂ fuelled aircraft are unable to fulfil the mission without significantly increasing the size of the aircraft, from narrow body to wide body. This is because of restricted fuel tank volume from the fuselage and external tanks. Furthermore, this implies cryogenic fuels are not suitable for low capacity design because of available space for fuselage fuel tanks and external fuel tanks.

The specific energy consumption performance of cryogenic fuelled designs shows a higher specific energy consumption at a shorter mission range and eventually outperforms kerosene-based jet fuel and biofuel designs. A 20.8% reduction in specific energy consumption is calculated between kerosene based jet fuel and LH₂ fuelled design for 400 pax and 8500 nm mission range. Similarly, 13.7% reduction is estimated for 800 pax with the same comparison. This validates the hypothesis in which low density cryogenic fuel is more suitable for long-range missions despite the weight and drag penalties from fuselage and external fuel tanks.

However, narrow body designs have the best specific energy consumption given the same mission range and fuel choice compared to wide body designs. This means that from a sustainable perspective it is more beneficial to operate narrow body aircraft. However, this is limited by other factors such as increased operational cost as an airliner, decreased passengers' comfort and increased air traffic.

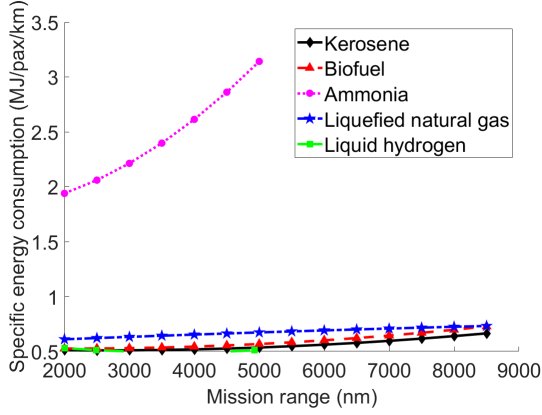


Fig. 22 200 passengers capacity

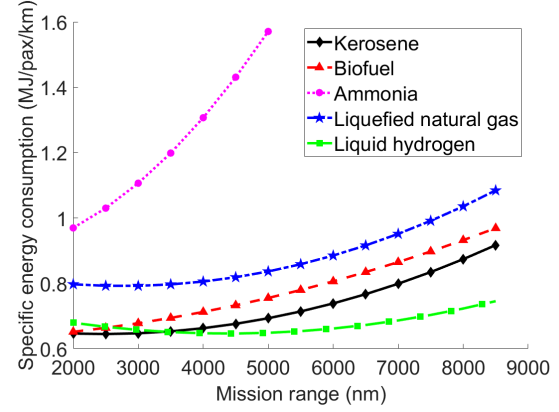


Fig. 23 400 passengers capacity

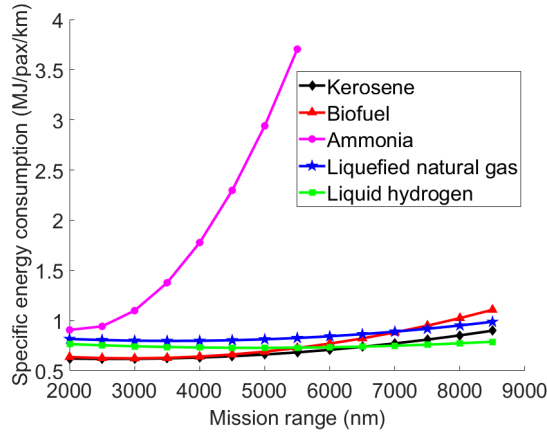


Fig. 24 800 passengers capacity

VII. Conclusion

The aim of this study is to model the conventional TAW configuration with the application of different alternative fuels, including biofuel, LH₂, LNG and NH₃, with different mission ranges. This is to determine how different fuel properties affect the designs and performance of aircraft and quantify the reduction of GHG emissions by utilising alternative fuels. The early section of this paper established how the application of cryogenic fuels changes the configurations and layout of the aircraft with the introduction of external fuel tanks and fuselage fuel tanks. Followed by an analysis of how different tank configurations behave as the required tank volume changes. The design of the integral wing tank is restricted by the design and aerodynamic requirement of the wing, which makes it inflexible in sizing and has a direct effect on the aerodynamic performance. On the other hand, the sizing of the fuselage fuel tanks and external fuel tanks is more flexible and suitable for cryogenic fuels. However, they both undergo significant additional weight and drag penalties. Supplementarily, a trade-off between the aft tank and passenger capacity is studied and to investigate how longitudinal stability will be affected. The stability is heavily dependent on the total weight of the fuel tank against

the total weight of the passengers. The aircraft will tend to be stable if the total weight of the cabin and passengers is heavier than the aft fuel system, as this will keep the centre of gravity in front of the neutral point.

The second half of this paper focuses on how different applications of alternative fuels affect the performance and GHG emissions over a range of mission ranges. First, the use of external tanks or fuselage fuel tanks will increase energy consumption due to drag and weight penalties and as a consequence increase energy consumption and emissions. Yet, LH₂ has an exceptionally high specific energy density, which is able to overcome the penalties and achieve a 20.8% and 13.7% reduction in specific fuel consumption at 8500 nm for 400 and 800 pax respectively. This again confirms the hypothesis that LH₂ is more suitable for long range missions. Second, the fuel production methods heavily affect the overall emission level and should be taken into consideration instead of just focusing on in-flight emissions. Both biofuel and LH₂ show a good potential to outperform conventional kerosene-based fuel in regards to sustainability given the fuel is produced through sustainable pathways.

VIII. Future work

The next step of this project is to look into the application of alternative fuels in other novel configurations, such as high aspect ratio wing (HAR) aircraft and blended wing body (BWB) aircraft. These novel configurations provide different fuel tank packaging naturally which possibly is more suitable for cryogenic fuels and will reduce the penalties from external tanks and fuselage fuel tanks.

IX. Data availability

The dataset generated during and/or analysed during this study is available at <https://doi.org/10.17862/cranfield.rd.25002659> and from the corresponding author on reasonable request.

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Airliner conceptual designs for the application of alternative fuels

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