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Exploration of sustainable aviation technologies and alternative fuels for future inter-continental passenger aircraft

ESA report

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Abstract

Global aviation demand and its environmental impact are projected to grow significantly in the next two decades. The primary objective of this thesis is to assess aircraft technology and low-carbon energy combinations, considering lifecycle effects, to enable climate-neutral subsonic long-range flight (14,000 km) for a large aircraft (~300 passengers) – a complex area to decarbonize. First, using Breguet's range equation, it is found that liquid hydrogen (LH2) and 100% synthetic paraffin kerosene (SPK) are the only alternative fuels suitable for this sector. With current technology, the specific energy consumption (SEC in MJ/tonne-km) of LH2 and 100% SPK aircraft are 11% higher and 0.2% lower compared to Jet-A, respectively. Second, a global sensitivity analysis is performed using the range equation to investigate the effects of four technologies – aerodynamics, lighter structures, cryo-tank weight, and overall efficiency (ηo) – on the design performance of an LH2 tube-wing aircraft. Compared to current technology, it is found that for an LH2 aircraft: (i) enhancing ηo and aerodynamics significantly reduces its SEC; and (ii) with the most optimistic technology projections, its SEC improves by 33%, requiring a 22% longer fuselage. Third, by applying weight-sizing methods and GasTurb simulations, it is observed that the SEC of a futuristic BWB aircraft powered by Jet-A, 100% SPK, and LH2 decreases by 47.9%, 48%, and 53.5%, respectively, compared to a present-day Jet-A aircraft. Lastly, a comparative lifecycle analysis is conducted for these three BWB aircraft, quantifying both CO2 and non-CO2 impacts. After evaluating over 100 manufacturing pathways/feedstocks for 100% SPK and LH2, it is found that only LH2 could achieve climate-neutral long-range flight when produced from biomass-based sources with carbon sequestration. The findings of this thesis could help guide future aviation technology development and policy decisions.

Table of contents

Nomenclature

LTO:	Landing and take off
IPCC:	Intergovernmental panel on climate change
IATA:	International air transport association
ICAO:	International civil aviation organization
NASA:	National aeronautics and space administration
CAEP:	Committee on aviation environmental protection
ASTM:	American society for testing and materials
SPK:	Synthetic paraffin kerosene
FT:	Fischer-Tropsch
HRJ:	Hydro-processed renewable jet fuel
HEFA:	Hydro-processed esters and fatty acids
HFS-SIP:	Hydro-processed fermented sugars to synthetic iso-paraffins
ATJ:	Alcohol to jet fuel
CO_2:	Carbon dioxide
CO:	Carbon monoxide
NO_x:	Oxides of Nitrogen
SO_x:	Oxides of Sulphur
PM:	Particulate matter
OC:	Organic carbon
BC:	Black carbon
VOC:	Volatile organic compound
O_3:	Ozone
TeDP:	Turbo-electric distributed propulsion;
SELECT:	Silent efficient low-emissions commercial transport;
SUGAR:	Subsonic Ultra Green Aircraft Research
GHG:	Greenhouse gas
GWP:	Global warming potential
GREET:	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
RF:	Radiative forcing
NANG:	North-American natural gas
NNANG:	Non- North-American natural gas
NNAFG:	Non- North-American flared gas
NG:	Natural gas
S.:	Standalone plant type
D.:	Distributed plant type
CDM:	Corn with dry mill
FR:	Forest residue
CS:	Corn stover
Ms:	Miscanthus
SG:	Switchgrass
CUM:	Corn US mix
CDMWOE:	Corn dry mill without extraction
CDMWE:	Corn dry mill with extraction
CWM:	Corn wet mill

SW:	Solid waste
B.:	Biological plant type
CWE.:	Catalytic with external H_2 plant type
CWI.:	Catalytic with in-situ H_2 plant type
CBG.:	Catalytic with H_2 from biomass gasification plant type
W:	Willow
P:	Poplar
OPR:	Overall pressure ratio
BPR:	Bypass ratio
UHB:	Ultra-high bypass ratio
WTWa:	Well-to-wake
W_{TO}:	Take-off weight
W_{MF}:	Mission fuel weight
W_P:	Payload weight
T+W:	Tube and wing
OWN:	Over wing nacelle
DD:	Direct drive turbofan engine
GTF:	Geared turbofan engine
OR:	Open rotor
MFN:	Mid fuselage nacelle
HWB/BWB:	Hybrid/Blended wing body
AIAA:	American Institute of Aeronautics and Astronautics
SLS:	Sea-level static
TSFC:	Thrust specific fuel consumption
FF:	Fuel fraction
L/D:	Lift to drag ratio
LPT:	Low-pressure turbine
IPT:	Intermediate-pressure turbine
HPT:	High-pressure turbine
LPC:	Low-pressure compressor
IPC:	Intermediate-pressure compressor
HPC:	High-pressure compressor
C_L:	Lift coefficient
C_D:	Drag coefficient
SFB:	Specific fuel burn
ERA:	Environmentally responsible aviation
LH_2:	Liquid hydrogen fuel
PtL:	Power-to-liquid fuel
LCV:	Lower calorific value
IPPD:	Integrated product-process development
BLI:	Boundary-layer ingestion
RJ:	Regional jet
SA:	Single aisle
STA:	Small twin aisle
LTA:	Large twin aisle
VLTA:	Very large twin aisle

1. Introduction

1.1 Background

Passenger and cargo air-travel demand is anticipated to grow in future and thus the global air-traffic is expected to rise significantly through year 2036 [1]. Boeing anticipates annual worldwide average growth rate of 4.7% for passenger air-traffic and 4.2% for cargo air-traffic, during year 2017-2036 timeframe [2]. In year 2016, the aviation industry delivered services to approximately 4 billion passengers and 62 million tonnes of freight, and while doing so it contributed to 3.6% of the global gross domestic product [3]. The aviation sector contributes 2% to the global man-made carbon dioxide (CO_2) emissions [4]–[7]. In year 2018, the global aviation sector reached 895 million tonnes of CO_2, and this is expected to rise to 927 million tonnes in year 2019 [8]. In year 2018, it is estimated that the aviation industry consumed 94 billion gallons of fuel globally. This consumption is forecasted to rise to 97 billion gallons in year 2019 (ibid).

The exhaust of aircraft operating on conventional jet fuel includes: CO_2, water vapor, nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons, sulfur oxides (SO_x), traces of hydroxyl family and nitrogen compounds, small amounts of soot particles, and normal atmospheric oxygen and nitrogen [6]. The human health impacts of different emissions can be found in next section. Aircraft contrails also have an impact, but it is inconclusive whether there is a net warming or cooling effect on the earth. Under some meteorological conditions, they can last in the atmosphere in the form of 'cirrus' clouds, which can contribute to climate change. These clouds can have different warming and cooling effects, depending on flight times (night or day) [4]–[7], [9]. Aviation has a greater effect than other sectors because of the altitude at which the emissions are released. The most significant greenhouse gas (GHG) CO_2, does not have any additional impact due to difference in altitude. However, emissions like NO_x and water vapor can have amplified climate change impact at higher altitudes. During aircraft cruise, NO_x emitted from engine reacts with hydrocarbons/volatile organic compounds in the presence of sunlight to form ozone, which is a GHG [4]–[7], [9]. When non-CO_2 emissions and their impacts are considered, the Intergovernmental Panel on Climate Change (IPCC) estimates that aviation accounts for approximately 3% of total man-made climate impact (ibid). For the future, the IPCC estimates that aviation's total contribution (CO_2 and other effects), would likely increase to 5% (with a worst-case scenario of 15% of human emissions) by year 2050. It is important to note that the proportional impact of aviation will also depend on the environmental performance (emission regulation success) of the other sectors (ibid).

The environmental impacts mentioned above place challenges for the aviation industry to mitigate its climate change impact, while ensuring the supply of required quantity of fuel for the increasing air-travel demand. With rising aviation-related human and environmental health concerns, the aviation industry is exploring paths to make the air-transportation sector more sustainable. In future, as the aviation sector expands to meet the increased demands, the IPCC forecasts that the share of this sector's global man-made CO_2 emissions will increase to around 3% in year 2050 [4]–[7], [9].

Presently, a New York ↔ Mumbai return air-travel emits similar amount of greenhouse gas a car in UK/~USA emits on an annual basis (calculated using [10]–[12]). To reduce aviation's climate-change impacts, the International Air Transport Association (IATA) has set three-goals and a four-pillar strategy to meet these goals [13]. These goals are in-line with the goals of the UN's Paris Treaty on Climate change. The three goals are as follows:

i. An average improvement in fleet fuel-efficiency of 1.5% per year from 2009 to 2020;
ii. A cap on net aviation CO_2 emissions from year 2020 (carbon-neutral growth); and
iii. A reduction in net aviation CO_2 emissions of 50% by year 2050, relative to year 2005 levels.

The four-pillar strategy comprises:

i. Improved technology, including the deployment of sustainable low-carbon fuels;
ii. More efficient aircraft operations;
iii. Infrastructure improvements, including modernized air traffic management systems; and
iv. A single global market-based measure, to fill the remaining emissions gap.

In-line with environmentally responsible aviation (ERA) program, National Aeronautics and Space Administration (NASA) initiated the concept of 'N+i' goals to reduce noise, fuel consumption and landing and take-off (LTO) NO_x emissions, and to improve aircraft performance [14]. This will encourage advanced aircraft concepts and technologies along with the use of 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 (ibid). Each generation is an improvement over its previous one, in terms of LTO NO_x emissions, noise, fuel consumption and performance.

1.2 Objectives

The broader aim and scope of this research is to evaluate future aircraft technologies and alternative fuels, that will be essential to identify feasible technology and energy vector combinations for future inter-continental 300-passenger aircraft, towards the goal of sustainable aviation. This aim is in-line with IATA strategy #1 of the four-pillar strategy discussed above. The rationale for this aim is as follows. The present aviation-related technology development and regulations are limited only to the use-phase or direct use of aircraft. The present regulations are for noise and air-quality. In year 2016, International Civil Aviation Organization (ICAO) released CO_2 standard (kg/km) for new aircrafts [15]. Cruise emissions are unregulated currently, and the study by Barrett et al. [16] suggests that cruise emissions have the highest air-quality impact over aircraft's flight mission. Additionally, because an aircraft spends majority of its flight time/range in cruise, it is expected to have highest climate impact during cruise. Moreover, not all alternative fuel pathways are energy efficient. For example, using the conventional perspective of looking at direct emissions, liquid hydrogen seems to be an excellent candidate for aviation use because of its higher energy density and zero-carbon emissions during aircraft operation, compared to the conventional jet fuel. From the GREET 2018 model [17], it is found that liquid hydrogen production from coal has approximately 19 times more GHGs compared to the conventional jet fuel. Therefore, in general, a holistic approach needs to be used in evaluating the performance of future aircraft technology and energy vector combinations. A long-range aircraft (300 passengers) spends majority of its flight-time in cruise and will therefore have the highest climate impact, compared to mid-range and short-range aircraft. Similarly, the measures for reducing the climate and air-quality impacts of aviation will be better observed in a long-range aircraft.

To achieve this aim, the detailed objectives are to:

1. Review future aircraft, airframe and propulsion concepts, and develop a modelling tool for estimating operational energy consumption
2. Review current and potential energy vectors including alternative fuels and electrification, and to develop a database of their life-cycle impacts.
3. Evaluate aircraft technology and energy vector combinations with respect to their potential to reduce aviation GHG emissions on a lifecycle basis.
4. Holistic socio-environmental impacts including non-CO_2 climate impacts, air quality, water use, resources and land-use.
5. Operational cost analysis for different energy vectors.

1.3 Structure of report

The subsequent chapters of this report are organized as follows. Chapter II includes the comprehensive literature review with a summary of this review. The research methodology and progress till date is presented in chapter III. Thereafter, a research plan is presented in chapter IV. This chapter includes a summary of proposed research, which is to be conducted in the remaining time of the Ph.D. timeline, along with a Gantt chart/research activity schedule indicating the same. Appendix is included in chapter VI with sub-sections, after references in chapter V. The sub-sections in appendix include detailed information pertaining to the methodology and/or research completed till date. The objective of including the appendix was to include a concise content in the main body of the report.

2. Literature review

The following literature review develops the context for this research, particularly with respect to the impacts of aviation, and solutions to minimize these. The literature review also includes research addressing the measures included in IATA's four-pillar strategy to mitigate the human and environmental health impacts, and it is divided into multiple segments/chapters.

2.1 Impact of aviation on climate

Aviation has climate impacts through gases and particulate emissions which change the 'greenhouse' properties of the atmosphere [5], [9]. This contributes to climate warming and climate change (ibid). Aviation has climate change impacts via CO_2 and non-CO_2 effects [9]. CO_2 is a key pollutant from aviation, and it is a well understood and quantified greenhouse gas. CO_2 has been assigned a 'very high' level of confidence in its share of net anthropogenic forcing (ibid). Aviation also has a number of significant non-CO_2 impacts through its emissions of water vapour, particles, and NO_x; affecting clouds, aerosols and atmospheric composition [5]. The primary metric used for attributing the contribution of the changes that affect global mean surface temperature is 'radiative forcing' (RF), measured in watts per square metre ($W\ m^{-2}$) as changes in RF are approximately proportional to the expected (equilibrium) global mean surface temperature changes [9]. In the case of impacts of soot emission on cirrus cloud formation at high altitudes, both the sign (cooling or warming) and magnitude of the forcing are uncertain [9]. In the case of impacts of aviation sulphur compound emissions on low-level clouds, even though the sign of the impact is known (cooling), the magnitude is still uncertain [9]. There is a significant progress made on modelling the impacts of aviation NO_x emission, and the formation and impacts of linear contrails and contrail-cirrus (ibid). However, there is a large uncertainty as to whether contrails and contrail-cirrus warm the Earth's surface as much as other aviation effects, per unit forcing (ibid).

Aircraft NO_x emission causes the formation of atmospheric ozone (O_3), a radiatively active gas (a GHG), via complex atmospheric chemistry. NO_x emission also result in the formation of the short-lived hydroxyl radical (OH), which is the principle reactant that leads to the removal of ambient methane (CH_4) by about 1 – 2%. Methane in the atmosphere is primarily from natural sources (e.g. wetlands) and anthropogenic sources (e.g. agriculture and industry). Therefore, the destruction of ambient CH_4 is a negative RF (cooling) and the formation of O_3 is a positive RF (warming). The net NO_x RF term is a combination of these two terms, but overall is a positive RF.

The non-CO_2 pollutants can have both negative and positive RF effects (cooling and warming), though scientific consensus puts the overall non-CO_2 effects of aviation as having a net positive (warming) RF effect, which in terms of RF is thought to be approximately two to three times that of the RF effect from aviation's historical CO_2 emissions [5], [9]. 'Radiative Forcing Index' (RFI) is defined as the total RF from aviation divided by the RF from historical aviation CO_2 emissions, and was introduced by the Intergovernmental Panel on Climate Change (IPCC) in their 1999 Special Report, 'Aviation and the Global Atmosphere' [5]. It should be noted that the RFI is not an emissions metric for comparing effects of equivalent emissions to CO_2, like the Global Warming Potential (GWP) [9].

According to the study by Lee et al. [18], the uncertainties for aviation RF, other than that of CO_2 (including ozone, a GHG), are highly uncertain. The total aviation RF (excluding induced cirrus) in year 2005 was approximately 55 mW m^{-2} (23–87 mW m^{-2}, 90% likelihood range), which was 3.5% (range 1.3–10%, 90% likelihood range) of total anthropogenic forcing (ibid). Including estimates for aviation-induced cirrus RF increases the total aviation RF in year 2005 to 78 mW m^{-2} (38–139 mW m^{-2}, 90% likelihood range), which represents 4.9% of total anthropogenic forcing (2–14%, 90% likelihood range) (ibid). In other words, the non-CO_2 effects comprise 50 – 60% of this 4.9%. The non-CO_2 impacts have a larger scientific uncertainty than the CO_2 impacts, particularly for impacts on cloudiness [9].

2.2 Impact of aviation on air-quality

Air quality in the airport vicinity is important, because of relatively high concentration of different pollutants which affect human-health. The human health impacts of some of the common emissions are as follows [19]:

a. Carbon monoxide (CO):
   At high levels CO causes drowsiness, headaches, slowed reflexes and nausea, and at very high levels it results in death. At low levels it can impair nervous system function and concentration, and it may cause heart pain in people with coronary heart disease.
b. Oxides of nitrogen (NO_x):
   NO_x impairs respiratory cell function, and damage cells of the immune system and blood capillaries. It may aggravate asthma and increase susceptibility to infection. In children, exposure may result in colds, coughs, breathing problems, phlegm, respiratory diseases including bronchitis, and chronic wheezing.
c. Particulate matter (PM):
   PM is strongly related with a broad range of symptoms such as colds, coughs, chest pain, asthma, breathing problems, phlegm, respiratory diseases including bronchitis, chronic wheezing, sinus problems, emphysema and loss of lung efficiency. As many as 7% of chronic obstructive pulmonary disease and 15% of asthma cases in the urban population are estimated to be possibly associated with prolonged exposure to high concentrations of PM. Long term exposure to PM is associated with high risk of death from lung and heart diseases. It may carry carcinogens such as polycyclic aromatic hydrocarbons (PAHs), therefore may increase the risk of developing cancer.
d. Volatile organic compounds (VOC):
   This type of pollutant includes thousands of various chemicals, many of which are hydrocarbons (HC). VOC may cause breathing difficulties and skin irritation. Long term exposure to VOC may impair lung function. Many individual compounds are carcinogenic (including benzene). Benzene can cause leukemia. Those most at risk are people exposed to benzene at work or who live or work in vicinity of vehicle activity.
e. Sulphur Dioxide (SO_2):
   SO_2 is associated with chronic bronchitis and causes irritation of lungs. People suffering from asthma are particularly vulnerable and SO_2 exposure of few minutes may trigger

an attack. However, the most serious effect occurs when SO_2 is absorbed by PM which is then inhaled deep into the lungs. Inhaling air with high concentrations of SO_2 can release sulfuric acid in the lungs (SO_2 reacts with moisture in lungs to form sulfuric acid). This can result in widespread illness and death. For example, it is likely to have been the main cause of the 4000 deaths during the notorious 1952 London smog.

f. Ozone:
Ozone is formed when VOC reacts with NO_x in the presence of sunlight. Ground level ozone reduces lung function in healthy people as well as those with asthma. It may increase susceptibility to responsiveness and infection to allergens such as pollens and house dust mites. It may cause cough, nausea, headaches, chest pain and nose, eye and throat irritation, and loss of lung efficiency; and it increases the likelihood of asthma attacks.

In a given aircraft flight mission, the aircraft spends majority of the time in cruise, especially in long-haul flights. The study by Barrett et al. [16] estimates that cruise emissions dominate global health impacts attributable to air pollution caused by aviation; in one year approximately 8000 premature deaths are attributable to aircraft cruise emissions. This is approximately 80% of the total impact of aviation (including the landing and take-off impacts), and it is approximately 1% of air-quality related premature deaths from all sources (ibid). Secondary H_2SO_4-HNO_3-NH_3 aerosols dominate the mortality impacts (ibid). Cruise emissions, which are not regulated currently, should be explicitly considered in policy, technology and operations development process for mitigating the air-quality impacts of air transportation (ibid).

Koo et al. [20] perform a long-term (greater than one year) simulations with a global atmospheric chemistry-transport model with a focus on population exposure to fine particulate matter ($PM_{2.5}$) and associated risk of early death. Sensitivities relevant to high-altitude and intercontinental PM pollution are estimated for aircraft emissions. Specifically, the sensitivities of premature mortality risk in different regions to SO_x, NO_x, VOC, CO, and primary $PM_{2.5}$ emissions as a function of location are calculated. They find that NO_x emissions are responsible for 93% of population exposure to aircraft-attributable $PM_{2.5}$. Aircraft NO_x accounts for all aircraft-attributable nitrate exposure and 53% of aircraft-attributable sulfate exposure due to the strong ‘oxidative coupling’ between aircraft NO_x emissions and non-aviation SO_2 emissions in terms of sulfate formation (ibid). Of the health risk-weighted human $PM_{2.5}$ exposure attributable to aviation, 73% occurs in Asia and 18% in Europe. 95% of the air quality impacts of aircraft emissions in the US are incurred outside the US.

2.3 Impact of aircraft noise

Noise is an ‘unwanted sound’, and aircraft noise has one of the most detrimental impact on the community, especially in the airport vicinity [21]. It causes sleep disruption, community annoyance, adversely affects academic performance of children, and could increase the risk for cardiovascular disease/hypertension of people living in the airport vicinity. In some airports, noise constrains air traffic growth (ibid). Additionally, noise can cause cognitive and emotional impairment, physiological stress reactions, endocrine (pituitary and adrenal gland) imbalance, and affect autonomic nervous system (sympathetic nerve) [22].

2.4 Environmental cost of aviation

Wolfe et al. [23] model the distribution of environmental damages and net cost from one year of aviation operations. They find that community staying at airport boundaries face damages between \$5–16 per person per year from climate damages, and \$100–400 per person per year from aircraft noise (in 2006 dollars). The expected damages from air quality depend on the number of operations at the airport. They range from \$20 to over \$400 per person per year with air quality damages approaching those of noise at high volume airports (ibid). The mean expected air quality and noise damages decay with distance from the airport, but for noise the range of expected damages at a given distance can be high. This depends on the orientation with respect to flight patterns and runways. Damages from climate change caused by aviation dominate those from degradation of local air quality and noise pollution further away from the airport (ibid). However, air-quality damages may exceed those from climate when considering the impact of cruise emissions on air-quality (ibid).

2.5 Systems-level measures and policies

In a study to examine the air-quality impacts of UK airports, Yim et al. [24] estimate that up to 65% of the health impacts of UK airports could be reduced by: desulfurizing jet fuel, avoiding use of auxiliary power units (APUs), electrifying ground support equipment, and using single engine taxiing.

The study by Sgouridis et al. [25] evaluates the impact of policies for reducing the emissions of commercial aviation. These policies include: technological efficiency improvements; operational efficiency improvements; use of alternative fuels; demand shift; and carbon pricing (i.e. market-based incentives) (ibid). The evaluation of impacts of the said policies on total emissions, air transport mobility, airfares and airline profitability, is carried out by using dynamics modelling approach (ibid). It is to be noted that this study takes rebound effect into account. The rebound effect in this case is: the induced demand created because of decreasing operating costs (and thus average fares), which in turn stimulates demand (ibid). Sgouridis et al. observed that no single policy can maintain emissions levels steady while increasing forecasted air-transportation demand (ibid). A combination of policies that includes aggressive levels of operations and technological efficiency improvements, use of biofuels along with moderate levels of carbon pricing and short-haul demand shifts achieves a 140% increase in capacity in year 2024 over year 2004 while only increasing emissions by 20% over year 2004 (ibid). Additionally, airline profitability is moderately impacted (10% decrease) in comparison with the other scenarios where profitability is reduced by over 50% which can impede necessary investments and the implementation of measures to reduce CO_2 emissions (ibid).

2.6 Alternative aviation fuels

One of the IATA strategies that can significantly reduce aviation sector's carbon footprint and potentially enable carbon-neutral growth, on a life-cycle or well-to-wake (WTWa) basis, is the use of low-carbon fuel [26]. However, according to the study by Nygren et al. [27], the use of alternative fuels can be helpful in increasing the availability of fuel for growing aviation demand, but it is less likely to provide large contribution, considering that there is work-in-progress in this domain. The possibility of bio-jet fuels replacing conventional jet fuel is limited, but the development of bio-jet fuel is still significant for the future aviation sector (ibid).

On a WTWa basis, some bio-jet fuels have the potential to significantly reduce the GHG emission from the aviation sector, depending on the feedstock type/source [28]. Study by Hileman et al. [29] examines performance of bio-jet fuels based on a first-order approach using the Breguet-range equation. The results from this study show that the fleet-wide (hypothetical) use of pure (100%) synthetic paraffinic kerosene fuels (SPK), like fuels produced from hydro-processing of renewable oil sources or Fischer–Tropsch (FT) synthesis, can decrease aircraft energy consumption (in-flight) by 0.3% (ibid). A study by Blakey et al. [30] reveals that the use of FT-SPK can help in reducing the local air-quality as a result of reduced particulate matter release. Also, the use of correct alternative fuel has the potential to make aviation sector carbon-neutral (ibid). A study by Daggett et al. [31] provides fuel solutions for the future to reduce the environmental impact of aviation. Daggett et al. propose 50/50 blend of FT-SPK/conventional jet fuel to be used in present day aero engines as a near-term solution; 0-50% HEFA-SPK/100-50% FT-SPK to be used in advanced engines like inter-cooled recuperated engines, and ultra-high bypass ratio engines like geared turbofan engines and un-ducted propfan as a mid-term solution; and liquid hydrogen and/or liquid methane to be used in cryo-fueled engine as a long-term solution to dramatically reduce aviation sector's GHG emissions (ibid).

A study by Jagtap [32] examines hydro-processed renewable jet fuel (HRJ) synthetic paraffin kerosene (SPK) from algae based on the three pillars of sustainability: economics, social aspect, and environmental aspect. Algae has highest biofuel productivity and oil content (ibid). It can be cultivated in low-quality water and doesn't require cultivable land (ibid). Therefore, its water-use and land-use effects are lowest compared to biofuel from other feedstocks (ibid). It does not compete with food-crops and cultivation of algae helps in carbon sequestration (least life-cycle GHG emissions) [32]. Overall, algae as a feedstock to produce bio-jet fuel is promising (ibid). Jagtap also conducts a detailed review of fuel properties, handling properties and thermodynamic behavior of HRJ-SPK on engine operability, maintenance and performance; and addresses fuel certification aspect.

Not all bio-jet fuels (i.e. fuel from different production pathways) can be directly used in present aircraft (called as 'drop-in' fuels), because some of fuel properties and chemical contents are not same as that of the conventional jet fuel [33]. Some systems within the aircraft are designed considering the properties of conventional jet fuel. For example: The aromatic content of conventional jet fuel causes rubber seals used in the high-pressure fuel system to swell, thereby preventing fuel leakage during aircraft operation at different altitudes; and synthetic paraffin kerosene (SPK) jet fuel cannot be used in neat form (100%) without modifications to aircraft or without addition of synthetic aromatics/additives [33]. So far, the American Society for Testing and Materials (ASTM) has approved certain bio-jet fuel pathways which can be used in aircraft as 'drop-in' fuels. These are Fischer-Tropsch (FT) SPK (FT-SPK) with maximum 50% blend, Hydro-processed lipids/hydro-processed renewable jet fuel or Hydro-processed esters and fatty acids (HRJ/HEFA-SPK) with maximum 50% blend, Bio-chem sugars or hydro-processed fermented sugars to synthetic iso-paraffins (HFS-SIP) with maximum 10% blend, Syngas FT with aromatic alkylation (FT-SPK/A) with maximum

50% blend, and alcohol to jet (ATJ-SPK) with maximum 30% blend; where the blending is done with the conventional jet fuel [34].

A study by Schmidt et al. [35] demonstrates a recently developed fuel called 'power-to-liquid' (PtL) jet fuel. Electricity produced from renewable sources like solar and wind energy is used in the electrolysis of water for hydrogen production. After carbon (CO_2) capture, hydrogen and CO_2 undergo chemical process to form hydrocarbon fuel (PtL). This study provides information on different pathways of producing PtL fuel, and it estimates the life-cycle greenhouse gas (GHG) from the production pathways. PtL has significantly lower/near zero life-cycle GHG emission and about 55% lower water consumption compared to conventional jet fuel. It has higher fuel productivity per hectare land compared to all bio-jet fuels. Its thermo-physical and fuel handling properties are like conventional jet fuel, which means that PtL can be potentially used as a 'drop-in' fuel (ibid). This enables status-quo in aircraft powerplants. Presently, it costs 7.3-10 times than conventional jet fuel. Similar information is revealed in the report by the German Environmental agency [36], where details of PtL fuel production, life-cycle GHG, and its current and year 2050 production costs are provided. In year 2050, the cost of PtL is predicted to be 1.4 – 4.5 times the cost of conventional jet fuel.

Liquid hydrogen (LH_2) as an aviation fuel comes across as an interesting candidate, primarily because of its higher energy density (lower calorific value [LCV]) of 120 MJ/kg compared to conventional jet fuel's LCV of 43.2 MJ/kg [37], and because hydrogen combustion does not release emissions like CO_2, CO, volatile organic compounds, $PM_{2.5}$ and PM_{10}, black and organic carbon, and SO_x during direct-use. The products of hydrogen combustion include water vapor and NO_x, and therefore it has the potential to make aviation cleaner and carbon-neutral in the use-phase. However, the density of LH_2 is 71 kg/m^3 while that of conventional jet fuel is 808 kg/m^3; i.e. conventional jet fuel is about 11.4 times denser than LH_2 (ibid). This implies that the fuel tanks on LH_2 powered aircraft will require more volume storage (bigger tanks with insulation), which will further increase aircraft weight. To maintain the same payload capacity, it is necessary to re-design the aircraft (fuselage and wing-loading) to account for extra fuselage and fuel tank weight. The increase in aircraft weight and size, increases the drag on aircraft. Verstraete [38] models the use of LH_2 in different sizes of aircraft and finds that use of LH_2 shows energy-consumption improvements only in long-range aircrafts. The use of LH_2 in long-range mission leads to an improvement in energy efficiency of up to 12% (ibid). For short and mid-range aircrafts, there is an increase in energy use.

2.7 Heat recovery in aircraft engines for improving efficiency

Heat recovery in aircrafts (thrust-powered and shaft-powered) is being pursued for a long-time, especially in the past two decades, to improve the overall efficiency of aircrafts. With such systems, there is always a balancing act between efficiency improvement and weight addition. A patent application by Fonseca [39], [40] reveals a heat recovery system for a thrust-powered aircraft engine (i.e. turbofan engine in this case). A design-optimization study based on this system, by Perullo et al. [41], shows that the addition of this heat recovery system will have thrust-specific fuel consumption improvement of 0.9%-2.5%. In another patent application, Jagtap [42],[43] reveals a heat recuperation system for the family of shaft-powered aircraft gas turbine engines (turbo-shaft and turbo-prop engines). A study based on this patent, Jagtap [44] presents the conceptual design of a novel compact heat-exchanger for application within annular fluid-flow path.

The study by Misirlis et al. [45] reveals an intercooled recuperated aero-engine (IRA engine) of MTU Aero Engines AG. This engine uses an alternative thermodynamic cycle with intercooling and heat recuperation, where the heat recovery system comprises of heat exchangers installed in its exhaust nozzle (ibid). The IRA engine reduces the specific fuel consumption by 9.1%-13.1% depending on the selected heat exchanger type (ibid).

2.8 Air-to-air refuelling

The civil-aviation sector's fuel efficiency can be increased by implementing air-to-air refueling and reducing short-haul flights. Study by McRoberts et al. [46] shows that air-to-air refueling can give up to 14% fuel-burn and 12% operating-cost savings when compared to a similar technology-level aircraft concept without aerial refueling, which represents up to 26% in fuel burn and 25% in total operating cost over the existing operational model at present standard fleet performance and technology. However, these potential savings are not uniformly distributed throughout the network, and the system is highly sensitive to the routes serviced, with decrease in revenue-generation potential observed throughout the network for air-to-air refueling operations due to decrease in passenger revenue [46]. Another study on air-to-air refueling by Nangia [47] shows that aerial refueling can have 15%-30% improvement in fuel burn. A research thesis by Verhagen [48] finds that shape formation/flocking can have up to 4% fuel improvement. Aerial refueling reduces aviation-related noise and emissions (local and global air quality) with energy reduction in ground system at airport [47]. Medium-range flights (approximately 3000 nautical miles [nm]) will be efficient with air-to-air refueling (ibid). For passenger aircrafts, safety is the paramount concern, and safety issues with air-to-air refueling persists with defense-sector aircrafts. Air-to-air refueling is not yet certified for civil aviation use. Moreover, sector which is predicted to contribute 3% to global CO_2 emissions, if short-haul flights are removed, then the transportation load on ground and rail transportation will increase, which already contribute significantly to the global emissions. Also, the proposed removal of short-haul flights will cause inconvenience to people in the need of travel emergency. For example: The distance between Seattle, USA and Miami, USA is approximately 2800nm [49], which approximately represents the maximum (diagonal) distance in USA. According to Nangia [47], medium-range aircrafts will be efficient with air-to-air refueling. If short-haul flights are removed to support it, then the domestic aviation sector in USA will collapse i.e. it will have economic as well as social impacts. For air-to-air refueling to succeed (after certification), it is required to re-design aircrafts, re-structure air-traffic system, routing revisions, and development of automated systems for air-to-air refueling.

2.9 Infrastructure, supply chain and life-cycle analysis of aviation systems

A comprehensive and detailed life-cycle energy and emissions assessment of passenger transportation has been carried out by Chester et al. [50] to help the decision makers in appropriately developing technology and policies for mitigating environmental impacts of transportation. For aviation sector, depending on the type of aircraft (small, midsize or large), active operations account for 69%–79% and inactive operations account for 2%–14% of air travel life-cycle energy (ibid). Aircrafts have the largest operational to the total life-cycle energy ratios due to their large fuel requirements per passenger kilometer travelled (PKT) and relatively small infrastructure (as aircraft is in cruise for majority of the flight-time) (ibid). During the life-cycle of an aircraft, the majority of SO_2 emissions come from the non-operational phase (primarily from the electricity required during individual paths in aircraft's life-cycle), majority of NO_x comes from operational phase of aircraft, and majority of CO emissions come from vehicle manufacturing and infrastructure operation (ground support equipment [GSE]) (ibid). Therefore, technological advancements for improving fuel economy and switching to lower-carbon fuels are the most effective measure for improving the environmental performance of the aviation sector (ibid). Additionally, the use of alternative fuels/green-energy instead of diesel or gasoline equipment, or stronger emission controls can reduce aircraft's total life-cycle CO emissions via GSE operations and truck transport (ibid).

2.10 Recent efforts towards sustainable aviation

In the past few years, there have been efforts in terms of implementing unconventional aviation propulsion systems (prototype or for pilot-use/small-scale); and using alternative fuel and renewable energy. Test flights using biofuels (SPK) from algae and camelina were successfully conducted which marks the beginning of using alternative fuel in aviation [32],[33],[51],[52]. Additionally, Lufthansa successfully completed a six-month flight-operation using 50% blended biofuel on Airbus A321 between Hamburg and Frankfurt, without any technical problems or operational inconsistencies [32],[33],[53]. Cochin airport in the Kerala state of India, is the world's first airport to be powered 100% by solar energy [54]. Solar impulse [55], is the world's first solar-powered aircraft with a seating capacity of one passenger. This solar-powered aircraft has successfully toured the globe (ibid). Researchers at the University of Cambridge have developed a single-seater hybrid-electric aircraft and have flown it successfully [56]. An ion-based propulsion method has been applied to a model aircraft (no passengers) by researchers at MIT, and test flights have been conducted [57]. The above efforts are in-line with the measures suggested to mitigate the impacts of aviation, via aircraft technology, alternative fuels and/or airport energy systems.

2.11 Future aircraft technology

A thesis by Cullen [58] examines the energy-efficiency of various energy systems. The analysis also includes the possible improvements to energy systems for increasing their efficiencies. In the chapter on aircraft, the author finds that significant fuel efficiency improvements can be made via structural/airframe, aerodynamics and propulsion systems. The author conducts comparison of presently used ‘swept-wing aircraft’ and a future ‘laminar-flow wing aircraft using un-ducted fan engine’ (LFW-UDF). This analysis is based on the specific fuel burn model from the ‘greener by design report’ [59]. The study by Cullen finds that approximately 46% fuel efficiency improvement can be achieved with the LFW-UDF configuration, which is essentially a combination of improved structural/airframe, aerodynamics and propulsion systems.

The ‘greener by design’ (GBD) report [59] provides a simple specific fuel burn (SFB) model/equation, which is a modified form of Breguet’s range equation. The Breguet’s range equation is a very fundamental equation in Aeronautics which estimates the flight range, where the flight range is influenced by aircraft aerodynamics, engine overall efficiency, aircraft structure and material and calorific value of fuel. The SFB equation is a parametric equation and it estimates the specific fuel burn (kg/ton-km), which is a result of simplifying the Breguet’s range equation by making certain assumptions. The derivation of this equation can be found in Appendix C (source [59]). The GBD report [59] provides the parameters for present-day and year 2050 technology aircrafts, using conventional jet fuel and liquid hydrogen fuel. In the GBD report [59], the parameters for individual aircrafts using respective fuels, are provided as per aircraft range viz. mid-range and long-range aircraft, and not by aircraft type or aircraft names. The aircraft type is important because it also encapsulate the passenger seating capacity and is a crucial aspect to define aircraft in a fleet. For example, long-range aircrafts (a range category) comprise of small twin aisle, large twin aisle and very large twin aisle.

Table 1. NASA N+3 subsonic fixed wing aircraft technology goals [60]

Corners of the trade space	*N+1 (service entry year 2020 and beyond) technology benefits relative to a single aisle reference configuration (Boeing 737/CFM 56)*	*N+2 (year 2025 and beyond) technology benefits relative to a large twin aisle reference configuration (Boeing 777/GE 90)*	*N+3 (year 2030 and beyond) technology benefits*
Noise	-32 dB	-42 dB	-71 dB
LTO NO_x emissions (below CAEP 6)	-60%	-75%	Better than -75%
Performance (Aircraft fuel burn)	-33%	-50%	Better than -70%

Study by Benzakein [60], guides the readers through the technologies for commercial aviation of the future, more specifically until year 2050. The discussion in this study is primarily about NASA N+i concepts[1], especially the propulsion systems involved in these concepts (ibid). Table 1 lists the NASA N+i subsonic fixed-wing aircraft technology goals

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[1] For N+i technology description and nomenclature, please refer the introduction section

(ibid). N+1 (year 2020 and beyond) will have advanced turbofan engines with high by-pass ratios (BPR), and N+2 (year 2025 and beyond) will have ultra-high BPR (UHB) turbofan engines (open-rotor [OR] and/or ducted geared turbofans [GTF]), via improvement in the thermal efficiency by increasing the overall pressure ratio (OPR) [14],[60]. The N+3 generation (year 2030 and beyond) will include ultra-high BPR propulsion (net effective BPR), hybrid engines, alternative cycles, integrated propulsion, variable cycle engine, and/or engines with inter-cooling (ibid). The technological improvements in N+1 category include: improving the current aerodynamics and structure (tube and wing body) and using efficient turbofans (high BPR) [61]. Also, advancements in the N+2 category include use of: advanced form of tube and wing body and unconventional aircraft body; efficient turbofans (UHB/GTF); low NO_x combustor concepts for high OPR environment; improved thermal efficiency of engines (or high operating temperatures) without increasing NO_x emissions (ibid). Overall, the N+2 category engines will have cleaner combustion, partial pre-mixed, and lean direct multi-injection; lightweight ceramic matrix composite (CMC) liners to handle higher temperatures associated with higher OPR; advanced instability controls; improved fuel-air mixing to minimize hot spots that create additional NO_x; and will have the flexibility to implement emerging alternative fuels [61]. Study by Ashcraft et al. [14] provides a systems-level review of the N+3 aircraft concepts which include Boeing's SUGAR (Subsonic Ultra Green Aircraft Research) concepts (more specifically Boeing SUGAR Volt concept); MIT's Double-bubble; Northrop Grumman SELECT (Silent Efficient Low-Emissions Commercial Transport); General Electric concept developed in partnership with Cessna and Georgia Tech; and NASA's N3-X Turboelectric Distributed Propulsion (TeDP) concept. Additionally, a study by Jagtap [62] (in press) conducts a systems-level assessment of subsonic hybrid-electric propulsion concepts for NASA N+3 goals with conceptual aircraft sizing (300 passengers). This comparative study is conducted using systems engineering methods to select the best concept from Boeing SUGAR Volt, MIT Double-bubble, Northrop Grumman SELECT and NASA N3-X TeDP [62]. This study is helpful in phase 1 of such a project. The 'Georgia Tech Integrated Product-Process Development (IPPD)' method is used in the study by Jagtap [62] to conceive a commercial aircraft which meets the rigorous N+3 goals set by NASA. The benefits of such a study is that it enables design changes to be made in early life of the project, thereby decreasing life-cycle costs (ibid). This study evaluates the NASA N3-X TeDP concept to be the best of the four concepts under consideration (ibid).

The N+1 technology is almost similar in architecture (tube and wing body) and in propulsion type, to most of the present-day aircrafts. The N+1 technology can be thought of as an improvement in performance relative to the present-day aircraft, which is majorly a result of using high BPR engines, and improved aerodynamics and reduced weight of the aircraft. The aircraft concepts under N+1 are undergoing development-manufacturing with a goal of entry in service from year 2020. The N+3 aircraft concepts have their own set of technology challenges to make them feasible for entering service in the targeted year. The study by Ashcraft et al. [14] shows feasibility criteria and constraints for N+3 hybrid-electric aircraft. For N+3 aircraft concepts, the electric motors and boundary layer ingestion (BLI) require significant technological developments (ibid). The BLI affects the propulsion system design due to flow distortion, and it has to be accurately included within the propulsion system design and optimization via high-fidelity multi-physics approach [63]. According to Ashcraft et al.

[14], considering past battery development cycles, it is unlikely that new chemistries will be available for year 2035 advanced concepts. Also, fuel-cells are unlikely to be ready for powering propulsion systems on large aircraft by year 2035 but they are more likely to be used for augmenting a primary power source [63]. A study by Grönstedt et al. [64] finds that aircraft fuel is currently 50-100 times more power dense than batteries and historical improvement rate of 2-3% makes it uncertain whether batteries will reach the power density required for (approximately) year 2050 timeframe. Brelje et al. [65] raise safety concerns, as batteries are a known aviation hazard and have much less service experience, and fail in seemingly more-complex modes. The design of economically-viable fixed-wing electric-aircraft demands high-end technology (ibid). According to studies by Pornet et al. [66] and Voskuijl et al. [67], the current technology is not ready, and significant development in battery technology is required for hybrid-electric aircraft, especially for a 300 passenger aircraft.

The current battery energy density is 100-200 Wh/kg. Pornet et al. [66] investigated the use of batteries as energy source alongside conventional jet fuel as a retrofit for short-to-medium range single-aisle turbofan aircraft. They conclude that the use of batteries with an energy density of 1500 Wh/kg, as an energy source, can provide a block fuel reduction (of 16%) on short-range missions. Further analysis by Pornet et al. demonstrates that batteries with an energy density below 1000 Wh/kg provide no significant fuel savings at all. In study by Friedrich et al. [68], a Boeing 737–800 aircraft was retrofitted with a hybrid electric propulsion system. Assuming a specific energy of 750 Wh/kg, 10.4% fuel saving was computed on a two-hour mission. Voskuijl et al. [67] consider a regional aircraft (70 passenger turbo-prop aircraft) with a range of 1528 km using 1000 Wh/kg energy density batteries, comprising of 34% electric shaft power. This requires 28% less mission fuel at the expense of a larger aircraft in terms of weight and wing area. Additionally, turbo-prop noise effects are not accounted in this study. The study by Schäfer [69] on all-electric aircraft with battery packs of 800 Wh/kg, enables a range of up to 600 nautical miles (1,111 km) for 150 passengers, mitigate airport area NO_x emissions by 40%, and reduce fuel use and direct CO_2 emissions by 15%. Overall, with the assumption of battery energy density reaching 4-8 times the present capacity, the maximum fuel consumption reduction of 28% is observed in a turbo-prop aircraft. Additionally, if life-cycle effects are taken into consideration, the savings in fuel consumption come at the expense of extra electricity production.

The N+2 aircraft concepts and the studies based on it, show the potential to meet the set targets. Some of these concepts include: advanced tube-wing body, blended/hybrid wing body, and box-wing body aircraft versions by different companies/organizations. These concepts use an ultra-high BPR direct-drive, or open-rotor (OR)/un-ducted turbofan or geared turbofan (GTF) engine. From Table 1, it can be observed that the N+2 goals have significant fuel savings (50% reduction) compared to the present fuel consumption. This is achieved through technological advancements in aircraft concepts, architecture and propulsion systems, including the unconventional aircraft architecture like blended/hybrid wing body (BWB or HWB). The blended/hybrid wing body is also a part of the N+3 concept (NASA N3-X TeDP), as discussed previously. A dedicated literature review is conducted on BWB aircraft architecture, and it is included in Appendix A. Additionally, the use of UHB engines/propulsion system will be started with N+2 technology. A study by Nickol et al. [70] (NASA) models a fleet of advanced N+2 aircrafts and conducts their performance evaluation.

The fleet comprise of regional jet/RJ (small-range), single aisle/SA (mid-range), very large twin aisle/VLTA (long-range), small twin aisle/STA (long-range) and large twin aisle/LTA (long-range); with at least 2 options of aircrafts for each aircraft type. A graphical representation of these concepts can be seen in Figure 10 (in Appendix B). RJs use conventional tube-wing architecture with high BPR engines, and SAs use tube-wing architecture with UHB engines; and VLTA, STA and LTA options have both tube-wing and BWB architecture using UHB engines. The best option in each of the aircraft types in the N+2 fleet provide direct fuel consumption reduction of 45.3% to 49.4% compared to the 2005 level baseline aircraft (ibid). Most aircrafts in the N+2 fleet meet the LTO NO_x reduction goals. Additionally, only the BWB concept with UHB shows the potential of tending towards NASA N+2 noise, fuel consumption and LTO NO_x reduction goals. Overall, N+2 is a generation where technology starts transitioning significantly and rapidly. N+2 concepts appear to be technologically feasible as indicated by studies.

2.12 Summary of the literature review:

To summarise, the literature review provides insights into different pathways of making aviation more sustainable, along with the consideration of technology feasibility and passenger safety aspect. ‘N+i’ technology, in general, is in-line with the four-pillar strategy of IATA (discussed before) for mitigating the impacts of aviation. Overall, N+i is inclusive of aircraft technology improvements and the use of alternative fuels, which will offer significant fuel savings/reduction in emissions.

The battery-powered aircraft (full and hybrid-electric) cases, were reviewed from literature. Overall, with the inherent assumption of battery energy-density in future reaching 4-8 times the present capacity, though not supported by the trend of battery technology development-rate, the maximum fuel consumption reduction of 28% is observed in a turbo-prop aircraft for a short-range mission of 70 passengers (noise effects of turbo-prop not accounted). It is to be noted that the studies on hybrid-/full-electric are mostly based on retrofitting existing aircraft with a battery pack, and the reduction in fuel consumption is solely a result of battery use. Additionally, if life-cycle effects are taken into consideration, the savings in fuel consumption come at the expense of extra electricity production. On a life-cycle basis, there is a possibility that there might not be any savings in GHG emissions, after including the GHGs from electricity production. Moreover, GHGs from electricity production vary from country-to-country as each country has different energy mix. Based on the published literature so far, it is unlikely that batteries will enable operation of full- or hybrid-electric 300 passenger aircraft for a long-range mission.

N+2 is identified as the aircraft technology level that appears to be technologically feasible as indicated by studies. Also, several alternative aviation fuels are identified, which include: ASTM approved ATJ-SPK (30% blending), sugar-to-jet (STJ) SPK (10% blending), HRJ-SPK (50% blending) and FT-SPK (50% blending); PtL; and LH_2. Moreover, in a life-cycle of a conventional aircraft, active operation (direct fuel-use) dominates life-cycle energy and GHG emissions (~75% of the total life-cycle energy), followed by fuel production (~10% of the total life-cycle energy). Hence, a life-cycle approach is deemed necessary for the alternative and conventional jet fuel, to be used in the future aircraft concepts. Additionally, not all alternative fuels mentioned above are ‘drop-in’ fuels, therefore it is required to examine the operability issues and the interaction between alternative fuels and aircraft. For example: LH_2 has lower density than conventional jet fuel, so it requires more volume storage on aircraft.

In terms of methodological approaches, three studies are identified which are relevant to this research. The methodological approach used in this study is a combination of the following studies, with identified/mentioned gaps. The study by Chester [50] conducts life-cycle assessment (LCA) of present passenger aircraft fleet using conventional jet fuel. It finds that fuel life-cycle GHG/energy dominates (~85% of) aircraft’s life-cycle GHG/energy. However, the effects of improvement in aircraft design/architecture, alternative fuel and source/feedstock for alternative fuel production on aircraft’s life-cycle energy, are not explored. Thesis/study by Cullen [58] uses model from Greener-by-design (GBD) report [59], to evaluate aircraft’s direct fuel-use, in current and future aircraft, using simple computational model called SFB model. These studies do not consider: alternative aviation fuels except liquid hydrogen (LH_2), and life-cycle effects of alternative fuel use.

From the literature review, it is found that cruise emissions are currently unregulated, yet have the highest air-quality impacts over aircraft’s flight mission. A long-range (e.g. 14,000 km) aircraft, like Boeing 777-200LR (~300 passengers), spends the majority (~ 90%) of its range in cruise. This implies that it is emitting CO_2 and non-CO_2 emissions at high-altitude over a significant distance (~12,600 km). A long-range aircraft will therefore have the highest climate impact compared to mid-range and short-range aircraft. Similarly, the measures for reducing the climate and air-quality impacts of aviation will be better observed in a long-range aircraft.

This research therefore examines N+2 aircraft technology concepts for 300 passengers, and the use of various alternative fuels from different feedstocks and/or sources, on a fuel life-cycle basis, along with the assessment of operability issues and the interaction between alternative fuels and aircraft. In addition to the methodological approach, the novelty of this research is underscored by the computation models developed towards the research objectives which is described in the next chapter.

3. Methodology

The broader aim of this research is to evaluate future aircraft technologies and alternative fuels, that will be essential to identify feasible technology and energy vector combinations for future inter-continental 300-passenger aircraft, towards the goal of sustainable aviation. For this research, a holistic approach will be used for evaluating the performance of future aircraft technology and energy vector combinations. The detailed objectives of this research, to meet the overall aim, are as follows:

1. Review future aircraft, airframe and propulsion concepts, and develop a modelling tool for estimating operational energy consumption.
2. Review current and potential energy vectors including alternative fuels and electrification and develop a database of their life-cycle impacts.
3. Evaluate aircraft technology and energy vector combinations with respect to their potential to reduce aviation greenhouse gas emissions on a lifecycle basis.
4. Holistic socio-environmental impacts including non-CO_2 climate impacts, air quality, water use, resources and land-use.
5. Operational cost analysis for different energy vectors.

In general, life-cycle assessment (LCA) helps in addressing the environmental concerns by accumulating an inventory of the total environmental releases, energy and material inputs, from cradle to grave i.e. extraction of raw material, processing of materials, product manufacturing, product distribution, product use, maintenance and repair, and recycling or disposal [32]. Additionally, it helps in the examination of the potential impacts associated with the inputs and emissions, and in the interpretation of the outputs which enables informed decision making.

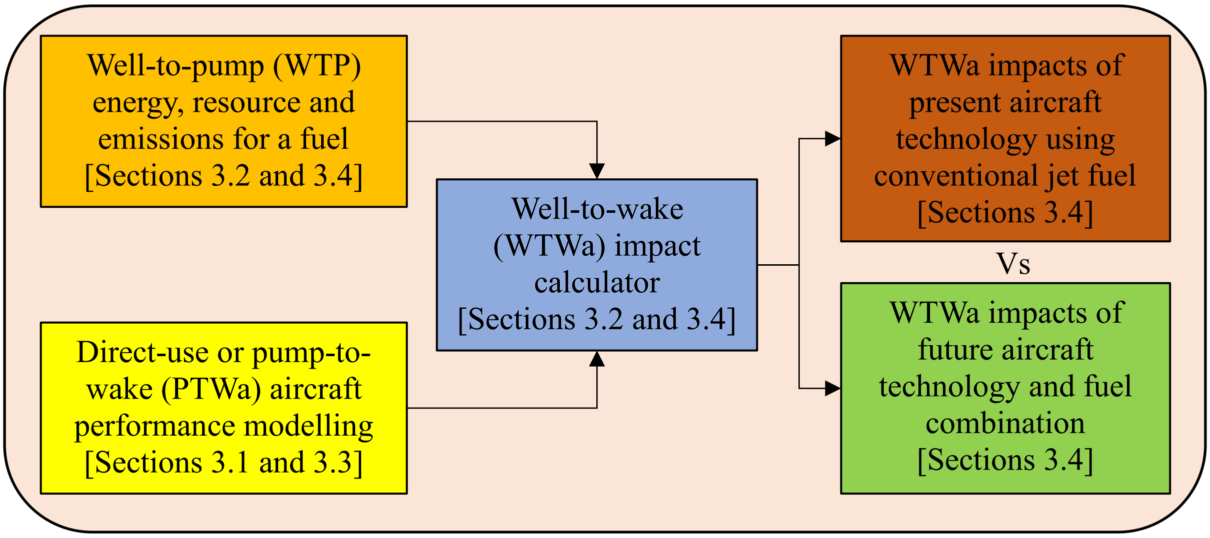

Figure 1. Schematic of overall research methodology

In terms of methodological approaches, three studies are identified that are relevant to the research under consideration, with identified/mentioned gaps. The study by Chester [50] conducts LCA of present passenger aircraft fleet using conventional jet fuel. It finds that fuel life-cycle GHG/energy dominates (~85% of) aircraft's life-cycle GHG/energy. However, the effects of improvement in aircraft design/architecture, alternative fuel and source/feedstock for alternative fuel production on aircraft's life-cycle energy, are not explored. Thesis/study by

Cullen [58] uses model from Greener-by-design (GBD) report [59], to evaluate aircraft's direct fuel-use, in current and future aircraft, using simple computational model called SFB model. These studies do not consider: alternative aviation fuels except liquid hydrogen (LH_2), and life-cycle effects of alternative fuel use. The methodological approach used in this study is a combination of the above studies, and such an approach has not been used so far. Figure 1 is a schematic representation of the overall methodology used in this research. The yellow block (PTWa) in Figure 1 is addressed in this chapter via models developed in this research. These are provided in sub-chapters 3.1 and 3.3. The orange block (WTP) and blue block (WTWa) are addressed in sub-chapters 3.2 and 3.4. The brown and green blocks are addressed in sub-chapter 3.4. The above mentioned sub-chapters provide detail description for individual models.

The research efforts until chapter 2 cover the literature review of future aircraft technology and energy vectors, which are part of objectives 1 and 2. In this chapter, the author has developed two models towards objectives 1, 2 and 3.

1. The first model is a specific fuel burn model for current and future (NASA N+2) aircraft fleet. With this model, one can understand the effects of aircraft size/weight, payload capacity (passengers), and range, on the specific fuel burn.
2. The second model is a conceptual (preliminary) design model of a liquid hydrogen aircraft. For this model, the author begins with design model of a baseline aircraft (Airbus A350XWB). This model is used to predict the energy consumption over flight mission profile using conventional jet fuel and liquid hydrogen (LH_2). The objective of this study is to examine the performance potential of LH_2 use in aircraft. Additionally, this model is helpful towards the estimation of use-phase emissions and therefore the life-cycle emissions calculation for LH_2 use in aircraft.

Additionally, towards objectives 2 and 3, the author has recorded the fuel production and life-cycle emissions of different alternative fuels from various feedstocks/pathways. Moreover, towards objectives 1, 2 and 3, the author has modelled a (preliminary) case of the life-cycle (WTWa) effects of different alternative aviation fuels for its use in futuristic NASA N+2 BWB aircraft and has made comparisons with present day Boeing 777-200LR aircraft. A preliminary air-quality, water-use, land-use and cost analysis is conducted for this case, towards objectives 4 and 5.

3.1 Specific fuel burn (SFB) model for present and future aircraft

In this sub-chapter, the author presents the specific fuel burn model (SFB) based on the Breguet's range equation. The 'greener by design' (GBD) report [59] provides a simple specific fuel burn (SFB) equation, which is a modified form of Breguet's range equation. The Breguet's range equation is a very fundamental equation in Aeronautics that estimates the flight range, where the flight range is influenced by aircraft aerodynamics, engine overall efficiency, aircraft structure and material, and the calorific value of fuel. The SFB equation is a parametric equation and it estimates the specific fuel burn (kg/ton-km). The GBD report [59] provides the parameters for present-day and year 2050 technology aircrafts, using conventional jet fuel and liquid hydrogen fuel. In the GBD report [59], the parameters for individual aircrafts using respective fuels, are provided as per aircraft range viz. mid-range and long-range aircraft, and not by aircraft type or aircraft names. The aircraft type is important because it also encapsulate the passenger seating capacity and is a crucial aspect to define aircraft in a fleet. For example, long-range aircrafts (a range category) comprise of small twin aisle, large twin aisle and very large twin aisle. In this sub-chapter, the author presents the SFB model parameters for individual present-day and NASA N+2 technology aircrafts as per aircraft type/aircraft names viz. regional jet, single aisle, very large twin aisle, small twin aisle and large twin aisle. Table 2 provides the present aircraft fleet information. This SFB model is developed and presented in this sub-chapter by the author, where the parameters for the individual present-day and NASA N+2 technology aircrafts, are collated from multiple literature resources. The description for individual parameters is provided in respective sub-sections ahead. This SFB model for the individual present-day and NASA N+2 technology aircrafts i.e. SFB variation with range for the present and future aircraft fleet, is novel, and is validated by plotting the known data points for individual aircrafts in present and future from literature.

Table 2. Current passenger aircraft fleet (source [70])

Aircraft type	Name	Passengers (PAX)	Range (km)	Block fuel (kgs)
Regional jet (RJ)	Embraer ERJ 190	98	4,445	11,000
Single Aisle (SA)	Boeing B737-800	160	5,325	17,738
Very large twin aisle (VLTA)	Boeing B747-400	400	10,742	134,996
Small twin aisle (STA)	Boeing B767-200 ER	216	12,223	65,568
Large twin aisle (LTA)	Boeing B777-200 LR	301	13,890	125,705

The GBD report [59] provides a simple SFB equation, represented by Equation 1, by modifying/simplifying the Breguet's range equation. This equation estimates the specific fuel burn (kg/ton-km), and it assumes that the fuel consumed from engine-start to beginning of cruise is 2.2% of the take-off weight (W_{TO}), for conventional jet fuel and 'drop-in' fuel [59]. For a liquid-hydrogen combustion aircraft, the corresponding lost fuel is 1.4% of take-off weight [59]. The coefficients of the exponential term of equation 1 for conventional jet fuel and liquid hydrogen are 0.978 and 0.986 respectively [59]. The derivation of this equation can be found in Appendix C (source [59]). The parameters c_1 and c_2 are structural constants for each aircraft type, $Z = R/X$, $X = H \eta L/D$, η is the engine overall efficiency, L/D is the cruise lift to drag ratio, H is the fuel calorific value: 4,350 J/N for conventional jet fuel and 11,750 J/N for liquid-hydrogen [59], and W_P and W_{MF} are payload and mission fuel weight respectively. The SFB model is applicable to future aircraft technology (only 100% fuel-combustion aircraft) using conventional jet fuel and alternative aviation fuels, if individual parameters of the SFB equation, specific to the case under consideration, are known. The effects of aircraft technology and alternative fuel use/performance are captured through c_1, c_2, η, L/D, and H. The effects of future aircraft technology gets captured through c_1 and c_2 (relates the improved airframe weight and mission-fuel weight), η (represents the improved overall engine efficiency), and L/D (represents the improved aircraft aerodynamics). The effects of alternative fuel use/performance are captured through c_1 and c_2 (includes the effect of improved mission fuel weight [higher energy density fuel will have lesser mission fuel weight]), η

(represents the impact of alternative fuel on performance [positive or negative, if any], viz. power required for cryo-cooling of stored liquid-hydrogen on-board, is extracted from the engine which reduces the engine efficiency), L/D (the effect of mission fuel weight, along with aircraft aerodynamics is reflected here), and H (different fuels have different energy density). Additionally, the coefficient of the exponential term of equation 1 for individual fuel, remains constant for future aircraft technology as it represents the amount of fuel consumed (weight) from engine-start to the beginning of cruise as a fraction of aircraft take-off weight. With future aircraft technology, it is inherently assumed by the SFB equation of GBD report [59] that improvements in fuel consumption from engine-start to the beginning of cruise will be similar in magnitude to the improvements in the aircraft take-off weight, therefore their ratio (i.e. the exponential term of equation 1) remains constant.

$$\mathrm{SFB} = \left(\frac{c_2}{X}\right)\left[\frac{(1-0.978e^{-Z})}{Z(0.978e^{-Z}-c_1)}\right] \tag{1}$$

$$W_{TO} = c_1 W_{TO} + c_2 W_P + W_{MF} \tag{2}$$

Table 3. Current and N+2 passenger aircraft fleet (source [59], [70], [71])

Known from literature [59]			
Aircraft technology	**Aircraft name/type**	**c_1**	**c_2**
Present	B737-800 (SA)	0.315	2
	B777-200LR (LTA)	0.300	2
	B767-200ER (STA)	0.300	2
	B747-400 (VLTA)	0.300	2

Calculated using references [70], [71]							
Aircraft technology	**Aircraft name/type**		**W_{TO} (kg)**	**W_P (kg)**	**W_{MF} (kg)**	**c_1**	**c_2**
Present	ERJ 190	RJ	47,790	9,800	11,000	0.359690	2.00
NASA N+2	T+W98-DD		41,212	9,800	5,908	0.392957	1.95
	OWN98-DD		40,728	9,800	5,783	0.388810	1.95
	T+W160-GTF	SA	66,338	17,128	10,143	0.343642	1.95
	OWN160-GTF		64,350	17,128	9,709	0.330110	1.95
	HWB301-DD	LTA	243,869	53,570	68,763	0.344605	1.70
	HWB301-GTF		242,440	53,570	66,683	0.349323	1.70
	HWB216-GTF	STA	142,364	20,185	35,869	0.507014	1.70
	HWB400-GTF	VLTA	318,661	67,059	68,268	0.428016	1.70

3.1.1 Estimation of c_1 and c_2 for aircrafts using conventional jet fuel

The c_1 and c_2 values for medium and long-range aircraft in current fleet are obtained from the GBD report [59], and for short range aircraft c_1 and c_2 are not available. The values for c_1 and c_2 for present-day: medium range aircraft (B737-800) are 0.315 and 2; and long range aircrafts (B767-200ER, B777-200LR and B747-400) are 0.3 and 2, respectively; from the GBD report [59].

For present regional jet (small range aircraft) and for future aircraft fleet (N+2 aircrafts), c_1 and c_2 are estimated by accounting the aircraft take-off, payload, and mission fuel burn weight, using equation 2. The values of W_P and W_{MF} for ERJ 190 is found from resource [70], and W_{TO} is found from resource [71]. These three weights for N+2 aircrafts is found from resource [70]. These three weights and the estimated c_1 and c_2 values for ERJ 190 and N+2 aircrafts is listed in Table 3.

The N+2 aircraft nomenclature is as follows: Tube and wing (T+W), Over wing nacelle (OWN), DD-Direct drive turbofan engine, GTF-Geared turbofan engine, HWB/BWB-Hybrid/Blended wing body, and MFN-Mid fuselage nacelle.

a. For ERJ 190 c_2 value is assumed as 2 and c_1 is calculated using equation 2. This is because for mid and long range aircraft, in the GBD report [59], c_2 value is 2. For N+2 aircraft fleet c_1 and c_2 combination is chosen such a way that the trend of SFB variation with range matches the trend from using c_1 and c_2 from the GBD report, in a future/advanced (year 2050) aircraft for individual range [59]. Also, it can be observed that for N+2 RJ and SA aircrafts, the value of c_2 is constant as all aircrafts are of T+W structure. The resulting value of c_1 for these aircrafts give a trend of the SFB. For example: OWN 190-GTF case has lowest value of c_1 of the four aircrafts, and it also has lowest SFB of all cases.
b. A similar process mentioned in (a), is employed for c_1 and c_2 combination for N+2 STA, VLTA and LTA aircrafts, where all have HWB/BWB architecture.

3.1.2 Cruise lift-to-drag (L/D) ratio for aircraft using conventional jet fuel

The cruise L/D ratio for the N+2 aircrafts is known from resource [70], and these values are listed in Table 4. For the present aircraft fleet, L/D ratio are found from literature. The cruise L/D value for B777-200LR is found to be 19.3 from resource [72], [73]. For other aircrafts in current fleet, the maximum L/D values are known from literature. The GBD report [59] suggests using a 2% penalty on maximum L/D to account for vortex induced drag. The cruise L/D value for ERJ 190 is not available directly from literature, so L/D ratio of a similar aircraft size/type (100 passengers) BAE 146 is assumed. Figure 12 (in Appendix C) from resource [74], suggests maximum L/D of ~14.5 for BAE 146 aircraft. The maximum cruise L/D value for B737-800 is 17.26 according to resource [75]. For both B747-400 and B767-200ER, the maximum L/D ratio is found to be 18 from resource [76] and [77] respectively. Therefore, after using the 2% penalty in maximum L/D ratio, the cruise L/D values that is used in this study for ERJ 190, B737-800, B747-400 and B767-200ER is 14, 16.92, 17.64 and 17.64 respectively. These values are listed in Table 4 for the SFB model.

3.1.3 Overall efficiency for aircraft using conventional jet fuel

Overall efficiency (η) is the product of η_{thermal} and $\eta_{\text{propulsive}}$. The overall efficiency for different aircrafts is as follows:

i. The overall efficiency for ERJ 190 is not known directly, however, resource [78] provides Figure 13 (in Appendix C) which plots the overall efficiencies (η) according to the bypass ratio (BPR) of the engines used on individual aircrafts. ERJ 190 uses CF34-10E turbofan engines with BPR of 5.4 and using the Figure 13 (in Appendix C) from resource [78], the η is estimated to be 0.33.

ii. Similarly, for B737-800 which uses CFM 56 7B24 turbofan engines with BPR of 5.3 [79], the η is estimated to be 0.32 using Figure 13 (in Appendix C) from resource [78].

iii. B767-200ER aircraft uses CF6-80C2 turbofan engines and its η is found from resource [80] to be 0.31, which is indicated in Figure 14 (in Appendix C).

iv. The η for B747-400 and B777-200LR are known directly from resource [78] to be 0.37 and 0.35 respectively.

v. As mentioned, η is the product of η_{thermal} and $\eta_{\text{propulsive}}$. The η_{thermal} and $\eta_{\text{propulsive}}$ are measures of overall pressure ratio (OPR) and bypass ratio (BPR) respectively. The η for N+2 engines using ultra-high BPR (UHB) engines are not known directly. However, the OPR and BPR of these engines are known. For advanced ultra-high BPR (UHB) engines, resource [80] gives the η value of ~0.49. η value (of 0.49) is assumed as the efficiency for the UHB engine with highest OPR and BPR combination, and likewise for other UHB engines the η value is assumed between 0.42 and 0.49. The OPR and BPR values for N+2 engines, and their assumed overall efficiency values for individual N+2 engines are listed in Table 6 (in Appendix C). Additionally, the overall efficiency values for individual N+2 engines are listed in Table 4 for the SFB model.

3.1.4 SFB model parameters for LH_2 BWB aircraft

A preliminary examination of LH_2 BWB aircraft is conducted using the SFB model. It is to be noted that the coefficient of the exponential term of equation 1 becomes 0.986 instead of 0.978, for LH_2 use as per the GBD report [59]. The parameters such as c_1, c_2, H, η and L/D ratio should ideally be different for LH_2 use in aircraft compared to the conventional jet fuel case. The values of c_1 and c_2 for LH_2 BWB aircraft is taken from the GBD report [59]. Because this is a preliminary examination, the L/D ratio for this aircraft is assumed to be equal to the conventional jet fuel case. The overall efficiency value from GBD report [59] for LH_2 aircraft suggest 6-7% reduction from the conventional jet fuel case. Therefore, a value of 0.46 is assumed for the overall efficiency of LH_2 BWB aircraft compared to 0.49 for the conventional jet fuel case. It is to be noted that the calorific value H for LH_2 is 11,750 J/N (~115 MJ/kg), compared to 4,350 J/N for conventional jet fuel, as per the GBD report [59]. As mentioned, this is a very basic analysis for the LH_2 case. The author plans to improve the SFB model parameters for this case based on a separate analysis which considers the weight of LH_2 fuel tank and insultation, and/or aircraft redesign.

Table 4. Current and N+2 aircraft SFB model parameters (source [59],[70], [72], [73]-[80])

Aircraft	Aircraft type	Range-type	Range (km)	c_1	c_2	η	L/D_{cruise}^{***}
ERJ 190	RJ	Small	4,445	0.3600 *	2.000 *	0.33 **	14.0 [74]
OWN N+2				0.3888 *	1.950 *	0.42 **	19.7 [70]
B737-800	SA	Medium	5,325	0.3150 [59]	2.000 [59]	0.32 **	16.9 [75]
OWN N+2				0.3301 *	1.950 *	0.47 **	19.6 [70]
B747-400	VLTA	Long	10,742	0.3000 [59]	2.000 [59]	0.35 [78]	17.6 [76]
BWB-GTF N+2				0.4280 *	1.700 *	0.49 **	24.3 [70]
B767-200ER	STA		12,223	0.3000 [59]	2.000 [59]	0.31 [80]	17.6 [77]
BWB-GTF N+2				0.5070 *	1.700 *	0.47 **	24.0 [70]
B777-200LR	LTA		13,890	0.3000 [59]	2.000 [59]	0.37 [78]	19.3 [72], [73]
BWB-GTF N+2				0.3460 *	1.700 *	0.49 **	23.7 [70]
BWB-UHB N+2 LH_2				0.2550 [59]	1.765 [59]	0.46 **	23.7 [70]
*Please refer section 3.1.1 for details; ** Please refer section 3.1.3 for details; *** Please refer section 3.1.2 for details							

3.2 Alternative aviation fuels

From the literature review several alternative aviation fuels are identified. These include: ASTM approved ATJ-SPK (30% blending), sugar-to-jet (STJ) SPK (10% blending), HRJ-SPK (50% blending) and FT-SPK (50% blending); Power-to-liquid (PtL); and LH_2. For well-to-wake (WTWa) data of ASTM approved bio-jet fuel and for well-to-pump (WTP) data of liquid hydrogen (LH_2), GREET 2018 model of Argonne National Laboratory, USA [17], is used in this study. LH_2 fuel has special operability requirement for aircraft use. Therefore, there is a need to model the operational energy consumption of LH_2 aircraft, which is included in sub-chapter 3.3. This will enable GHG emission in the use-phase/direct-use of aircraft. Thus, for LH_2 aircraft case, one can estimate the WTWa emission/energy inventory. Additionally, for PtL fuel, the WTWa GHG emission is known from literature. The details of each alternative aviation fuel is as follows.

3.2.1 ASTM approved bio-jet fuels

GREET 2018 model [17], is used in this study. It is a life-cycle based software tool, developed by Argonne National Laboratory, USA, and it supplies the well-to-wake (WTWa) information for fuel produced from different feedstock/pathway viz. quantity of energy and fossil-fuels/resources utilized, and quantity of emissions released. It is to be noted that GREET model provides US specific information for different fuels.

i. *FT-SPK (50% blending):*

In this report, there are in total seven FT-SPK feedstocks to be evaluated. These feedstocks are North-American (NA) natural gas, Non-NA natural gas, Non-NA flared gas, biomass, coal, coal-biomass, and natural gas-biomass. In the report, feedstocks are represented with abbreviations. NANG, NNANG, NNAFG and NG are abbreviations for North-American (NA) natural gas, Non-NA natural gas, Non-NA flared gas, and natural gas respectively.

ii. *HRJ-SPK (50% blending):*

In this report, there are four HRJ-SPK feedstocks to be evaluated. These feedstocks are Camelina, Jatropha, Algae and Carinata.

iii. *ATJ-SPK (30% blending):*

There are two types of fuel manufacturing plant scheme in this model: standalone and distributed plants. For the standalone type of plant, the feedstocks that are examined are corn with dry mill, poplar, forest residue, miscanthus, switchgrass, willow and corn stover. For the distributed scheme, the feedstocks that are examined are corn US mix, corn dry mill without extraction, corn dry mill with extraction, corn wet mill, poplar, forest residue, miscanthus, switchgrass, willow, corn stover and solid waste. In the further parts of this report, abbreviations are used to denote the pathways and feedstocks. Standalone and distributed scheme are prefix to the feedstock names and are denoted as 'S.' and 'D.' respectively. CDM, FR, CS, Ms, and SG are abbreviations for corn with dry mill, forest residue, corn stover, miscanthus and switchgrass respectively. CUM, CDMWOE, CDMWE CWM and SW are abbreviations for corn US mix, corn dry mill without extraction, corn dry mill with extraction, corn wet mill, and solid waste respectively. Therefore, a total of 18 feedstock-manufacturing plant combinations are available for ATJ-SPK.

iv. *STJ-SPK (10% blending):*

There are four types of fuel manufacturing plant scheme considered in this report: Biological plant type, catalytic with external H_2 plant type, catalytic with in-situ H_2 plant type, and catalytic with H_2 from biomass gasification plant type. In this report, for each of the four type of plants, the feedstocks that are examined are poplar, willow, switchgrass, miscanthus, corn stover and forest residue. In the further parts of this report, feedstock/pathways are denoted with abbreviations in the figures and discussion. Biological plant type, catalytic with external H_2 plant type, catalytic with in-situ H_2 plant type and catalytic with H_2 from biomass gasification plant type, are prefix to the feedstock names, and are denoted as 'B.', 'CWE.', 'CWI.' and 'CBG.' respectively. W, P, SG, CS, FR and Ms are abbreviations for willow, poplar, switchgrass, corn stover, forest residue and miscanthus, respectively. Thus, a total of 24 feedstock-manufacturing plant combinations are available for STJ-SPK.

3.2.2 PtL

PtL has the potential to be used as a drop-in aviation fuel [36]. PtL has significantly lower life-cycle GHGs because of carbon capture during the manufacturing phase. It is not currently approved for civil aviation. The life-cycle GHGs of PtL from two paths [35], [36]; are as follows:

i. PtL (wind/photovoltaics[PV] in Germany, renewable world embedding[RWE]) = ~1 g/MJ
ii. PtL (wind/PV in Germany, today's energy landscape in material sourcing and construction) = 11 to 28 g/MJ

The details of the above two paths are not known, in terms of time-frame. One of the process involved in fuel refining is Fischer-Tropsch process. It is to be noted that 50% blended FT jet fuel is approved by ASTM, and 50% blend of PtL from FT process can be used directly.

3.2.3 Liquid hydrogen (LH_2)

GREET 2018 model [17], is used to obtain the well-to-pump (WTP) or fuel manufacturing GHG for LH_2. Currently in USA, north-American natural gas (NANG) is used on commercial scale for liquid H_2 production. The other feedstocks for LH_2 production include: solar energy, high temperature gas reactor (HTGR), coal, high temperature electrolysis-solid oxide electrolyzer cell (SOEC), nuclear energy (water cracking), by-production from chlorine plants, by-production from natural gas liquid (NGL) cracker plant, biomass, coke oven gas, and integrated fermentation. In total these are eleven feedstocks for LH_2 production in the GREET 2018 model [17]. A comparison of WTP GHG emissions for these 11 cases with conventional jet fuel is provided in Figure 19 (in Appendix E). It is to be noted that LH_2 is more energy dense than the conventional jet fuel, and so lower quantity of LH_2 fuel might be required for use in aircraft. Additionally, because of this potential reduction in fuel weight, the aircraft will have improved lift to drag ratio (because of lower lift induced drag) compared to the conventional jet fuel case. However, as discussed in the literature review, LH_2 fuel has special requirements on aircraft viz. bigger fuel tanks, insulation etc., which increase the weight of the aircraft. Therefore, none of the 11 cases can be directly ruled out by just comparing the WTP GHG. There is a need for modelling the LH_2 aircraft to considering these effects.

3.3 LH_2 aircraft preliminary model

For the well-to-pump (WTP) data of liquid hydrogen (LH_2), GREET 2018 model of Argonne National Laboratory, USA [17], is used in this study, as mentioned in previous sub-chapter. LH_2 fuel has special operability requirement for aircraft use. Thus, there is a need to model the operational energy consumption of LH_2 aircraft, which is included in this sub-chapter. This will enable GHG emission calculation in the use-phase/direct-use of aircraft. Therefore, for LH_2 aircraft case, one can estimate the WTWa emission/energy inventory.

For the LH_2 aircraft model, the author begins with a design model of a baseline aircraft. These models are used to predict the energy consumption over flight mission profile using conventional jet fuel and liquid hydrogen (LH_2) respectively. The objective of this study is to examine the performance potential of LH_2 use in aircraft. Additionally, this model is helpful towards the estimation of use-phase emissions and life-cycle emissions calculation for LH_2 use in aircraft. After modelling the baseline aircraft case necessary modifications are made to it, for the use of LH_2 fuel.

Airbus A350-XWB (900) is selected as a baseline aircraft, because it is a latest aircraft, and the data required (weights and engine design parameters) for modelling the fuel performance, is available. The range for this aircraft is 15,000 km [81]. The cruise altitude for this aircraft is 12,190 m and cruise Mach 0.85 [82]. The aircraft fuel burn methodology is provided in Appendix F. This methodology is described in detail in the Airplane design-Part 1 book by Roskam [83]. It is used in the aircraft weight sizing process which determines the aircraft weight, and the fuel burn over an entire flight mission profile.

The Airbus A350-XWB uses two Rolls-Royce Trent XWB turbofan engines. An aero-thermodynamic and mechanical model of this engine is developed in GasTurb 13 [84] software tool. The details of Trent XWB turbofan engine modelling are provided in Appendix G. The engine design targets (SLS thrust, BPR, OPR) and most turbo-machinery input parameters are taken from the design competition document of the American Institute of Aeronautics and Astronautics (AIAA) request for proposal (RFP), which can be found in resource [82]. These inputs provide a good starting point to develop the engine. The engine model further undergoes optimization with the identified design variables/parameters and known-identified constraints for minimizing the thrust specific fuel consumption (TSFC) in GasTurb 13 [84] software tool. Additionally, the turbo-machinery disks are optimized for weight and mechanical stress in GasTurb 13 [84] software tool, as disk weight contributes significantly to the total engine weight and mechanically overstressed disk cause engine failure. Moreover, the engine is checked for turbomachinery ‘stall’ for different operating conditions in the mission profile.

The aircraft fuel-burn model requires the TSFC values for climb, cruise, and loiter which comes from the engine model developed in GasTurb 13 [84] software tool. These TSFC values are used in the calculation of the fuel fraction (FF) of climb, cruise, and loiter segment. The FF value for start, taxi, take-off, descent, approach and landing come from the airplane design-Part 1 book by Roskam [83]. For example, FF for conventional jet fuel case, Roskam recommends a value of 0.99 for engine start and warm-up. This means that 1% of the aircraft start (gross take-off) weight is equivalent to the amount of fuel used in the engine start and warm-up. The mission fuel burn predicts A350-XWB aircraft’s fuel empty weight of 134,980 kg and take-off weight of 246,415 kg, for 111,435 kg of conventional jet fuel burn over a range of 15,000 km with an additional standard loiter of 350 km.

For the case of LH_2 use in aircraft, tank and insultation weight (and accessories like cooling units) of 7000 kg [85] is added to aircraft fuel empty weight. It is to be noted that the value 7000 kg is taken from a NASA report [85] from year 1955, and therefore this value acts as a worst-case in this design-analysis. The ratio of lower calorific value (LCV) of LH_2 fuel and conventional jet fuel is 2.79 (120/43), i.e. 35.833 kg of LH_2 is required to do work done by 100 kg conventional jet fuel. Using this proportion, the FF values for LH_2 use is calculated from the FF values of conventional jet fuel, for mission segment of start, taxi, take-off, descent, approach and landing. For example, FF for conventional jet fuel case is 0.99 for engine start and warm-up i.e. 1% aircraft start (gross take-off) weight. Using LH_2, only 35.833% of 1% aircraft start weight is required. Thus, the FF for LH_2 use for engine start and warm-up is 0.9964 (= 0.99 + (1-0.35833) x 0.01). Similarly, for taxi, take-off, descent, approach and landing, FF is calculated. For climb, cruise, and loiter, this model calculates the FF from TSFC. FF for climb, cruise, and loiter is dependent on TSFC and L/D. The L/D estimation for the model is done separately, as described in the methodology (in Appendix F). The direct effect of LH_2 use on the aircraft L/D is through the decrease in aircraft take-off weight (lower mission fuel requirement). To avoid double counting, the said energy proportion is applied to climb, cruise, and loiter TSFC values from conventional jet fuel, and not to their FF values. The mission fuel burn predicts take-off weight of 172,056 kg for 30,075 kg of LH_2 fuel burn (compared to 111,435 kg of conventional jet fuel) over a range of 15,000 km with an additional standard loiter of 350 km. It is to be noted that the ratio of conventional jet fuel burn to LH_2 fuel burn is 3.7 (111,435/30,075) compared to the earlier mentioned energy ratio of 2.79. The value of 3.7 is because of the effect of higher energy density of LH_2 (lower take-off weight) and its compound effect through improved L/D ratios (lower lift induced drag) over the mission. Another important point to be noted here is that in events of emergency landing immediately after take-off, the pilot performs fuel jettison or dumps the conventional jet fuel in air so that the aircraft weight goes below its maximum landing weight. The maximum landing weight of A350 XWB aircraft is 207,000 kgs [81], and the take-off weight of LH_2 aircraft is much below (172,056 kg) the maximum landing weight, so there is no need of fuel jettison/dumping (highly flammable fuel) or other modes of reducing aircraft weight. This aspect of fuel jettison has not been addressed in any literature published till now.

Additionally, the density of LH_2 is 71 kg/m^3 while that of conventional jet fuel is 808 kg/m^3; i.e. conventional jet fuel is about 11.4 times denser than LH_2. This implies that the fuel tanks on LH_2 powered aircraft will require more volume storage (bigger tanks with insulation), which will further increase aircraft weight. To maintain the same payload capacity, it is necessary to re-design the aircraft (fuselage and wing-loading) to account for extra fuselage and fuel tank weight. It is to be noted that the current study ignores the effect of extra-fuselage/body (weight increase) to encompass large and bulky tanks, for maintaining same payload. LH_2 requires power for cryo-cooling, which will be extracted from engine. Thus, the engine TSFC will increase (negative effect) than present values (not accounted here) or in other words more fuel will be consumed than considered presently. The objective of this section, as mentioned earlier, was to examine the performance potential of LH_2 use in aircraft. The author plans to improve the model of LH_2 use in aircraft, taking the above effects into consideration.

3.4 Preliminary comparative performance assessment of different alternative fuels in N+2 aircraft

The WTWa GHG emissions of different alternative fuels and the conventional jet fuel have been examined in the previous sub-chapters 3.1-3.3 of this report. The WTWa GHG emission of LH_2 from HTGR case is calculated from the developed model for A350 XWB aircraft. This WTWa GHG value will be used for performance in N+2 BWB-GTF aircraft. However, this value is expected to reduce for LH_2 use in more efficient aircraft like N+2 BWB-

GTF. Thus, using the calculated WTWa GHG value for LH_2 use in N+2 BWB-GTF is essentially a worst-case estimation. The WTWa GHG emissions for conventional jet fuel, 50% blended FT-Biomass SPK, PtL Germany-renewable world embedding (RWE) and PtL Germany-today are estimated from the method described in sub-chapter 3.2.

LH_2 use will have maximum benefits if used on BWB because of its higher aircraft volume storage for same payload and wetted area/drag, compared to T+W architecture. The author continues this discussion on BWB's potential for LH_2 use, in next chapter. Primarily, from the study by Nickol et al. [70] is found from the N+2 BWB aircraft (300 passengers/PAX) with GTF will have direct fuel consumption reduction of 47%. N+2 BWB-GTF aircraft (300 passengers/PAX) option has the maximum savings of the options available and it has the potential of LH_2 use with fewer modifications compared to T+W architecture (discussed in next chapter). A preliminary examination of the life-cycle impacts of using conventional jet fuel and different alternative fuels in N+2 BWB-GTF aircraft is conducted. These cases are compared to the year 2005 level aircraft technology viz. Boeing 777-200LR (large twin aisle), and the comparison is presented in next chapter (in Figure 6).

4. Preliminary results/research progress

4.1 SFB model results

Figure 11 (in Appendix C) provides the SFB data points for present and future aircraft fleet (data point plotted using resource [67], [70]). Figure 2 provides the SFB variation with range for the present and future aircraft fleet with data points for individual aircrafts in present and future, using the model developed in 3.1. In most cases, the individual aircraft data points lie close/on the curve, which in a way validates the developed SFB model. To be noted that this is a simple model, which captures the aircraft's structure, passenger and fuel weight through c_1 and c_2, aerodynamics through L/D ratio, and engine performance through η. This model can also be validated by experiments, but it would be very expensive. Most aerospace projects in academia, industry or start-ups, are primarily numerical/computational models in the design-development phase until the point of proto-type tests or specific physics problem solving viz. wind-tunnel model testing, turbine-cooling, compressor-bleed effects, etc.; because of the enormous costs associated with the experimental set-up. For example: a simple combustion rig experimental project can cost on the order of few million USDs.

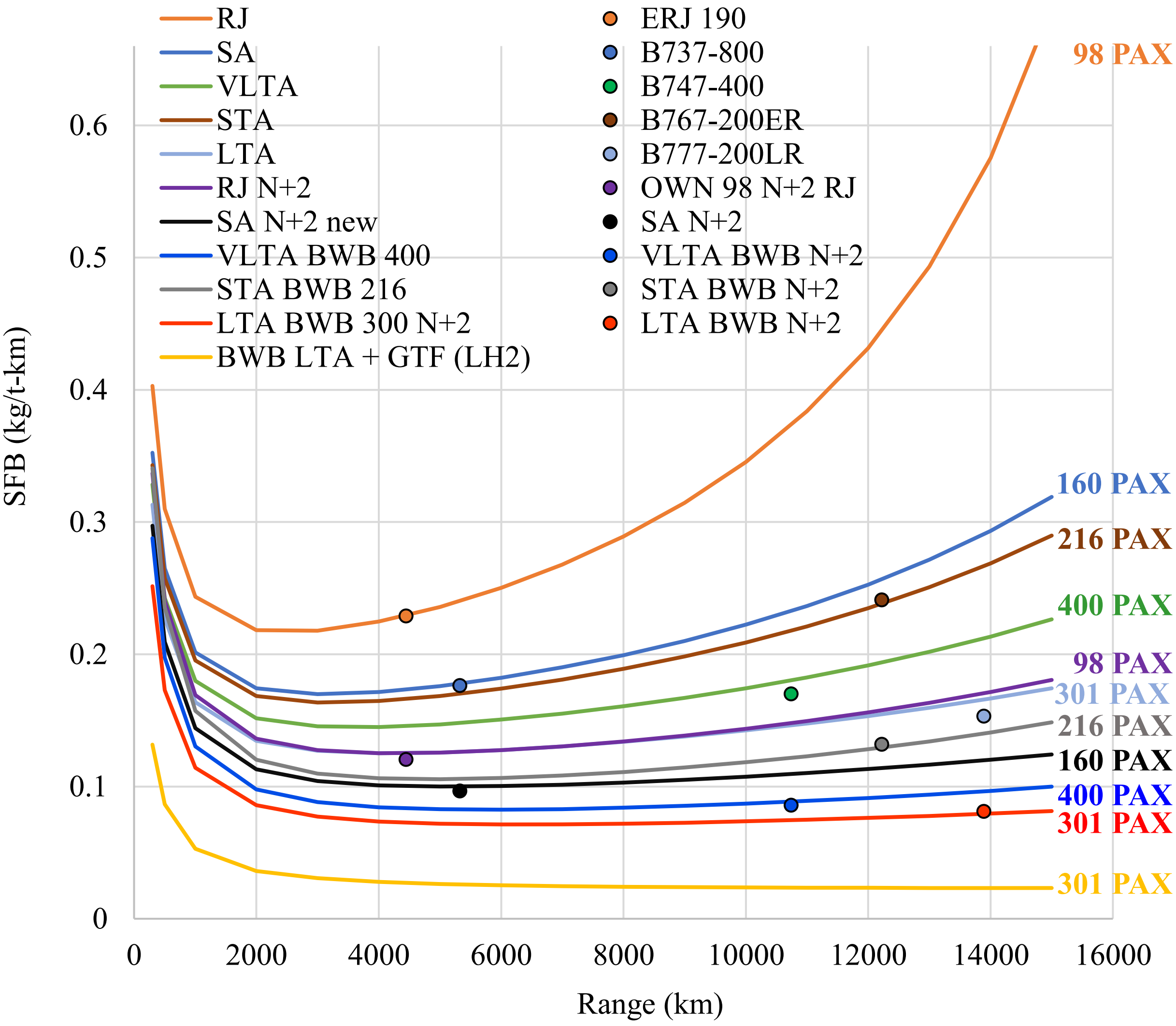

Figure 2. SFB variation with range for the present and future aircraft fleet

4.2 Alternative aviation fuels

Figures 15, 16, 17, and 18 (in Appendix D) provide the life-cycle (WTWa) GHG emission for FT-SPK (7 cases), HRJ-SPK (4 cases), ATJ-SPK (18 cases) and STJ-SPK (24 cases) respectively, for fuel use in large twin aisle (LTA) aircraft like Boeing 777-200LR, with individual approved blend quantity. The WTWa GHGs from GREET 2018 model include CO_2, NO_x, nitrous oxide (N_2O), methane (CH_4), black carbon (BC), organic carbon (OC), VOC and CO.

Considering only the perspective of lowest GHG emission, 'Biomass', 'Carinata', 'distributed plant-Miscanthus' and 'catalytic with H_2 from biomass gasification plant type-Miscanthus' are the best feedstock-manufacturing plant combination for FT-SPK (50% blend), HRJ-SPK (50% blend), ATJ-SPK (30% blend) and STJ-SPK (10% blend) respectively. Figure 3 shows the comparison of WTWa GHG emissions of these best feedstock-manufacturing plant combination for each ASTM approved bio-jet fuel and conventional jet fuel (referred as Conv. Jet in figures from hereon). FT-SPK from biomass provides the highest reduction (47%) in WTWa GHG emissions of all the four bio-jet fuel cases considered here, compared to the conventional jet fuel. Figure 4 shows the comparison of WTWa water consumption (US gallons), and PM and SO_x emissions (grams) of ASTM approved blended bio-jet fuels with conventional jet fuel. On a life-cycle basis, FT-Biomass (50% blend) requires 46% less water and has lowest emission of $PM_{2.5}$, PM_{10} and SO_x, compared to conventional jet fuel, and other bio-jet fuels under consideration here.

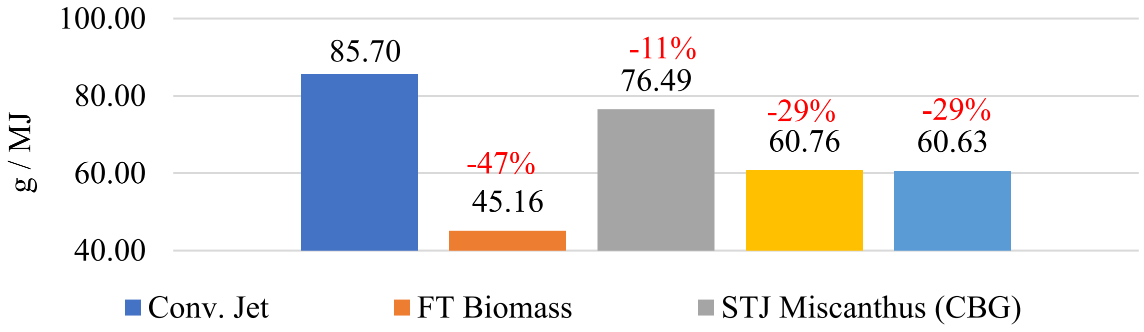

Figure 3. Comparison of WTWa GHG emission of ASTM approved blended bio-jet fuels with conventional jet fuel

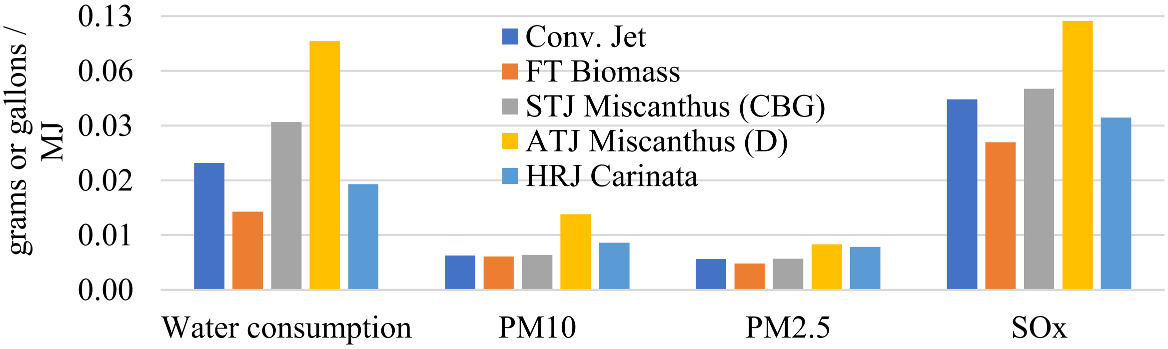

Figure 4. Comparison of WTWa water consumption (US gallons), and PM and SO_x emissions (grams) of ASTM approved blended bio-jet fuels with conventional jet fuel

4.3 LH_2 aircraft preliminary model

Table 5. Comparison of mission fuel burn for conventional jet and LH_2 fuel in aircraft

	FF_{LH2}	**FF_{Jet}**	**Start-weight$_{LH2}$**	**Start-weight$_{Jet}$**	**Fuel-used$_{LH2}$**	**Fuel-used$_{Jet}$**
	-	-	kg	kg	kg	kg
Start	0.9964	0.990	172,056	246,415	617	2464
Taxi	0.9964	0.990	171,439	243,951	614	2440
Take-off	0.9982	0.995	170,825	241,511	306	1208
Climb	0.9982	0.994	170,519	240,304	304	1365
Cruise	0.8405	0.581	170,215	238,939	27,157	100,087
Descent	0.9968	0.991	143,058	138,852	461	1194
Loiter	0.9990	0.990	142,597	137,658	136	1398
Approach	0.9995	0.999	142,460	136,260	71	191
Land	0.9971	0.992	142,389	136,069	408	1089
Mission	**0.8252**	**0.55**	**FEW 134,980 (+7000 kgs for LH_2)**		**30,075**	**111,435**

The comparison of conventional jet and LH_2 fuel burn over the flight mission is provided in Table 5. The mission fuel consumption for both fuels is estimated through the model developed in previous chapter, and therefore the WTWa effects of LH_2 use in aircraft can be analysed, where LH_2 is produced from different feedstocks, in comparison with conventional jet fuel. For conventional jet fuel the emission indices (EI) for individual emissions are: EI (CO_2) = 3155 g per kg fuel, EI $(H_2O)_g$ = 1250 g per kg fuel, and EI (SO_x) = 0.8 g per kg conv. jet fuel [86]. In case of LH_2 fuel, EI $(H_2O)_g$ = 9 kg per kg LH_2 fuel. The WTWa analysis and comparison can be seen in Figure 5. It is to be noted that of the 11 feedstocks for LH_2 production only 7 cases are included in this plot because the remaining 4 cases do not show reduction in WTWa GHG. The 'LH_2 from coal' case is included here as it has the highest value of WTWa GHG (and to use as an example).

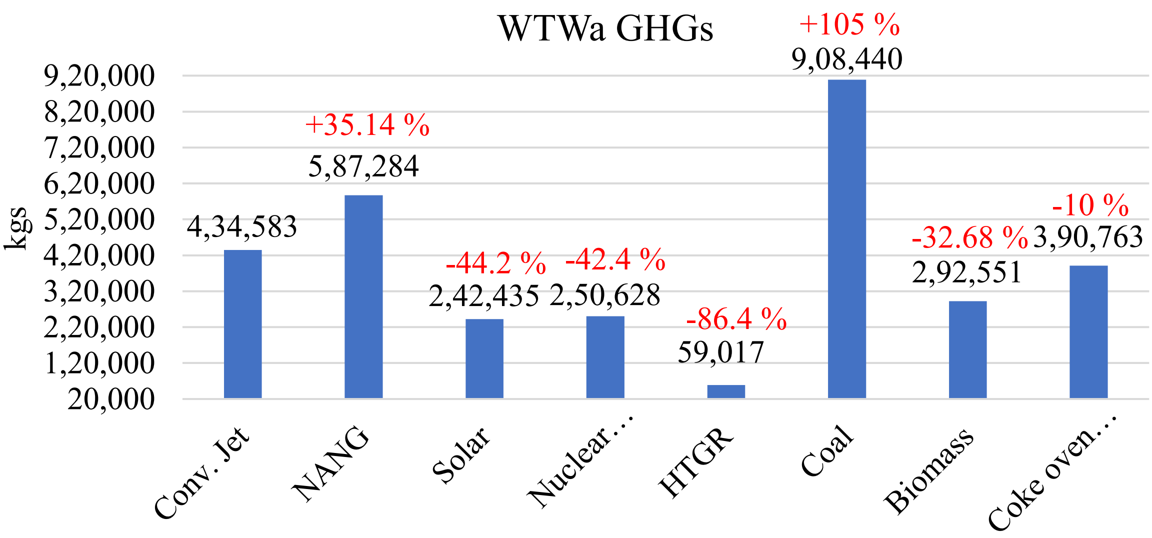

Figure 5. WTWa GHG from the use of LH_2 (in aircraft) produced from different feedstocks in comparison with conventional jet fuel

It is to be noted that in this analysis, a global warming potential (GWP) of 0.165 (average of 0.1 and 0.23 [87]) is assumed for water vapour, though there is no published journal literature which provides GWP of water vapor. Considering only the perspective of lowest GHG emission, LH_2 from high-temperature gas reactor (HTGR) is the best case as it provides the highest reduction (86.4%) in WTWa GHG emissions of all the cases considered here, compared to the conventional jet fuel. The WTWa GHG emission of LH_2 from HTGR case is calculated to be 16.35 g/MJ, for use in A350 XWB. It is to be noted that this value is subject to change, especially for more efficient aircrafts and/or different aircraft type. However, it is a good starting point for a preliminary examination.

Jet fuel currently (March 2019) costs \$0.503 per litre [88] (\$ 0.621 per kg) and H_2 from HTGR is predicted to cost \$1.53 per kg (it is unclear whether its liquid or gas) as claimed by General Atomic [89] (time-frame not known). Using these cost estimates for the A350 XWB mission fuel burn cost, using conventional jet fuel will cost \$69,200 (\$ 0.621/kg x 111,435 kg) compared to \$46,015 (\$ 1.53/kg x 30,075 kg) of HTGR H_2. Assuming \$ 1.53/kg cost to be for gaseous H_2, for the HTGR pathway to cost approximately same including liquefication cost, the cost of LH_2 from HTGR should be \$2.3 per kg. In year 2050, conventional jet fuel is expected to cost between \$0.46 and \$0.94 per kg [36], i.e. operational fuel cost of \$51,260 to \$104,748 in A350 XWB aircraft**.** It is to be noted that using LH_2 will reduce other operating costs like carbon tax, as there are no direct emissions except NO_x and water vapor.

Direct NO_x emissions are not considered in this study. Dincer et al. [90] suggest NO_x emissions 0.4 g/MJ for conventional jet fuel and 0.6 g/MJ of LH_2; i.e. 1916.6 kg NO_x for conventional jet fuel and 2165.4 kg NO_x for LH_2, over 15,000 km flight. However, NO_x production is dependent on combustor type. Baharozu et al. [91] suggest 12g-NO_x/kg-conventional jet fuel aircraft case compared to 4.28g-NO_x/kg-LH_2 aircraft, i.e. 1337 kg NO_x for conventional jet fuel and 128.7 kg NO_x for LH_2, over 15,000 km flight. The author plans to include direct NO_x emissions in future studies.

4.4 Preliminary comparative performance assessment of different alternative fuels in N+2 aircraft

In this section, a preliminary comparitive performance study is conducted between different alternative aviation fuel discussed earlier, for its use on NASA N+2 aircraft (300 PAX). This section evaluates aircraft technology and energy vector combinations with respect to their potential to reduce aviation GHG emissions on a lifecycle (WTWa) basis. This is a first of its kind life-cycle (WTWa) GHG analysis of future aircraft technology using conventional jet fuel and alternative aviation fuel, in comparison with present-day aircraft using conventional jet fuel.

The WTWa GHG emission of LH_2 from HTGR case is calculated to be 16.35 g/MJ (from 4.3), for use in A350 XWB. This WTWa GHG value will be used for performance in N+2 BWB-GTF aircraft. However, this value is expected to reduce for LH_2 use in more efficient aircraft like N+2 BWB-GTF. Thus, using WTWa GHG value of 16.35 g/MJ for LH_2 use in N+2 BWB-GTF is essentially a worst-case estimation. The WTWa GHG emissions for conventional jet fuel, 50% blended FT-Biomass SPK, PtL Germany-renewable world embedding (RWE) and PtL Germany-today are 85.70 g/MJ, 45.15 g/MJ, ~1g/MJ and 11-28 g/MJ respectively.

It can be observed from Figure 6 that using drop-in FT-SPK fuel from biomass (50% blend) in 300 PAX N+2 BWB aircraft, gives WTWa GHG savings of 71.4%. PtL (drop-in capability) from today's energy landscape in Germany, provides WTWa GHG savings of 82.3% - 93.1% for use in 300 PAX N+2 BWB aircraft. PtL (drop-in capability) from renewable world embedding (RWE) scenario in Germany, provides WTWa GHG savings of 99.3% for use in 300 PAX N+2 BWB-GTF aircraft. Lastly, using the WTWa GHG emission for LH_2 from HTGR of 16.35 g/MJ, evaluated for the A350-XWB case, is found to give WTWa GHG savings of 99.93% for use in 300 PAX N+2 BWB-GTF aircraft. The WTWa GHG emission for LH_2 from HTGR of 16.35 g/MJ is expected to improve for the N+2 BWB-GTF aircraft because of its improved direct-use performance. However, this study being preliminary doesn't consider these effects and the other associated effects with LH_2 use as described previously. Additionally, the author plans to explore these effects, and consider option of neat/100% bio-jet fuel from different feedstocks/pathways. 100% bio-jet fuel are not approved for civil aviation purpose currently. Because this research is targeted for future aircraft, which does not necessarily require drop-in fuels, the author plans to explore the GHG reduction potential of 100% bio-jet fuel from different feedstocks/pathways with the consideration of changes to aircraft/engine for using these fuels.

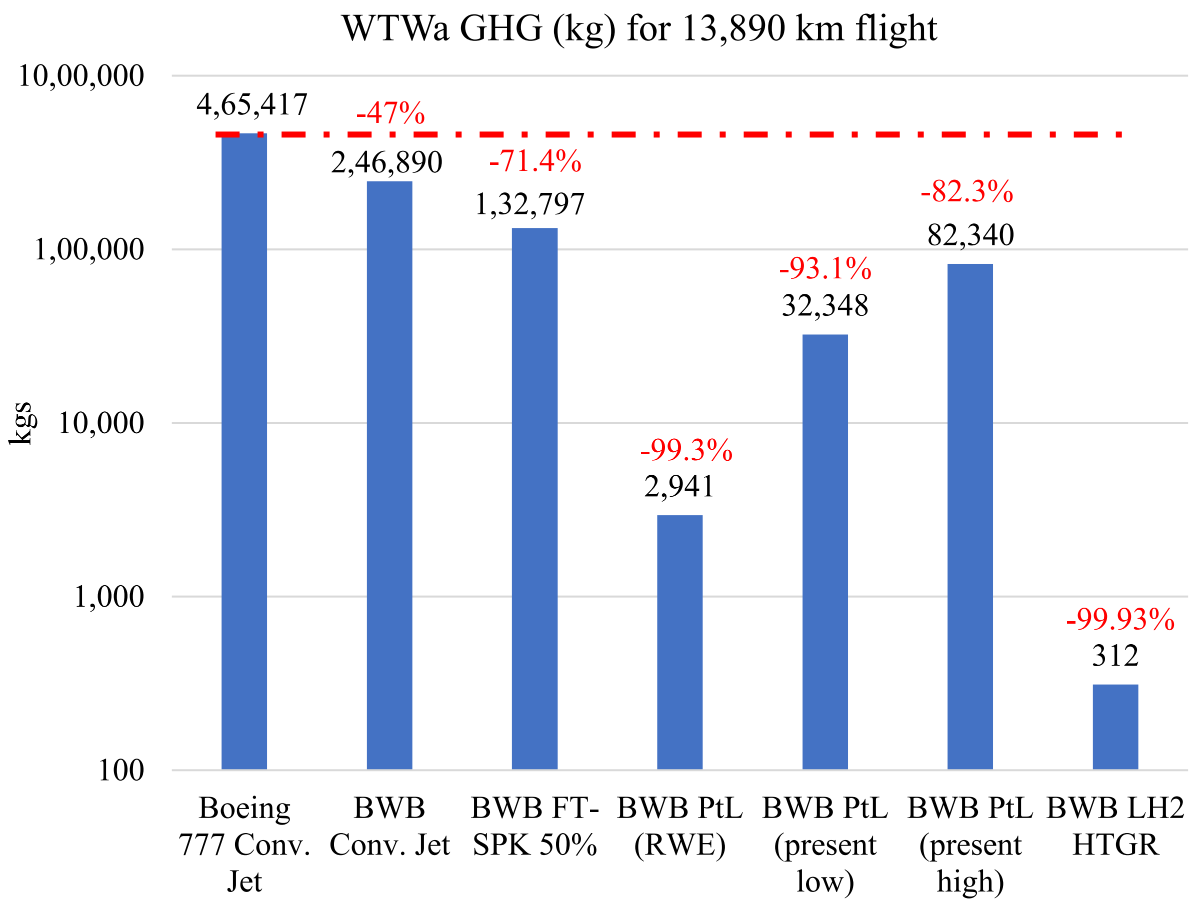

Figure 6. Comparison of WTWa GHG from the use of different alternative fuels and conventional jet fuel in N+2 BWB aircraft, with the use of conventional jet fuel in Boeing 777-200LR, for 300 passengers

FT-SPK fuel from biomass (50% blend) is expected to give lower $PM_{2.5}$ and PM_{10}, and SO_x emissions compared to the conventional jet fuel (as observed in 4.2), so it will have better air-quality performance. PtL might have similar air-quality performance as of conventional jet fuel, as the use-phase emissions are not known explicitly from literature. Compared to all fuels with drop-in capability, LH_2 on the other hand does not release CO_2, $PM_{2.5}$, PM_{10}, N_2O, CH_4, SO_x, BC, OC, VOC and CO in direct aircraft fuel use. Therefore, it has zero-carbon emissions in direct use phase, and therefore has an excellent air-quality performance compared to other fuels. However, it is not a drop-in fuel.

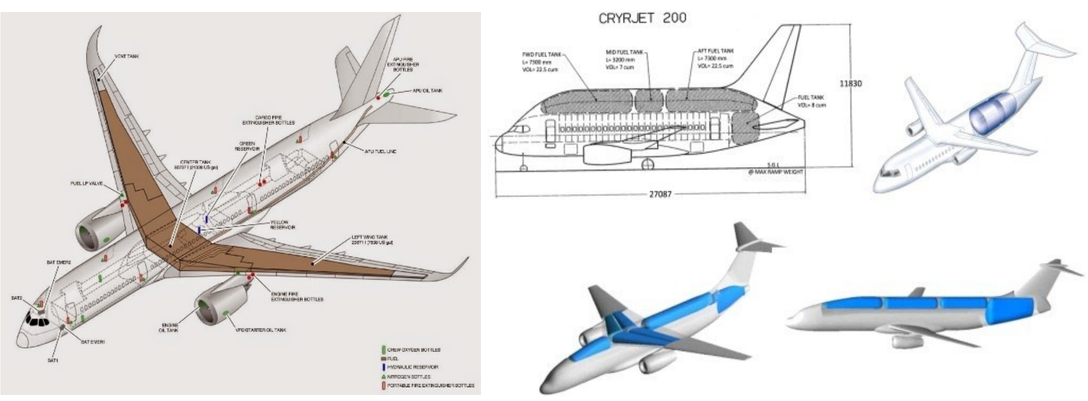

Figure 7. Comparison of conventional jet fuel tank and liquid hydrogen tank (source [92], [93])

There is a societal aspect considered here of water consumption during life-cycle of conventional jet fuel and different alternative fuels. For the same work/flight-mission-range, LH_2 from HTGR consumes approximately 9.33 times more water than conventional jet fuel (+833%), as per GREET 2018 [17] model. From literature review on PtL it is known that on a life-cycle basis PtL consumes approximately 55% less water. It is found from the GREET 2018 model [17] that FT-Biomass (50% blend) requires 46% less water on a life-cycle basis. The effects of water consumption need to be considered in a comprehensive evaluation.

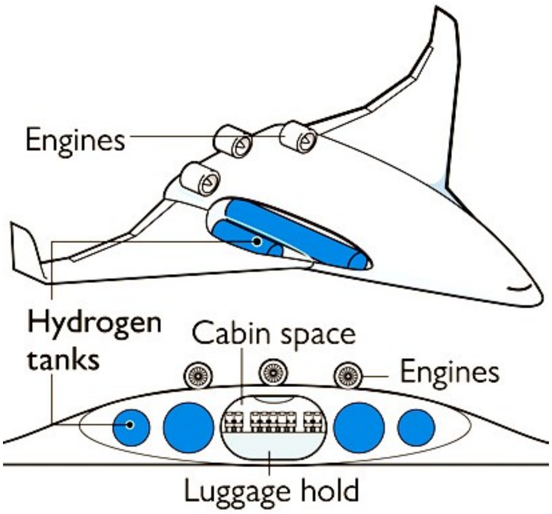

Figure 8. Representation of BWB aircraft with LH_2 tanks (source [94])

LH_2 is currently not approved for civil aviation. It is known from the literature review that a T+W aircraft requires re-designing/re-structuring (weight increase), which results into a bulged aircraft (top-fuselage) and it impacts the performance (more drag and fuel consumption). The bulge can be observed in Figure 7. Additionally, the literature review on

BWB aircraft (in Appendix A) suggests that BWBs have higher internal volume storage capacity for the same passenger capacity compared to the conventional T+W aircraft architecture. In other words, BWBs have higher volume to wetted area ratio, which means that they provide same drag for higher internal volume compared to T+W architecture. This enables storage of extra-large and bulky fuel tanks, which might not require re-designing/re-structuring of aircraft as suggested from Figure 8 (source [94]). The author plans to explore this aspect of BWBs and other aircraft architectures.

4.5 Research significance and inference

Recalling the example from chapter 1, the GHG emission from one New-York ↔ Mumbai round air-trip is similar in magnitude of the GHG emission from average car-use per year in UK/~US. The UK/~US average annual car GHG emission will be similar to: 2 New-York ↔ Mumbai round trips per year with N+2 BWB conventional jet fuel, which gives 47% GHG savings on direct and WTWa basis; 'N' (order of at least 100) New-York ↔ Mumbai round trips per year with N+2 BWB LH_2, which gives 100% savings in direct CO_2 emission and ~99% GHG savings on WTWa basis. The use of alternative fuels in N+2 aircraft, have the potential to significantly reduce aviation's predicted climate change impact of 5% (direct-use) by IPCC to the total man-made CC impacts in year 2050, and indirect climate change impact (GHG savings in fuel production phase). This life-cycle integrated design-development research can potentially guide future technology and policy development.

5. Research plan and expected contributions

The research progress included in Chapter III, is in-line with the set research objectives. A review of future aircraft, airframe and propulsion concepts, and current and potential energy vectors including alternative fuels and electrification has been conducted. A literature review on fuel operability aspects of LH_2 fuel in aircraft and its effects on performance, is deemed necessary. Based on the literature review and the already identified effects of LH_2 use on structure, aerodynamics and propulsion systems, the author plans to improve the LH_2 mission fuel burn model. Additionally, a literature review on PtL fuel for use-phase and/or production-phase emissions is also required. Moreover, the author plans to include 100% bio-jet fuels from different feedstocks/pathways. The research objectives, and the (current and expected) research outcomes and contribution to the knowledge pool, are as follows:

1. Objective:
   Review future aircraft, airframe and propulsion concepts, and develop a modelling tool for estimating operational energy consumption.

   Contribution:
   A model of aircraft operational energy consumption has been developed for present and future aircraft fleet, based on the literature review. The author plans to improve this model based on the identified gaps, e.g. SFB model parameters for N+2 LH_2 BWB-GTF aircraft. Additionally, a preliminary aircraft model of LH_2 fuel use in aircraft has been developed and will be improved. Additionally, the author plans to publish these models.

2. Objective:
   Review current and potential energy vectors including alternative fuels and electrification and develop a database of their life-cycle impacts.

   Contribution:
   In general, the life-cycle impacts of different alternative fuels have been reviewed and their quantitative impacts have been recorded. The author plans to develop a structured database of life-cycle impacts of different alternative fuels, which will facilitate evaluation of their fuel consumption/performance in present and/or future aircraft(s). This will enable a systematic examination of viability of aircraft technology and energy vector combinations with respect to their potential to reduce aviation greenhouse gas emissions on a lifecycle basis.

3. Objective:
   Evaluate aircraft technology and energy vector combinations with respect to their potential to reduce aviation greenhouse gas emissions on a lifecycle basis.

   Contribution:
   This research has identified a set of aircraft technologies and alternative aviation fuels for the future, and it has evaluated the preliminary life-cycle/WTWa GHG emissions of these combinations. Currently, aircraft technologies are evaluated on its direct-

performance and from literature review it is known that there are regulations only on noise and airport local-air quality, and cruise air-quality and performance is unregulated. With the current 'narrow' perspective of considering direct-performance metrics, fuels like LH_2 appear excellent but the source of its production is also important. It was observed that production of LH_2 from coal releases approximately 19 times more GHG than conventional jet fuel production, but LH_2 from HTGR provides approximately 100% WTWa GHG savings. This approach of using integrated life-cycle effects in the design-development is novel, and there are no publications so far which carry out such an integrated and holistic assessment of future aircrafts. In terms of publication, the contribution towards this research objective (combination of objectives 1 and 2) might lead to 2 articles. However, the higher aim (direct or indirect) of this research is to guide and direct future (mid- and long-term) technology and policy development, with the backdrop of identified gaps. This multi-disciplinary research might encourage more inter-disciplinary research.

4. Objective:
   Holistic socio-environmental impacts including non-CO_2 climate impacts, air quality, water use, resources and land-use.

   Contribution:
   The structured database developed in the contribution towards objectives 1, 2 and 3, will be helpful in the holistic assessment such as: socio-environmental impacts including non-CO_2 climate impacts, air quality, water use, resources and land-use. In the preliminary assessment so far, the author has tried to address these effects. The research so far has addressed air quality, water use, and land-use, at a preliminary level. In addition to the contribution of objective 3, estimation of these socio-environmental impacts of the performance of future aircraft technology and energy vector combinations, using integrated life-cycle effects in the design-development, is novel. In terms of publication, this research objective might lead to 2 publication/articles. However, the higher aim of this research is 'push the envelope' in technology and policy development which encompasses the above-mentioned life-cycle non-GHG impacts along with WTWa GHG impacts.

5. Objective:
   Operational cost analysis for different energy vectors.

   Contribution:
   Sustainability has three pillars: environment, society and economics [95]. The environmental and societal aspect is mostly covered by objectives 1-4. The research efforts will also include operational cost aspect, based on data availability from literature or preliminary cost evaluation. It is to be noted that conventionally the effects of water consumption are not estimated by socio-environmental life-cycle damage assessment methods like eco-indicator 99 method. The societal aspect of water consumption might be quantified via modifications to fuel-cost and WTWa emissions to account for energy and cost expenditure on water-treatment (viz. water obtained by treating low-quality water such as wastewater from natural gas and oil wells, brackish

groundwater, wastewater released from industrial, agricultural and domestic activities, ocean/sea water), depending on the water-quality requirement. In terms of publication, the contribution of this research objective should be included in the publications mentioned in contribution towards objectives 3 and 4.

As mentioned above, the higher target is to guide future technology and policy development. The future research efforts would be to work broadly along the lines of the UN's sustainable development goals (SDG) (17 SDGs) [96]. A preliminary observation shows that this research can support 8 SDGs of the UN.

A break-down of research plan into individual activities/tasks is listed in the schedule provided in the next three pages. The author plans to complete these activities/tasks within schedule which will help to achieve the set research objectives.

Activities		**2019**								
		Apr	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Year 1	ESA, and report revision	■								
	Literature review on fuel operability aspects of LH_2 fuel in aircraft and its effects on performance	■	■							
	Literature review on PtL fuel for use-phase emissions	■	■							
	Identification of aircraft technology/architecture for 300 passenger long-range aircraft		■							
	Developing fuel burn prediction-model for identified aircraft architectures for use of all identified alternative fuels		■	■						
	Journal article submission 1 *(Proposed topic: Conceptual design of a future long-range LH_2 aircraft)*			■	■					
	Formal documentation of research	■	■	■	■					
Year 2	Literature review of any new addition of aircraft technology and/or alternative aviation fuels					■				
	Structured database for all alternative fuels					■	■			
	Attending AIAA Propulsion and Energy conference 1					▐				
	Numerical life-cycle GHG performance model of aircraft(s) using different alternative fuels						▐	■	▌	
	Detailed examination of aircraft technology-energy vector combination								■	
	Conference abstract submission 1, to AIAA Aviation 2020 *(Proposed topic: Climate impacts of LH_2 use in aircraft using fuel life-cycle metrics)*								■	
	Journal article submission 2 *(Proposed topic: Potential of future aircraft technologies and alternative fuels towards carbon neutrality)*								▐	■

Activities		2020						
		Jan	Feb	Mar	Apr	May	Jun	Jul
Year 2	Examine non-CO_2 climate impacts of aircraft technology-energy combinations	■	■					
	Evaluate air-quality impacts of aircraft technology-energy combinations			■	■			
	Assess water-use impacts of aircraft technology-energy combinations					■	■	
	Conference travel 2: AIAA Aviation 2020 conference						■	
	LSR report drafting					■	■	
	LSR							■

Activities		2020					2021			
		Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Year 3	Estimate impacts on resources from the use of aircraft technology-energy combinations	■	■							
	Examine land-use impacts of aircraft technology-energy combinations			■	■					
	Journal article submission 3 *(Proposed topic: CO_2 and non-CO_2 climate impacts future aircraft technologies and alternative fuels)*					■	■			
	Conference abstract submission 2, to AIAA Propulsion and Energy 2021*(Proposed topic: Exploration of sustainable aircraft technologies and alternative fuels for future)*						■			
	Formal documentation of research	■	■	■	■					
	Evaluation of operational cost for different aircraft technology-energy combinations							■	■	
	Formal documentation of research							■	■	
	Writing thesis									■

Activities		2021								2022
		May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**
Year 3	Writing thesis	■	■							
	Submit the first draft - supervisor review and feedback			■						
	Conference travel 3, to AIAA Propulsion and Energy 2021				■					
Year 4	Journal article submission 4 (*Proposed topic: Socio-environmental impacts of future aircraft technologies and alternative fuels*)				◨	■				
	Viva examination						■			
	Thesis correction							■	◧	
	Buffer delayed								◨	■

6. Risk assessment

Risk description	Likelihood (L) [1-3]	Impact (I) [1-3]	Risk (L x I) [1-9]	Mitigation strategy
The SFB model for N+2 LH_2 aircraft is predicting the fuel consumption incorrectly	2	2	4	Improve the SFB model parameters for this case based on a separate analysis which considers the weight of LH_2 fuel tank and insultation, engine power off-take for cryo-cooling and/or aircraft redesign
Mission fuel burn model of LH_2 aircraft (A350 XWB) is predicting the mission fuel consumption incorrectly	2	2	4	Improve the mission fuel burn model considering engine power off-take for cryo-cooling and/or aircraft redesign.
Use-phase NO_x emission not included in LH_2 aircraft resulting in underprediction of WTWa GHG emission	3	1	3	A detailed analysis on emission modelling is required that would predict NOx emission for entire flight mission profile.
Mission fuel burn model of tube-wing (A350 XWB) LH_2 aircraft is used for future N+2 BWB aircraft which is predicting performance incorrectly	3	2	6	Develop a N+2 BWB aircraft specific LH_2 fuel burn model including the weight of LH_2 fuel tank and insultation, engine power off-take for cryo-cooling and/or aircraft redesign
Uncertainty in mission fuel cost of future technology and alternative fuel combination	2	2	4	A thorough and systematic literature review and/or development of cost prediction tool, is required
Technology and alternative fuels considered in the study are based on published literature; disruptive and unpublished/work-in-progress technology and alternative fuels are not known/included	2	2	4	An up-to-date or frequent literature review is required, with, may be, industry/academia collaboration/engagement

More information:

First author's other research work can be found in [32], [42]–[44], [62], [97]–[122].

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8. Appendix

8.1 Appendix A: Blended/hybrid wing body (BWB/HWB) aircraft

BWB aircraft:

The BWB is a new category of aircraft between conventional and all-wing aircraft configurations [123]. It is characterized by a low aspect ratio high thickness ratio inboard wing, a high aspect ratio outboard wing, and basic verticals (ibid). The lift to drag ratio (L/D) at cruise can be improved up to 25% compared to similar passenger capacity T+W aircraft, and the installed thrust and fuel savings are even higher (ibid). Figure 9 shows a typical large/very-large BWB aircraft with 3 podded engines (ultra-high BPR or UHB).

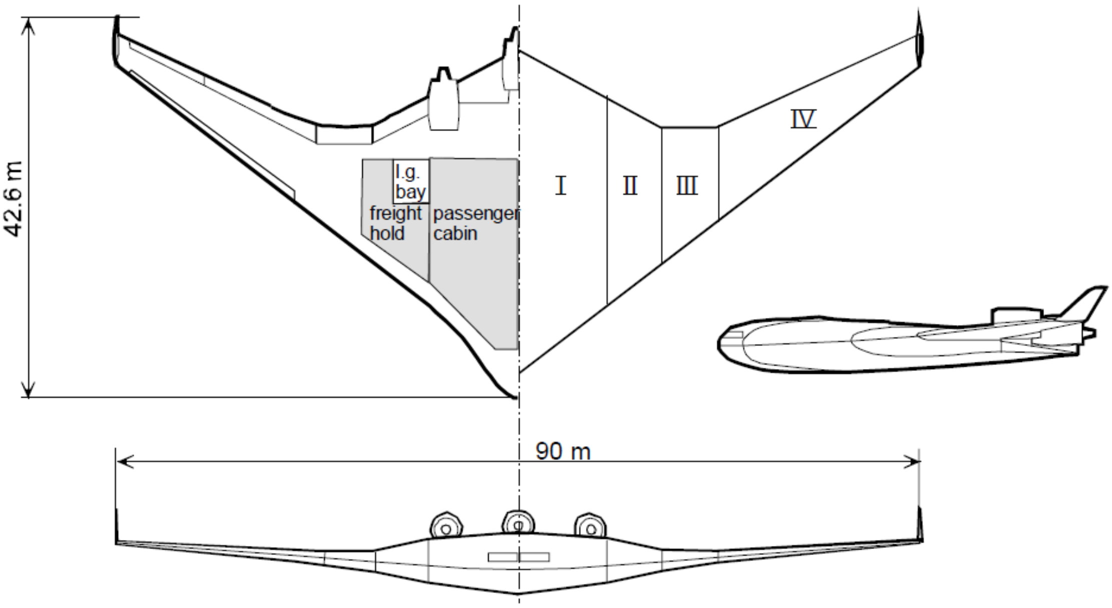


Figure 9. Typical large BWB aircraft (Image source [123]**)**

a) Advantages of BWB aircraft:

i. Aerodynamics:

The BWB is a flying wing. A crucial aspect of the BWB is its lift-generating centre-body i.e. a benefit over the cylindrical fuselage of a conventional aircraft. This improves the aerodynamic performance by decreasing the wing loading [124],[125],[126]. Additionally, the reduction in wetted area, by a smaller outer wing compared to a similar sized conventional aircraft results into an improved lift-to-drag ratio as it is proportional to the wetted aspect ratio. This aspect ratio increases because it its inversely proportional to the wetted area [127],[128][129],[130]. The lower wetted area to volume ratio for larger BWBs compared to the conventional aircraft, provides additional benefits. The interference drag is decreased due to the elimination and/or minimization of surface-intersections/junctions between the fuselage and wings of the conventional aircraft causing the BWB shape to be more streamlined

[124],[126], [129],[131],[132],[133]. The elimination of horizontal tail compared to conventional T+W aircraft, implies a decrease in the associated penalties due to friction and induced drag, causing further improvement in the lift-to-drag ratio [134]. The area-ruled architecture of the BWB, available naturally, translates to higher cruise Mach numbers, which are more easily achievable without changing the base shape or geometry [128],[135]. The BWB's cross-sectional area variation is like that of the body of minimum wave drag due to volume, the Sears-Haack body, which results into decrease in wave drag at transonic speeds [128],[135]. Some BWB aircraft concepts have engines partially embedded in the BWB aft-body. By doing so, the boundary layer ingestion (BLI) technology can be used. The BLI can be done from a portion of the centre-body upstream of the engine inlet BLI results in the ram drag reduction which improves propulsive efficiency [127],[128], and decreases the required thrust and fuel burn [8]. The aft installation of engine effectively balances the airframe and offsets the weight of the furnishings, payload and other systems. Additionally, this maximizes the benefits from BLI because the boundary layer is completely developed towards the aft of wing [136]. There is a potential for further reduction in drag via active and passive laminar flow control through laminar flow technology and wing shaping, on the engine nacelle and lifting surfaces. The BWB configuration is well suited for such technologies. This might result in substantial reductions in skin friction drag [129].

ii. Noise:

The BWB configuration has a low-acoustic signature [128]. The BWB airframe has smooth lifting-surfaces, no tail, and minimally-exposed cavities and edges, which are the reasons for its low-noise feature (ibid). The BWB shields noise (fan and exhaust), from passengers and community, as engines are placed on its upper surface, compared to the current conventional aircraft (mostly) where the engines installed/positioned below the wing [136].

iii. Aero-structure:

The BWB weight is distributed more optimally along the span, and has lower reduced structural weight (than conventional aircraft) [127] [31]. The BWB has lower total wetted area and such an architectural integration allows for a long wingspan [127],[137]. This results in the optimal aspect ratio of the outer wing being slightly higher than that of the conventional aircraft [134]. Therefore, BWB has a higher lift-to-drag ratio and is structurally efficient than conventional aircraft [127],[134], [134].

iv. Economics, marketing and manufacturing:

In terms of passenger-comfort levels, the vertical cabin walls in the BWB might offer a more spacious experience than the curved walls of current aircraft [128]. The direct operating costs per seat/mile for the BWB are forecasted to be 15% lesser than the conventional aircrafts [134]. Because of the design simplicity of the BWB, viz. the elimination of mechanical joints of highly-loaded structures at 90° to each other and fillets, a significant reduction, on the order of 30%, in the total number of parts can be achieved [128],[138]. In terms of design and reconfiguration, the BWB aircraft can be used for military and civil aviation applications; and it can be stretched laterally that will increase the span and wing, and resultantly the payload. These benefits are not possible with the conventional aircraft as they are longitudinally stretched for increasing payload [128],[138]. The commonality between 250-passenger and 450-passenger versions has been assessed, with the nose/cockpit section and outer wings being common between each member of this family/series of aircrafts. The required fuel volume in the outer-wing, is adequate for all the members of the family, and the modular centre-bodies are aerodynamically balanced and smooth. This commonality offers 12% and 23% reduction in recurring costs and non-recurring costs respectively, compared to the stand-alone cases of the 250-passenger and 450-passenger versions. Such cost reductions are anticipated to increase with the inclusion of more sizes of BWB viz. a 350-passenger version [128],[138]. With the Boeing cabin design, this commonality between families holds good even with the interior, as the cabin cross-sections would be the same for all aircrafts. For airlines, this would translate to advantages which are: a potential decrease in the manufacturing learning-curve penalties; fleet mix needs can be easily accommodated; and increased savings in maintenance and life-cycle cost. These can be achieved by variation of the span and wing area with weight, for maintaining the aerodynamic efficiency, which is an advantage only possible with BWB aircraft [128]. The BWB's natural area-ruled shape can decrease the manufacturing costs associated with conventional aircraft that must be manufactured with a variable cross-section, commonly referred as called 'coke-bottle' fuselage to obtain the area-rule [138]. So BWB aircraft has the potential to perform at higher speeds and at lower costs.

v. Stability and flight control:

According to Liebeck [127], a complicated high-lift system is not needed for the Boeing design due to the low-effective wing loading. For this design, he discusses the redundancy and reconfigurability of the trailing edge flight controls. This results in the reduction of the secondary power required by the control system [138].

vi. Safety:

The aft position of engines on the BWB displace the shrapnel from engine failure behind the pressure vessel, most of the flight controls devices, and systems and fuel tanks. The pressure vessel because of its unique structural needs, and the requirement to handle pressure loads and wing bending, should be robust and might potentially have substantial crashworthiness [127],[128]. Additionally, in some configurations, the passenger section and fuel are separated by broad cargo bays [127].

vii. Operations:

The potential benefits in terms of operations include increased loading and off-loading times due to the smaller fuselage length on a mid-sized BWB (200-passenger) [139], and smaller take-off field-length without the necessity of complicated high-lift devices [125]. Resultantly, in future, with the wider use BWB in the fleet (or fleet 100% BWB) will cause airport to use lesser land-space (land-use effects of aviation).

b) Challenges/current limitations of BWB aircraft:

i. Aerodynamics:

Atypical transonic air-foils of high thickness to chord ratio of about 17% in the Boeing designs [128] are needed inboard for accommodating the cargo, passengers, and landing-gear. Additionally, this thickness to chord ratio must be maintained along a substantial section of the chord-length [128],[137]. This poses problems for maintaining low drag [140]. Because of the deck angle limitations, the centre-body air-foils should be designed to produce the required lift at angles of attack that are consistent with the deck angle requirements [128],[137],[130]. The supersonic flow on the lower surface of the BWB is another challenge, which is not observed in the conventional configuration [137]. A smooth transition from the thicker centre-body air-foils to the thinner outer-wing air-foils might be problematic particularly for the medium-sized 200-passenger BWBs as such transition might be more abrupt for such smaller vehicles [125]. The benefit of the lower wetted area may not hold good in all cases, especially for smaller BWBs [125]. Lastly, though embedded engines and BLI technologies are promising, challenges persist with the airframe-engine integration, and including these technologies within the design of low-loss inlet system, inlet flow distortion control, and the turbomachinery integration [136]. In the aerodynamic design of the aircraft, manufacturing constraints should be considered. The complex 3D shapes which might be difficult and expensive to manufacture can be replaced with simple and smooth curved surfaces [128],[137].

ii. Propulsion:

There are difficulties with aft-mounted engines and airframe-propulsion integration aspect in BWB, because this integration impacts multiple disciplines more directly compared to conventional aircraft [127],[140]. Moreover, the interaction between the control surfaces, wing, and propulsion system increase the complexity of the design [137]. A recent study by Flamm et al. [141] focusses on the Ultra-High Bypass Ratio (UHB) engine integration for blended/hybrid wing body technology demonstration located within the Environmentally Responsible Aviation (ERA) vehicle systems integration sub-project. This study addresses the ERA technical challenge to show reduced component noise signatures leading to 42 EPNdB to Stage 4 noise margin for the aircraft system and simultaneously minimize the integration and weight penalties to enable 50% reduction in fuel burn at the aircraft system level. This study examines the UHB’s engine operability aspect where this engine is mounted on the upper surface of the aircraft; and it optimizes the high lift system for increasing the lift to drag ratio (L/D) and improving noise characteristics. Through this study is observed that all inlet distortion cases within the operating envelope of the BWB have acceptable blade stresses and engine operability. Systems assessments show that the BWB aircraft scaled-model obtained a fuel burn reduction of 53% than the reference configuration (ibid). The certification noise level examination concluded that the cumulative margin below Stage 4 is 38.4 dB for the vehicle including landing gear fairing and chevron nozzle technologies (ibid).

iii. Structures:

The BWB's non-cylindrical pressure vessel poses an important challenge. This pressure vessel must be light-weight, and it should be capable of handling cabin pressure loads and the wing bending loads. The stress associated with a box-type BWB fuselage could be about an order of magnitude greater than the stress in a cylindrical pressurized fuselage [142]. The increased stresses in such a pressure vessel results in increased structural weight [127],[143].

iv. Stability and flight Control:

The integrated BWB with the elimination of the tail, implies that interactions between aerodynamic loads, inertial forces, elastic deformations and the flight control system responses may greatly impact the aircraft’s stability and performance [128],[143],[144]. The aircraft must be balanced and simultaneously the control deflections should not adversely impact the drag and span-load [140]. For larger BWBs, control surface hinge moments are substantial [130]. Therefore, if the aircraft is unstable, and if it depends on the active flight controls, the secondary power requirements could be prohibitive [128],[130],[140].

v. Marketing and manufacturing:

The BWB presents a more spacious environment, but there are some aspects that can make marketing this configuration a challenge viz. passenger acceptance. Firstly, having only one window in each main cabin door and no windows on the cabin walls of BWB, the passengers might feel uncomfortable. A proposed solution is installing display screens connected to a series of digital video cameras for making every seat a window seat [128]. Secondly, considering the lateral offset from the centre of gravity, the quality of flight experience might deteriorate, especially in the outer portions of the BWB, compared to flight experience in conventional aircraft. Boeing performed a series of tests which piloted flight simulator tests of the B747-400 and BWB-450 with the flight profile and same pilots. It was observed that the ride quality only reduced slightly, by about 4%, with the NASA Jacobsen ride quality model to estimate the passenger satisfaction, for the best and worst seats on both aircraft [128],[138]. Additionally, BWB will have high angle of attack at take-off and landing, which might not be accepted by passengers [123]. Okonkwo et al. [145] recommend that the BWB should be designed for maximum productivity, because profitability and safety are the main needs of commercial aviation. This implies creating BWBs with good ride and handling quality; and determining the optimal altitude and cruise speed that improves operating efficiency and minimizes fuel burn (ibid). The good handling quality could be achieved by setting the best combination of planform variables (aerodynamic and geometric twist, sweep angles, etc.) that improves aircraft controllability and trimmability, and simultaneously the ride-quality is enhanced by minimising the impact of gust and increasing passenger comfort (ibid).

vi. Certification:

The certification of the BWB might be impacted due to the requirement of ‘efficient emergency exit’ [128]. This might be more problematic for larger BWBs because of the increased distance between exits [134]. The lack of clear views of the different exit doors on larger BWBs will be challenging for cabin crew to redirect passengers [146]. However, Liebeck [128] and Bolsunovsky et al. [134] argue that the procedures compliant with FAR-25 can be incorporated. Liebeck argues that passengers have a direct view of one or more exits, and they do not need a 90 degree turn from the aisle to get access to the door. This is supported by the fact that the Boeing design includes a main cabin door directly in front of every aisle and an exit via the aft pressure bulkhead at the back-end of every aisle. Moreover, four spanwise aisles intersect with the longitudinal aisles [128]. Computer simulations and full-scale evacuation trials were carried out by Galea et al. [146] for BWB aircraft with more than one thousand passengers, and it was observed that awareness of the aircraft layout and improved visual access are important for efficient exit during emergency situations. The fire simulations resulted in 12 fatalities which were deemed inevitable, but independent of the cabin architecture (ibid). In a worst-case scenario, the BWB can be used only for cargo application (civil and military).

vii. Miscellaneous:

These include landing approach speed and attitude, and stall and buffet aspects [128],[130]. Additionally, other studies of BWB have engines installed on pylons under the wing [134], which would take away a lot of the advantages previously discussed in terms of drag and noise reduction.

8.2 Appendix B: NASA N+2 aircraft fleet

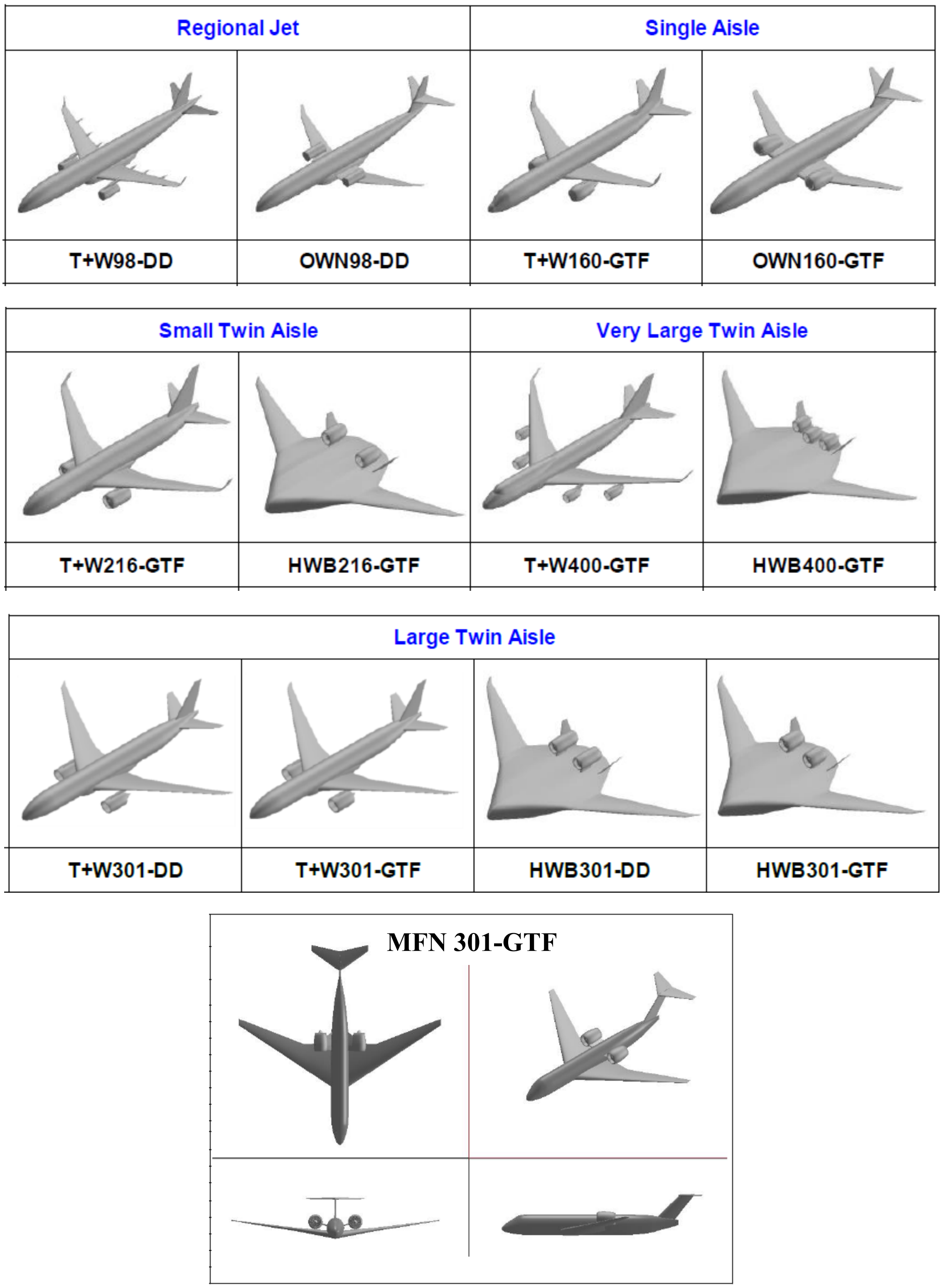


Figure 10. NASA N+2 aircraft concepts (source [70]); [T+W: Tube and wing, OWN: Over wing nacelle, DD: Direct drive turbofan engine, GTF: Geared turbofan engine, HWB: Hybrid/Blended wing body, and MFN: Mid fuselage nacelle]

8.3 Appendix C: Current and future aircraft fleet model data information

8.3.1 Derivation of modified form Breguet's range equation for specific fuel burn

Note: Resource [59] *is used as a basis for this derivation*

The classic Breguet range equation for an aircraft in level flight is derived from a differential equation which relates the rate of fuel burn with the rate at which the propulsion system does work against the aircraft drag and the rate at which the aircraft weight decreases. For a jet aircraft flying at constant lift coefficient and Mach number (i.e. in cruise-climb mode), the range parameter $X = H\eta L/D$, may be taken as constant. H has a value of 4,350 km for conventional jet fuel (kerosene), 11,750 km for liquid hydrogen.

Breguet result for the cruise range as: $R = X \ln(W_1/W_2)$, where W_1 and W_2 respectively are the weights of the aircraft at the beginning and end of cruise and the difference between them, W_{CF}, is the weight of fuel burned during cruise i.e. $W_{CF} = W_1 - W_2 = W_1(1 - \exp(- R/X))$. The total fuel load of the aircraft at take-off includes additional fuel for climbing to cruise and for climb during cruise, for accelerating to cruise speed, for manoeuvre during cruise, for taxying and reserves for diversion. For simplicity, it is assumed that the mission fuel can be taken as that derived from Breguet equation R, with the addition of the 'lost' fuel used during climb and manoeuvre on a normal mission, taken as 2.2% of take-off weight. Reserve fuel for diversions etc, which is not burned during a normal mission, is treated as part of the systems weight and assumed to be included in the simple structural weight formula given below. For a hydrogen burning aircraft, the corresponding lost fuel is 1.4% of take-off weight. Taking the lost fuel into account, we can write the mission fuel weight $W_{MF} = W_{CF} + 0.022W_{TO}$, for kerosene, and the weight at entry to cruise $W_1 = 0.978W_{TO}$. Substituting the individual terms defined above, $W_{MF} = W_{TO}(1 - 0.978\exp(- R/X))$. For hydrogen, the coefficient of the exponential term becomes 0.986. Although W_{MF} equation involves a degree of simplification which would not be appropriate for a rigorous project study.

$W_{TO}(1 - c_1) = c_2W_P + W_{MF}$, relates the take-off, payload (W_P) and mission fuel weight. In this form, the constant c_1 represents the weight of the structure and those systems which correlate with maximum take-off weight (wings, undercarriage and, for the purposes of this study, engines and reserve fuel) while (c_2 - 1) represents the additional weight associated with the payload (centre fuselage, seats, toilets, galleys, etc). From the weight data on twelve modern wide-body passenger aircraft, a best approximate fit to the above equation, c_1 and c_2 are estimated. Substituting the equation for W_{MF} into the above relation of weights, the payload weight equation is $W_P = W_{TO}(0.978\exp(- R/X) - c_1)/c_2$,

Specific fuel burn (SFB) = $W_{MF}/(W_P \times R)$; $\mathrm{SFB} = \left(\frac{c_2}{X}\right)\left[\frac{(1-0.978e^{-Z})}{Z(0.978e^{-Z}-c_1)}\right]$, where Z = R/X.

8.3.2 Present and future fleet information

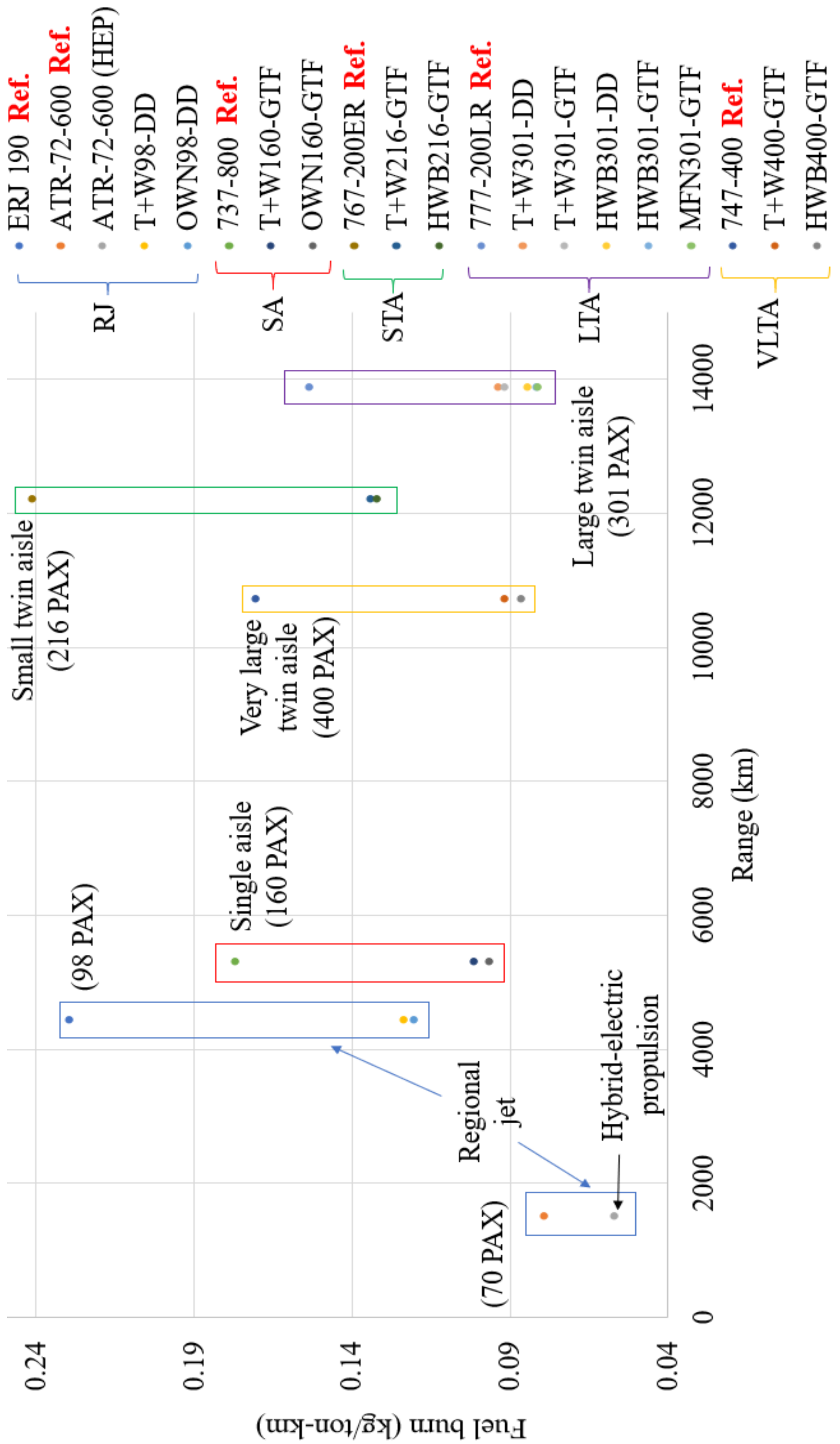


Figure 11. Present and future aircrafts (source for hybrid-electric propulsion data point is [67] and source for other points is [70])

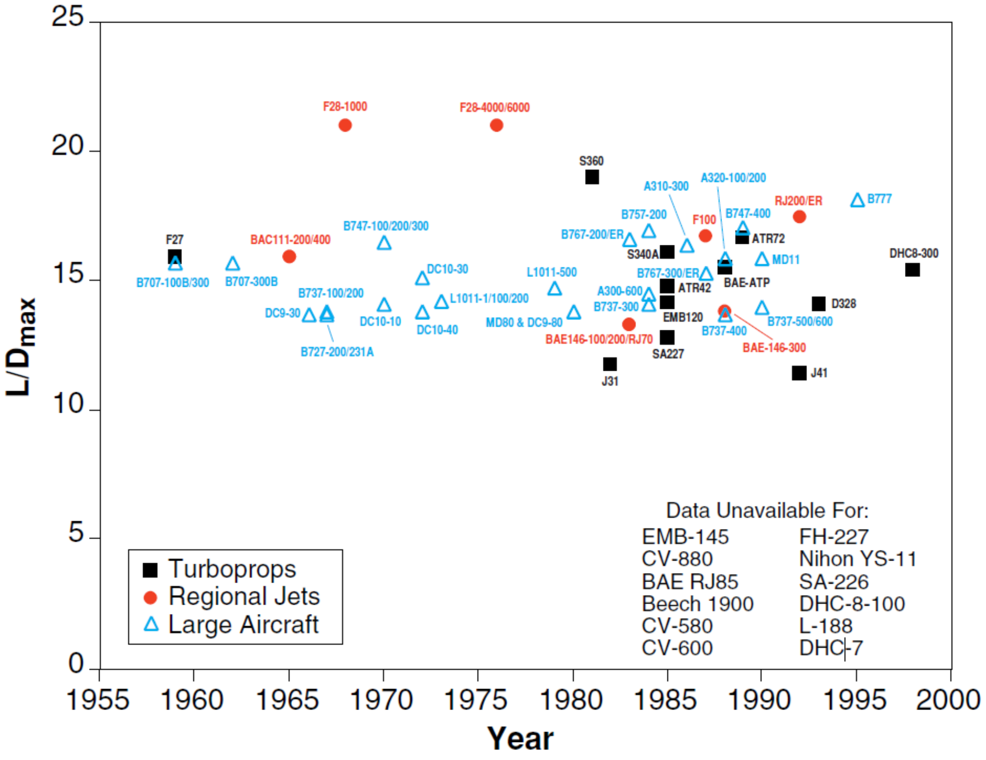


Figure 12. Maximum L/D for regional aircrafts (source [74])

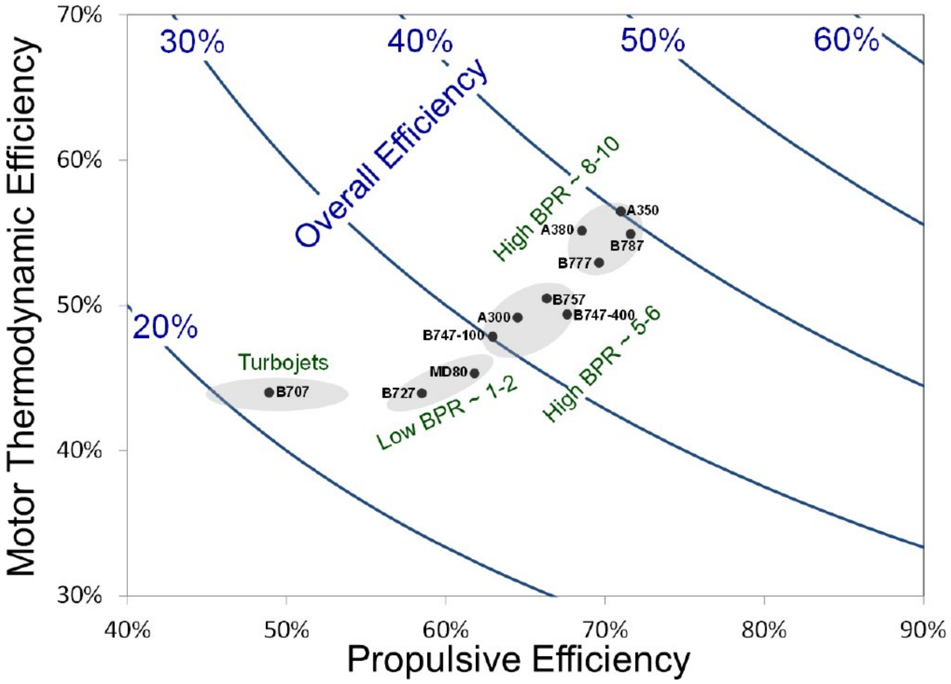


Figure 13. Overall efficiencies by aircraft names (source [78])

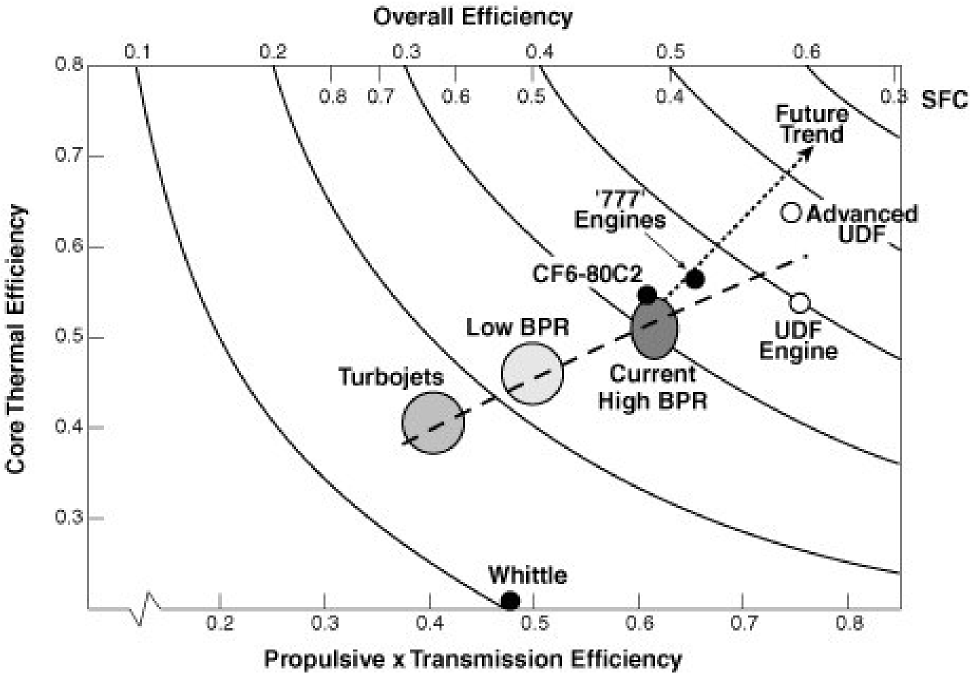


Figure 14. Overall efficiencies by engines names (source [80])

Table 6. N+2 engines for passenger aircraft fleet (source [70])

Aircraft name	**Engine type**	**BPR**		**OPR**		**η (assumed)**
		TOC	**SLS**	**TOC**	**SLS**	
T+W98-DD	Direct drive	9.7	10	35.0	28.7	0.42
OWN98-DD						
T+W160-GTF	Geared turbo-fan	23.45	27.4	35	24.85	0.47
OWN160-GTF						
HWB216-GTF	Geared turbo-fan	21.75	24.75	50	38.5	0.47
HWB301-GTF		17.65	20	60	47.1	0.49
HWB400-GTF		17.6	19.95	60	47.2	

8.4 Appendix D: Well to wake (WTWa) comparison of different feedstock and manufacturing plant type combination for use in large twin aisle (LTA) aircraft (like Boeing 777-200LR)

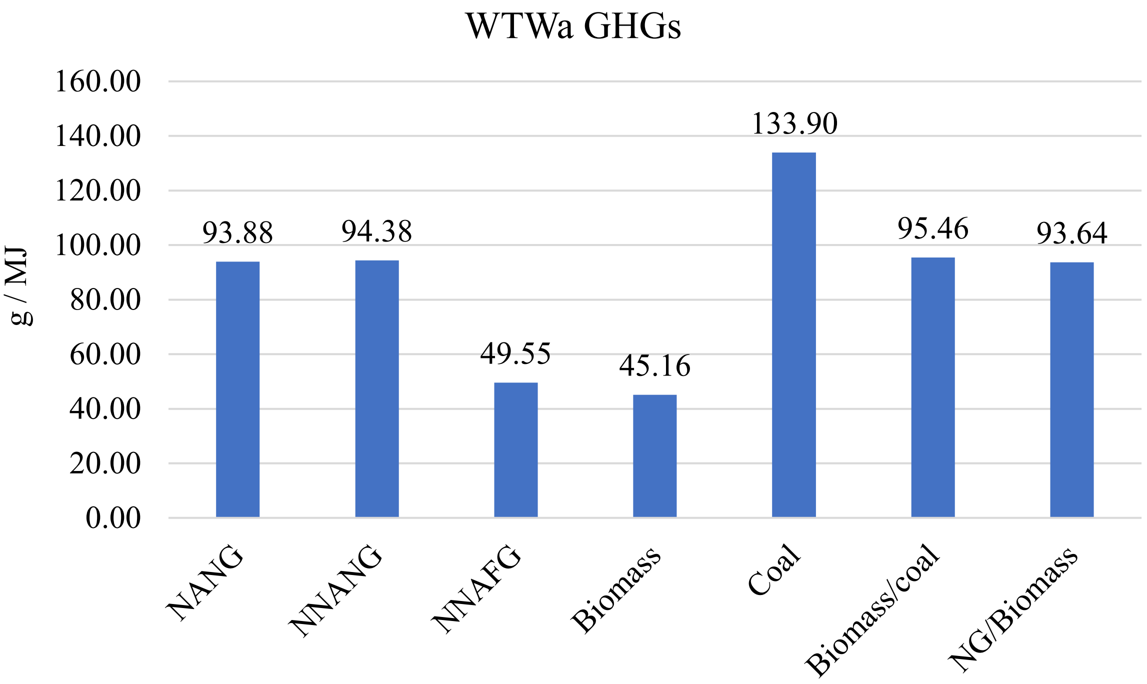


Figure 15. WTWa comparison of GHGs for 50% blended Fischer-Tropsch (FT) synthetic paraffin kerosene (SPK) from different feedstocks (7 cases)

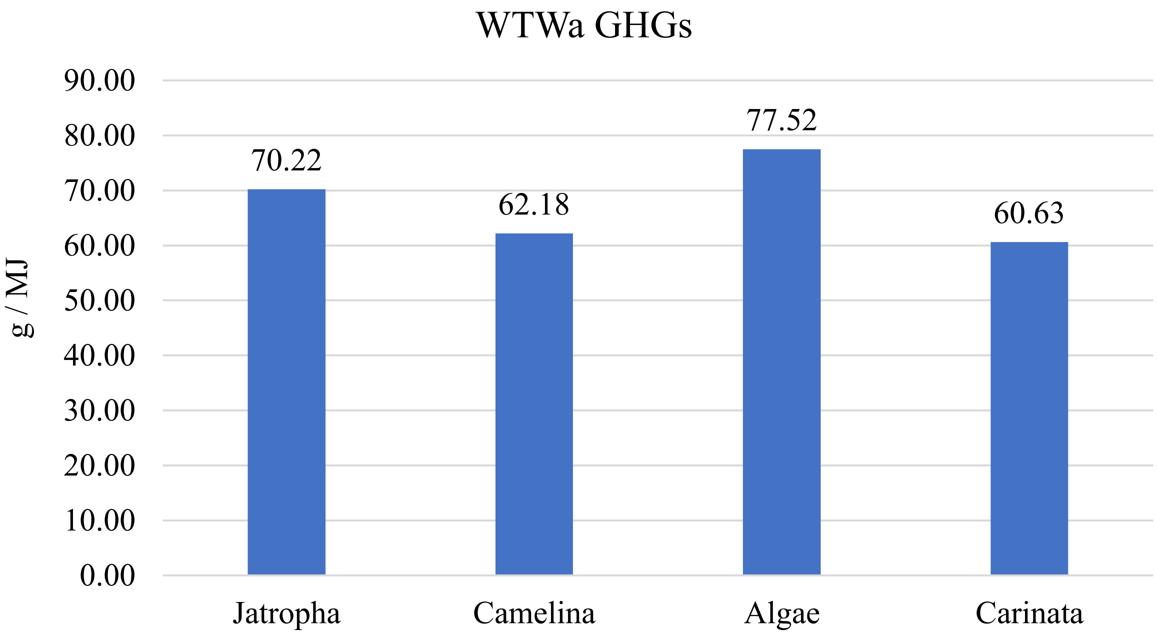


Figure 16. WTWa comparison of GHGs for 50% blended hydro-processed lipids/hydro-processed renewable jet fuel or Hydro-processed esters and fatty acids (HRJ/HEFA) SPK from different 'non-food' feedstocks (4 cases)

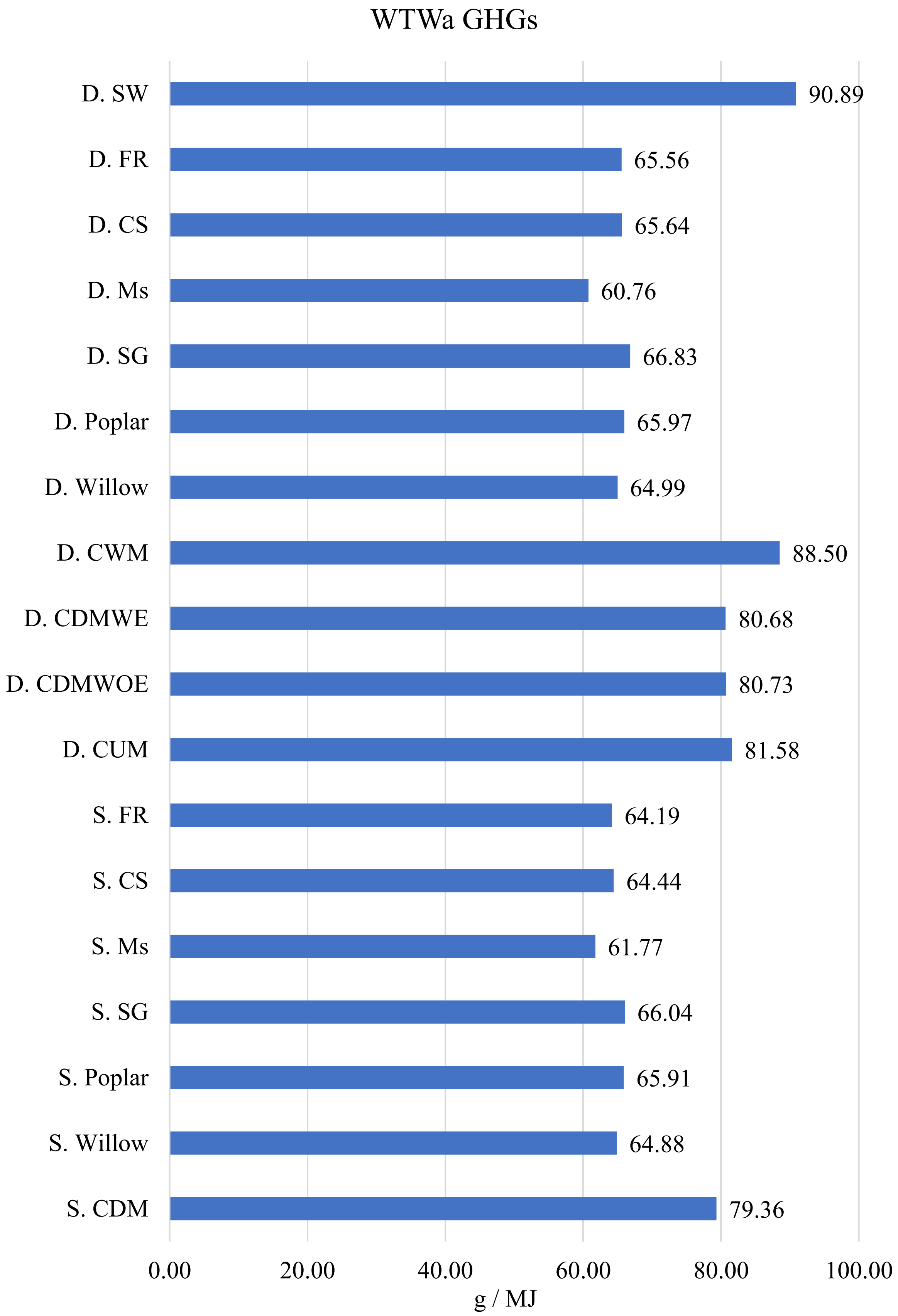


Figure 17. WTWa comparison of GHGs for 30% blended alcohol-to-jet (ATJ) SPK fuel from different feedstock and manufacturing plant type combinations (18 cases)

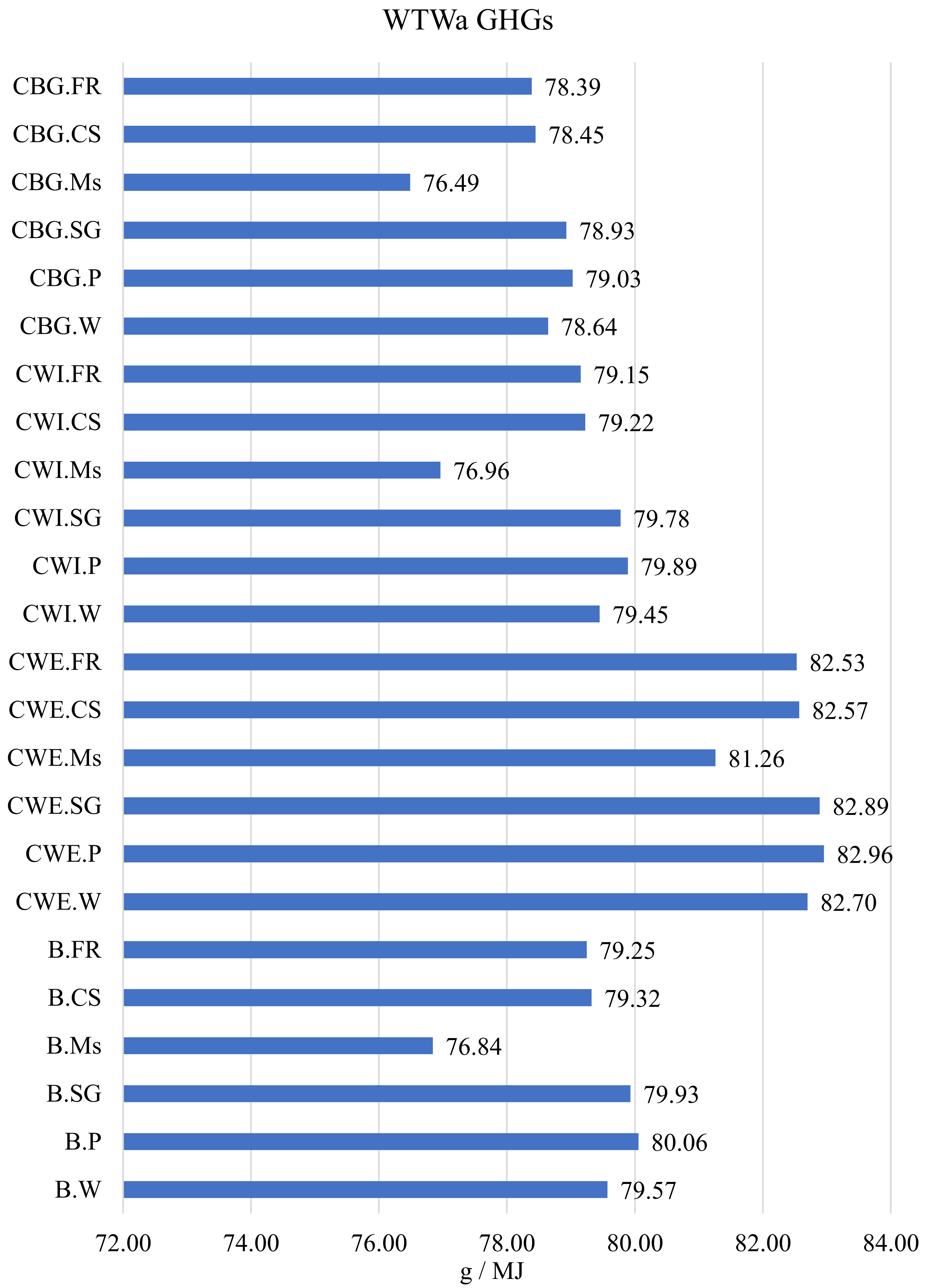


Figure 18. WTWa comparison of GHGs for 10% sugar-to-jet (STJ) SPK fuel from different feedstock and manufacturing plant type combinations (24 cases)

8.5 Appendix E: Liquid hydrogen (LH_2) production (well to pump [WTP]) GHGs

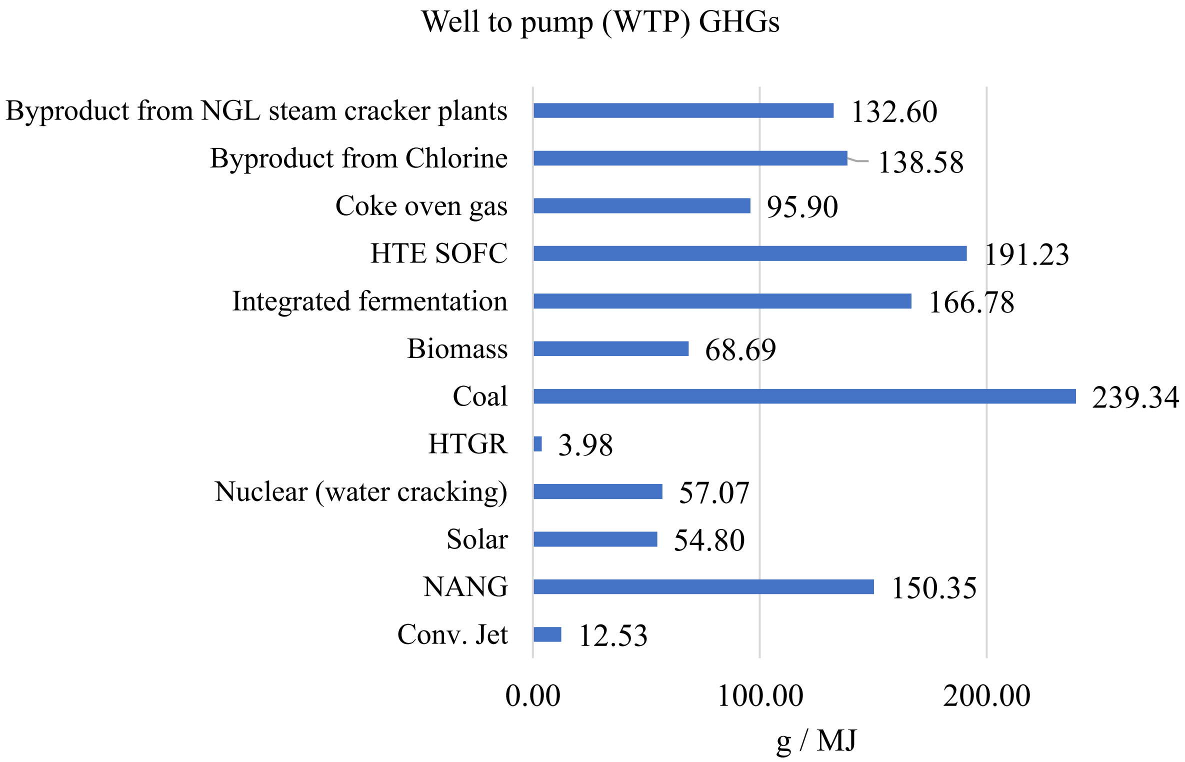


Figure 19. WTP comparison of GHGs for LH_2 from different feedstocks (11 cases) and conventional jet fuel

8.6 Appendix F: Aircraft fuel burn methodology

In this study, a fuel burn model for Airbus A350 XWB aircraft is developed. The range for this aircraft is 15,000 km [81]. The cruise altitude for this aircraft is 12,190 m and cruise Mach 0.85 [82].

Aircraft weight estimation:

The mission profile must be determined to calculate the fuel burn in each segment. Figure 20 shows the definition of the mission profile considered here. Note that there is no climb or descent credit given to the range of the aircraft. The entire range is modelled as the cruise range. The fuel fractions (FF) for the climb, cruise, and loiter segments will be calculated. However, for all other segment fuel fractions will be taken from Roskam Part I for transport jets [83]. For each segment, FF determines the aircraft weight at end of segment/beginning of next segment, in a given mission profile. The climb fuel fraction will be derived from the Breguet range equation with the form seen in Equation 3. The rate of climb (RoC) used is 3,000 fpm [147] (standard value used for transport jets). The altitude value is used as per mission specification. Given this information, an endurance segment, in minutes, is calculated (and equals cruise altitude/RoC) and used in Equation 3. For the cruise segments, including the additional reserve cruise, the method is similar. Instead of using endurance, range and velocity are considered, the values of which are known. Equation 4 shows the exact form used to calculate these fuel fractions. A standard value of range and velocity (350 km at altitude of 1,500 m and Mach 0.6) is considered for loiter/additional cruise. The product of all segment's FF in the mission gives the FF value for the mission. The thrust specific fuel consumption (TSFC) values for climb, cruise and loiter come from the engine model developed in GasTurb 13 software tool [84], and lift-to-drag ratio (L/D) is estimated from the process described ahead. The engine model is included in Appendix G.

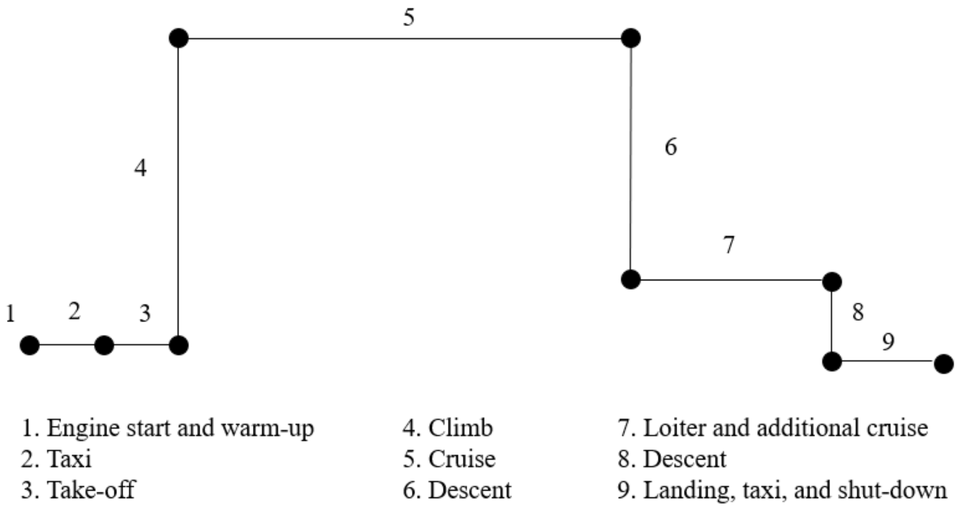


Figure 20. Aircraft mission profile

$$M_{ff,climb} = \frac{1}{e^{\left[\left(\frac{endurance}{60}\right)*TSFC \Big/ \left(\frac{L}{D}\right)\right]}} \tag{3}$$

$$M_{ff,cruise} = \frac{1}{e^{\left[range*TSFC \Big/ velocity*\left(\frac{L}{D}\right)\right]}} \tag{4}$$

By estimating an initial take-off weight (W_{TO}), the fuel empty weight ($W_{\text{fuel empty weight}}$) can be calculated using Equation 5. The fuel weight (W_F) is summation of all fuel consumed in all segments in the mission. Alternatively, knowing the mission FF and take-off weight, the fuel empty weight can be calculated by using $W_{\text{fuel empty weight}} = W_{TO}$ x FF. For the Airbus A350 XWB aircraft, the maximum fuel capacity is known from resource [81] to be 111,435 kg (141,000 liters). The take-off weight is estimated to be 246,415 kg, from the convergence of fuel weight to 111,435 kg. From resource [81], it is known that the maximum takeoff weight of this aircraft is 268,000 kg, and the calculated take-off weight is within the design limit.

$$W_{\text{fuel empty weight}} = W_{TO} - W_F \tag{5}$$

Drag polar:

The drag polar is estimated to verify the L/D estimate used during the cruise segments of the weight sizing process. The drag can be estimated using Equation 6 assuming there is no wave drag. ‘e’ is the Oswald’s efficiency factor (assumed standard value of 0.85) and AR is the aspect ratio (assumed standard value of 11 for large twin aisle aircraft). The parasitic drag, $C_{D,0}$, can be calculated using Equation 7, where C_f is skin friction coefficient (assumed value of 0.0035 [83]). The wetted area, S_{wet}, is calculated from a regression used in Roskam Part I [83]. Equation 8 shows the formula. The C and D coefficients used are 0.0199 and 0.7531 respectively as they are given for transport jets [83]. The planform area S, is known from resource [82] to be 443 m^2 (or 4768.41 ft^2) for Airbus A350 XWB aircraft. The wing loading (W_{TO}/S) can be estimated from the gross take-off weight (W_{TO}) from the aircraft weight estimation process, and S. The lift coefficient is given by Equation 9. Knowing the cruise Mach and altitude, both the velocity and density are known. The cruise weight (W_{cruise}) is the average weight of the aircraft during cruise estimated from the weight sizing process.

$$C_D = C_{D,0} + \frac{C_L^2}{\pi * \text{AR} * \text{e}} \tag{6}$$

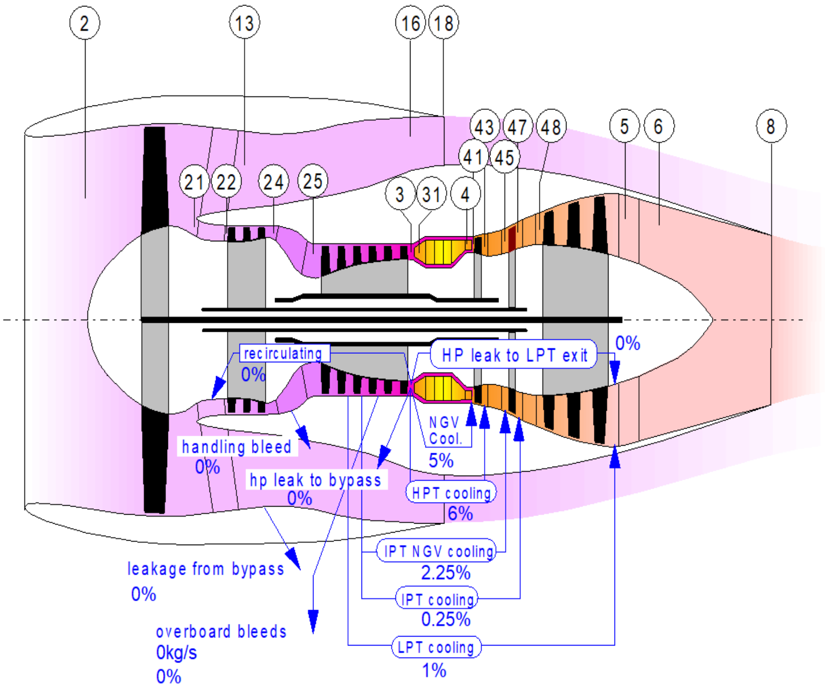
$$C_{D,0} = C_f * S_{wet} / S \tag{7}$$

$$log_{10}(S_{wet}) = D * log_{10}(\text{W}_{\text{TO}}) + C \tag{8}$$

$$C_L = \frac{W_{cruise}}{0.5 * \rho * \text{S} * V^2} \tag{9}$$

After both the lift coefficient and drag coefficient are calculated, the L/D is defined for the cruise segment. The L/D for the cruise segments is changed based on the results from the drag polar estimation until the L/D estimate matches the L/D used in the weight sizing process. This final step closes the loop and finalizes the gross take-off and fuel empty weight of the aircraft.

8.7 Appendix G: Trent XWB model



Name	*Where it is*
St2	Fan Inlet
St21	IP Compressor Inlet
St24	IP Compressor Exit
St25	HP Compressor Inlet
St3	HP Compressor Exit
St4	Burner Exit
St43	HP Turbine Exit
St45	IP Turbine Inlet
St47	IP Turbine Exit
St48	LP Turbine Inlet
St5	LP Turbine Exit
St6	Exit Guide Vane Exit
St8	*Core Nozzle Throat*
St13	Bypass Inlet
St16	Bypass Exit
St18	*Bypass Nozzle Throat*

Figure 21. Generic turbofan engine schematic (source [84])

Airbus A350 XWB (range of 15,000 km) uses two Trent XWB engines. A generic turbofan engine schematic is shown in Figure 21. The objective here is to design a turbofan engine (and optimize): non-geared, three-spool, separate flow, high bypass ratio, to be used on a twin-engine wide-body (passenger and freight) aircraft. The scope is: design and optimization of the Trent XWB engine with thrust, thrust specific fuel consumption (TSFC), geometry and weight targets; along with disk optimization. The design check is for on and off design constraints. The engine design data for Rolls Royce Trent XWB engine is provided in Table 7.

Table 7. Rolls Royce Trent XWB engine design data

Parameters	**Rolls Royce Trent XWB**
Engine Type	Axial, turbofan [82]
Drive type	Direct-drive [82]
Minimum take-off thrust from each of the two engines	374 kN [82]
Maximum net thrust at sea level	400.5 kN [82]
Overall pressure ratio at max. power	50 [82]
Bypass ratio	9.3 [82]
Turbine inlet temperature (max.)	1820 [148]
TSFC at SLS (target)	8 g/(kN*sec)
TSFC at cruise (target)	18 g/(kN*sec)

The excess power definition of service ceiling is used. It is defined service ceiling as the altitude at which excess power suffices for rate of climb (RoC) of 0.508 m/s (100ft/min) at just before the beginning of cruise. $Rate\ of\ Climb = \frac{Excess\ Power}{Weight} = \frac{V*(T-D)}{W}$

Rewriting these values using trigonometry: $T_{req} = W * (\frac{RoC}{V} + \frac{\sqrt{1-\left(\frac{RoC}{V}\right)^2}}{(L/D)_{max}})$, where V is the velocity and W is the aircraft weight at start of cruise. W is found via fuel burn analysis as discussed in Appendix F. The resulting thrust requirement is 57.134 kN per engine. The spool/shaft speeds for low pressure system, intermediate pressure system and high pressure system of the family of Trent XWB engines, are 2700 rpm, 8200 rpm, and 12600 rpm respectively [149]. Additionally, the fan diameter is 3 m [150] and the flange-to-flange length of engine is 4.064 m [82]. The number of turbine stages are 1 (high-pressure), 2 (intermediate-pressure), and 6 (low-pressure). The number of compressor stages are 1 (fan/low-pressure), 8 (intermediate-pressure), and 6 (high-pressure) [149].

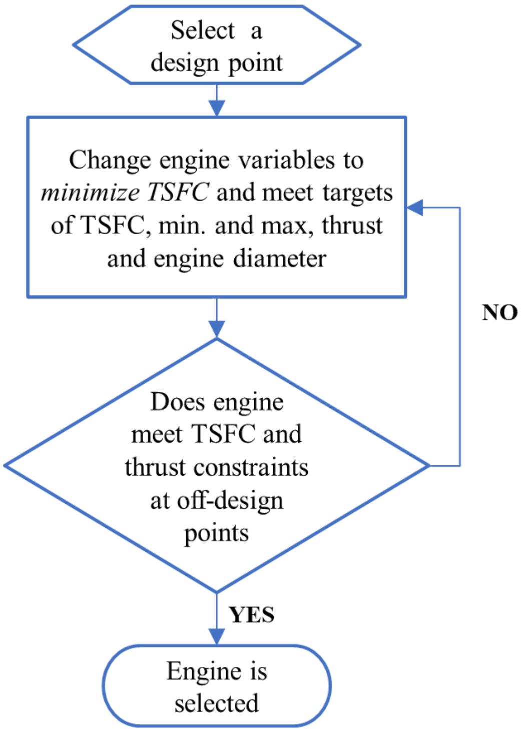


Figure 22. Engine optimization schematic

Table 8. Engine optimization constraints

System	Constraints	Comment
Engine	Thrust	Engine should meet the minimum thrust and TSFC requirement at all points in the mission
	TSFC	
Fan/Engine	Diameter	The engine should not be oversized
LPT, IPT, HPT	RPMs	Limit; Engine vibrations/noise; Whirling of shafts
	Inlet radius ratios	Geometry limits for velocity triangles and work loading

The engine optimization is done in GasTurb 13 [84], and the engine optimization schematic used in this study is provided in Figure 22. Similar approach is used for disk optimization. Table 8 and Table 9 list the constraints and optimization variables respectively. The objective function of the optimization is to minimize the TSFC. Figure 23 shows the optimized model of Trent XWB engine, with disk optimization. Table 10 provides the comparison of the model engine geometry and performance parameters with literature.

Table 9. Engine optimization variables

System	Variables	Comment
Low Pressure Turbine (LPT) system	LPT rotor inlet diameter	Sizing based on the operating conditions (Geometry, weight and Performance)
	LPT exit radius ratio	
Intermediate Pressure Turbine (IPT) system	IPT rotor inlet diameter	
	IPT exit radius ratio	
High Pressure Turbine (HPT) system	HPT rotor inlet diameter	
	HPT exit radius ratio	
Low Pressure Compressor (LPC) system	LPC inlet Mach no.	Fan/Engine area/diameter, weight and performance
	LPC inlet radius ratio	Sizing based on the operating conditions (Geometry, weight and Performance)
Intermediate Pressure Compressor (IPC) system	IPC inlet radius ratio	
High Pressure Compressor (HPC) system	HPC inlet radius ratio	
Combustor	Turbine inlet temperature	Directly related to thrust and fuel consumption
Overall Engine	Inlet air mass flow	Engine diameter, thrust, TSFC

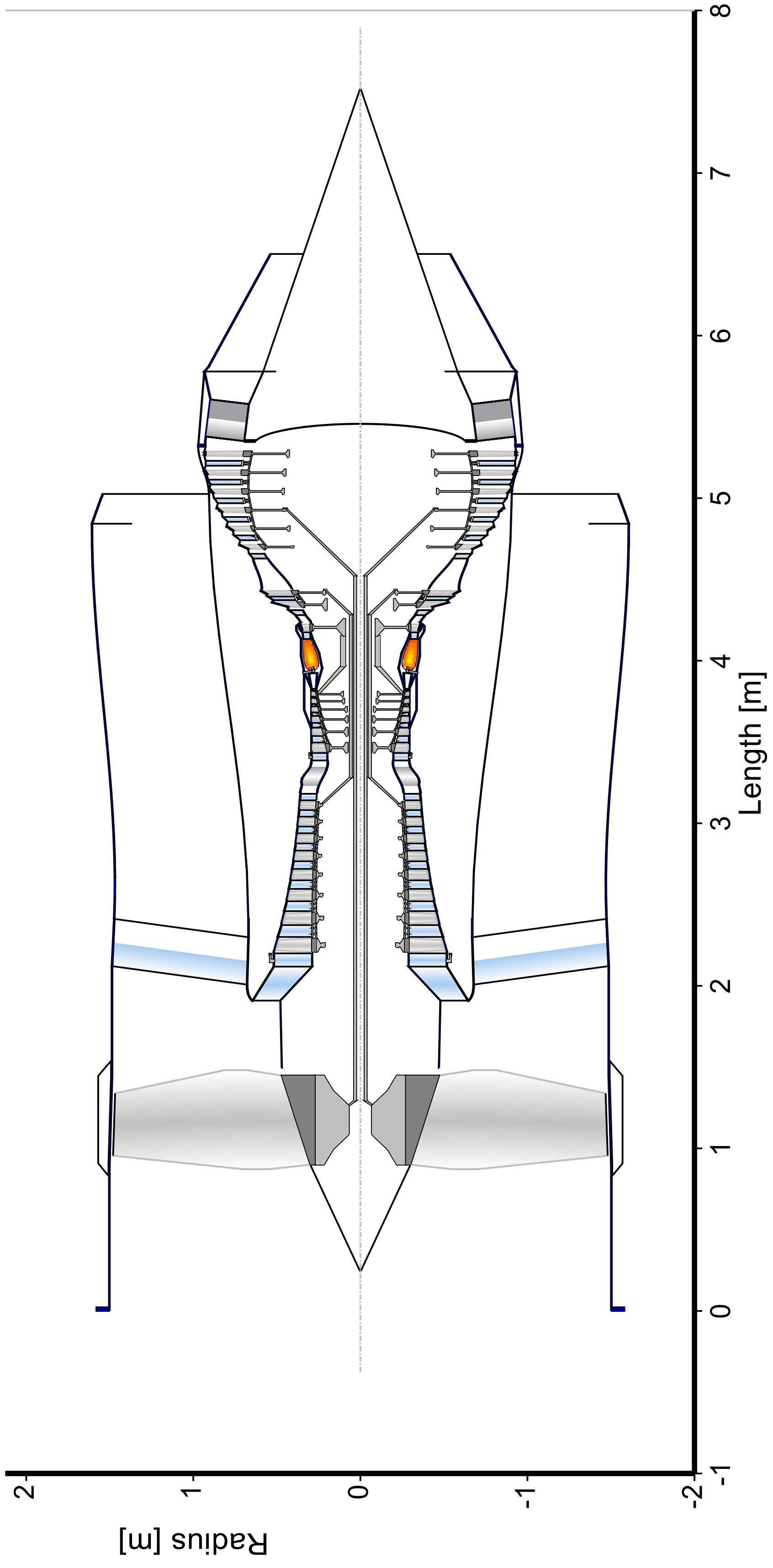


Figure 23. Optimized model of Trent XWB engine with disk optimization

Table 10. Comparison of the model engine geometry and performance parameters with literature

Parameters	Units	Values from literature	Model
Total Mass (dry weight without tail-pipe)	kg	5445 [82]	5437
Fan Diameter	m	3 [150]	3
Engine length (Flange to flange)	m	4.064 [82]	4.042
Turbine Stages (H,I,L)		1, 2, 6 [149]	1,2,6
Compressor Stages (H,I,L)		1, 8, 6 [149]	1,8,6
BPR		9.3 [82]	9.3
OPR		50 [82]	50
SLS thrust	kN	400.5 [82]	400.5
SLS TSFC	g/(kN*s)	8 [82]	8
Cruise thrust	kN	57.134 (calculated)	57.81
Cruise TSFC	g/(kN*s)	18 [82]	18