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Identification of sustainable technology and energy vector combinations for future inter-continental passenger aircraft

LSR report

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1. Abstract

Aviation contributes to negative environmental impacts. The future aviation demand is expected to double in the next two decades. Thus, the associated environmental impacts are expected to further increase. This growing aviation demand would result in more rigorous aviation policies for mitigating the impacts of aviation. The use of advanced aircraft technology and low-carbon alternative fuels are important strategies of the International Air Transport Association that have the potential to significantly reduce aviation's climate-change impacts. The aim of this research is to evaluate low-carbon technology and energy vector combinations for future inter-continental passenger aircraft, especially in the long-term. Firstly, in this research a comparative assessment of the performance characteristics of the six alternative fuels is conducted using the standard Breguet range equation and viable alternative fuel(s) for inter-continental travel are identified. It is observed that liquid hydrogen and 100% synthetic paraffin kerosene are the alternative fuels found to be feasible for intercontinental travel. Secondly, an advanced and/or novel aircraft and engine technology of the future is used for conducting a more precise performance analysis of these identified alternative fuels. The aircraft engine design and optimization is conducted in a commercial software by using a standard conceptual design scheme for the use of the conventional jet fuel and identified alternative fuels. The engine analysis includes engine performance simulation at on-design and off-design points for conventional jet fuel and identified alternative fuels. Thereafter, the aircraft energy consumption is modelled using standard aircraft weight sizing process/methodology for the conventional jet fuel and identified alternative fuels, where the engine performance parameters evaluated separately are inputs to the aircraft weight sizing process. It is found that liquid hydrogen fuel offers highest energy efficiency benefits in the future aircraft concept as compared to Jet-A case. Lastly, when considering low-carbon alternative fuels in the conventional aviation sense would mean low or zero carbon emissions in the use phase of the aircraft. However, there will always be some form of embodied emissions associated with any fuel. Therefore, it is also important to consider the life-cycle perspective for the alternative fuels under consideration, so that there are no unintended impacts of using the said fuel. This research compares different feedstocks and/or pathways of manufacturing different identified alternative fuels where the conventional jet fuel case is the reference case. This study evaluates all alternative fuel (manufacturing) feedstocks and/or pathways based on their performance, in future aircraft technology considering primarily greenhouse gas emissions. Such a holistic life-cycle integrated research can potentially guide researchers and decision makers in technology development, and policy makers, in making more informed decisions for the future. Particularly, this research will enable more research-development activities of low-carbon aircraft technology and feedstocks for alternative fuel production. This includes the impact on fuel production capacities, fuel costs and market penetration. Additionally, a systems-level interpretation of this study for global aviation would enable drafting of greener aviation policies.

2. Introduction

2.1 Background

The exhaust of an 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 [1]. Additionally, aircraft are also source of noise. The sustainability of any system is dependent on three fundamental dimensions: social, economic and environmental [2]. Using these three pillars of sustainability, the impacts of aviation sector is discussed below:

Social: In 2019, the aviation industry delivered services to approximately 4.5 billion passengers [3] and 61.3 million tonnes of freight [4]. The forecast for 2020 (lockdown year) the aviation industry delivered services to approximately 2.2 billion passengers [3] and 54.2 million tonnes of freight [5]. Additionally, aviation has human health impacts (noise and air pollution), especially on community health in the airport vicinity. These human health impacts of aviation are detailed in the next sub-section.

Economic: In 2019 aviation contributed to 1% of the global gross domestic product (GDP) whereas in 2020 it contributed to 0.5% of global GDP [3].

Environmental: The conventional jet fuel is manufactured from crude oil/petroleum, which is a resource impact of aviation. In 2019, the global aviation sector reached 914 million tonnes of CO_2 respectively, and this dropped to 574 million tonnes in 2020 [3], [6]. In 2019 and 2020, it is estimated that the global aviation industry consumed 363 billion liters and 228 billion liters of fuel respectively.

Aviation has climate change impacts, which can be classified into two categories: CO_2 effect and non-CO_2 effects. CO_2 effect is linearly dependent on the fuel burn. The aviation sector contributes to 2% of the global man-made carbon dioxide (CO_2) emissions [1], [7]–[9]. The non-CO_2 effects comprise of: NO_x emission, sulphur compounds, soot, contrails and cirrus [1], [7]–[10]. The non-CO_2 effects are uncertain, difficult to quantify and complicated, as these are not linearly dependent on fuel burn. The non-CO_2 effects also depend on aircraft technology and fuel type.

Aircraft contrails have a climate impact. 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) [1], [7]–[10]. Overall, contrails and cirrus clouds have a net warming effect (ibid). 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 the 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 [1], [7]–[10]. When non-CO_2 emissions and their impacts are considered, the Intergovernmental Panel on Climate Change (IPCC) estimates that currently aviation accounts for approximately 3% of total man-made climate impact (ibid).

Passenger and cargo air-travel demand is anticipated to grow in future [11]. Boeing anticipates annual worldwide average growth rate of 4% for both passenger and cargo air-traffic, during 2020-2039 timeframe [12]. Therefore, the global air-traffic is expected to approximately double in the next two decades. It is to be noted that these forecasts are made considering the effects of COVID-19 pandemic, though at an early stage. Due to the predicted increase in demand in future air-travel, 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 2050 [1], [7]–[10]. 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. Presently, a Washington DC ↔ New Delhi return air-travel emits similar amount of GHG a car in UK/~USA emits on an annual basis (calculated using [13]–[15]). In the 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 2050 [1], [7]–[10]. 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 [16]. IATA's 3 goals are as follows:

i. An average improvement in fleet fuel-efficiency of 1.5% per year from 2009 to 2020 [16];
ii. Capping net aviation CO_2 emissions (carbon-neutral growth) from 2020 [16]; and
iii. 50% decrease in net aviation CO_2 emissions by 2050 as compared to 2005 [16].

IATA's 4 pillar strategy comprises:

i. Use of advanced technology, including the use of sustainable low-carbon fuels [16];
ii. Increasing the efficiency of aircraft operations [16];
iii. Improvements to infrastructure, including advanced air traffic management systems [16]; and
iv. A single global market-based action for addressing the remaining emissions gap [16].

It is to be noted that according to IATA [17], the 'sustainability' evaluation of aviation fuels comprise of life-cycle analysis (net emissions).

In-line with the 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 [18]. This aims to 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.

2.2 *Overview of literature review*

A thorough literature review (traditional narrative type) is provided in the appended document. It provides insights into the social and environmental impacts of aviation, and different technologies, alternative fuels and pathways of making aviation more sustainable, along with the consideration of feasibility of future technologies and passenger safety aspect within the definition of 'sustainability'. '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. Overall, the review suggests that the efforts from academia and industry agree with each other and in-line with the IATA strategies for making future aviation more sustainable.

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 provides significant energy consumption improvements and it appears to be technologically feasible as indicated by studies. Also, several alternative aviation fuels are identified via the literature review that are widely studied, and these include: ASTM approved sugar-to-jet (STJ) synthetic paraffin kerosene (SPK) (10% blending), and hydro-processed renewable jet (HRJ) SPK, alcohol to jet (ATJ) SPK and Fischer-Tropsch (FT) SPK (50% blending); power-to-liquid (PtL); and liquid hydrogen (LH_2). Additionally, 100% SPK is also found to provide some energy efficiency benefit, though it is not a drop-in fuel. The performance characteristics of an aircraft powered by natural gas, ammonia, ethanol and methanol, especially for inter-continental travel are less published. These fuels require a separate viability examination for aviation application as the literature lacks it. This viability study is conducted separately in *Chapter 3* of the thesis. 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 volumetric energy density than conventional jet fuel, so it requires more volume storage on aircraft.

In terms of airframe selection, the literature review on blended wing body (BWB) aircraft suggests that BWBs have higher internal volume storage capacity for the same passenger capacity compared to the conventional tube-wing 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 tube-wing architecture. This enables storage of extra-large and bulky fuel tanks, especially for using LH_2 fuel, which might not require re-designing/re-structuring of aircraft. 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 the conventional tube-wing architecture. Therefore, BWBs enable a more flexible and efficient integration of new storage technologies such as LH_2 fuel storage tanks. *Chapter 3* of the thesis reveals viable alternative aviation fuels. The identified alternative fuels are considered for further detailed analysis in *Chapter 4* and *Chapter 5*. *Chapter 4* provides the performance metrics of the future aircraft powerplant using conventional and identified alternative fuels. In *Chapter 5*, the energy consumption of the future BWB aircraft fleet (conventional and identified alternative fuels) is evaluated. *Chapter 4* and *Chapter 5* collectively address the shortcomings in the literature addressed above. However, significant technical and operational challenges remain for BWB concepts ranging from structural integrity, manufacturability, aerodynamics and to whether it is possible to evacuate such a passenger aircraft safely.

From the literature review it is found that CO_2 emissions, contrails, and cruise NO_x emissions, are the three components that are responsible for 97% of climate and air quality damages per unit aviation fuel burn. Thus, these are principal targets for future strategies to mitigate the atmospheric impacts of aviation emissions. In terms of methodological approaches (high-level), multiple 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 [19] 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 [20] uses model from Greener-by-design (GBD) report [21], 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. A recent review study by Pinheiro Melo et al. [22] establishes the need for an integrated methodological framework that should consider life-cycle impacts of aircraft performance towards the goal of sustainable aviation. This framework will enable a better understanding of the implications of future technologies considering the three sustainability parameters by coupling different scenarios and examining the interactions between different designs, spatial differences, and product parameters. Additionally, novel methodologies are required to understand the implications of aviation technologies of the future, beyond the operational phase of the aircraft. Though advanced technologies and alternative fuels could provide solutions for mitigating aviation emissions, there might be new socio-economic and environmental challenges associated with these. Therefore, the authors establish the need for diversifying environmental indicators beyond GHG emissions and the need to consider social and economic aspects. This approach can help engineers towards a more sustainable aircraft design and operation (ibid). *Chapter 6* address these gaps in literature, as it evaluates the potential of aircraft in the fleet (using findings of *Chapter 4* and *Chapter 5*) to reduce lifecycle GHG emission, air-quality, and water and resource consumption. This evaluation includes development of a database of manufacturing emissions of different identified alternative fuels from different pathways and fuels; and estimation of the aircraft operational phase emissions.

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. There are technologies predicted for future travel, such as Hyperloop, which could be an alternative transport mode for short and medium distance (intra-continental) air-travel. The travel time predicted using Hyperloop is lesser than short and medium distance (range) air-travel [23]. However, there is no alternative to air-transportation for 'quick' long inter-continental travel. The long-range aircraft comprise of large twin aisle (LTA) aircraft such as Boeing 777 200-LR (approx. 300 passengers in a 3 class configuration) and very large twin aisle (VLTA) aircraft such as Boeing 747 (approx. 400 passengers in a 3-class configuration). The airline operations have been predominantly based on the hub-spoke model and such operations were/are enabled because of VLTAs such as B747 and Airbus A380s. In the past few years, advanced LTA aircraft such as Boeing 787s have enabled 235 new point-to-point routes [24]. During the 2020 COVID-19 lockdown, major airlines such as Lufthansa, Air-France, KLM, British Airways, etc. have retired their VLTA (A380s and/or B747s) [25]–[27]. Therefore, it is likely that LTAs would be the preferred air vehicle for inter-continental travel in short and medium term future.

Considering the above identified gaps, this research therefore examines N+2 aircraft technology 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 next.

3. Research aims and objectives

3.1 Aims and scope

The broader aim and scope of this research is to evaluate future aircraft technologies and alternative fuels, that will be essential to evaluate 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 within its 'sustainability' definition. The rationale for this aim is as follows. In the present setup, the 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 2016, International Civil Aviation Organization (ICAO) released CO_2 standard (kg/km) for new aircrafts [28]. Cruise emissions are unregulated currently, and the study by Barrett et al. [29] suggests that cruise emissions have the highest air-quality impact over aircraft's flight mission. Additionally, because an aircraft spends the 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 (considering the embodied emissions). 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. Using the GREET 2018 model [30], 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.

3.2 Objectives

Considering the literature review with identified gaps, and above rationale with the defined scope for LTA/inter-continental 300 passenger aircraft, the research aim can be achieved with the detailed objectives comprising:

1. Identify and evaluate viable alternative fuel(s) and their performance for inter-continental travel from long-list of options (*Chapter 3*).
2. Development a model for estimating the performance metrics of the aircraft powerplant using conventional and identified alternative fuels (*Chapter 4*).
3. Evaluate the mission energy consumption model for the future aircraft fleet (conventional and identified/shortlisted alternative fuels) (*Chapter 5*).
4. Evaluate the potential of aircraft in the fleet to reduce GHG emission, air-quality, and water and resource consumption based on fuel life-cycle (*Chapter 6*). This requires:
   a. Development of a database of manufacturing emissions of different identified alternative fuels from different pathways and fuels.
   b. Estimation of the aircraft operational phase emissions.

4. Progress/Methodology

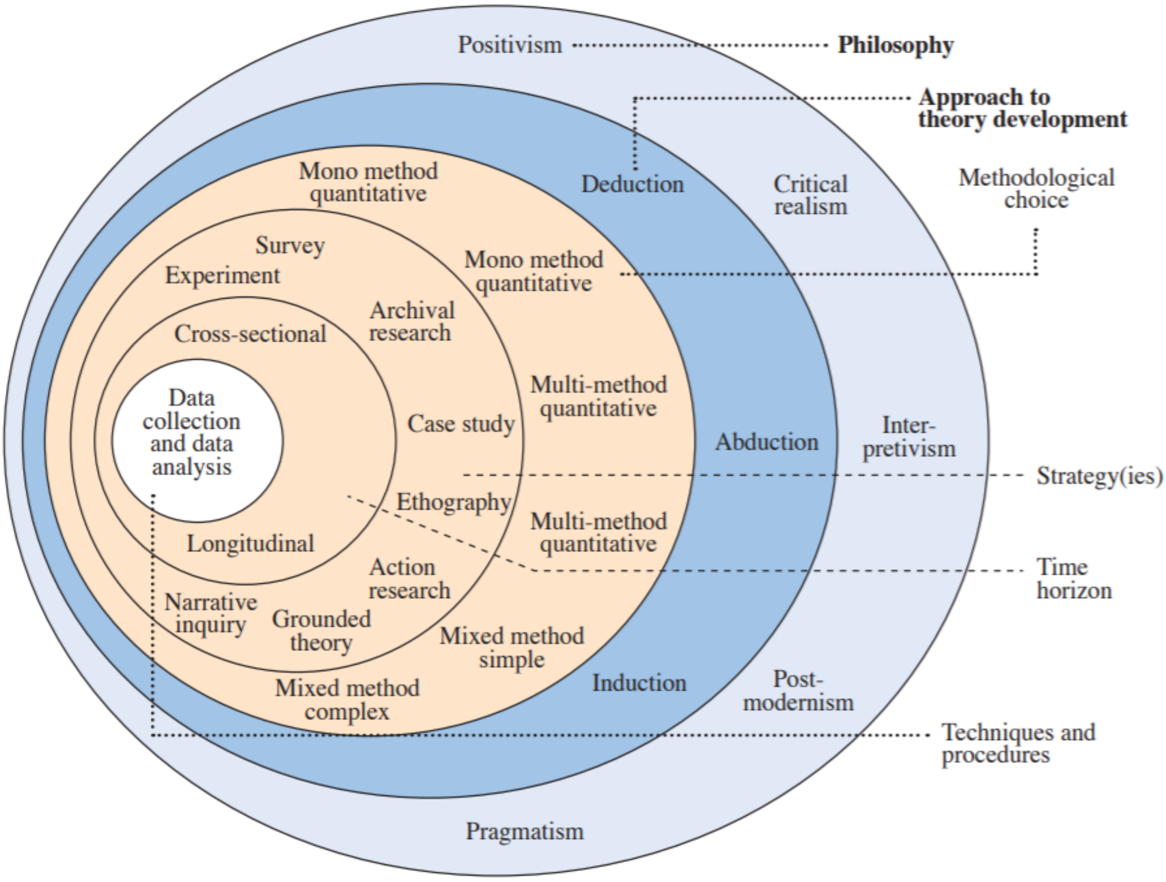

Figure 1. Schematic of the research 'onion' (source [31])

Figure 1 shows the schematic of the research 'onion', which includes different research philosophies, research approaches, methodological choices, strategies, time horizon, and techniques and procedures [31]. The research philosophy – forms a research basis by delineation of ontology – nature of reality, epistemology – nature, sources of knowledge or facts and axiology – values, beliefs and ethics of the research (ibid).

In an inductive approach, the research begins with observation and data collection, moving to discussion and analysis for forming a theory [31]. In a deductive approach the research begins with an existing theory, then putting forward a question or hypothesis and data collection for rejecting or confirming the hypothesis. With an abductive approach, the observation of an empirical phenomena is followed by the research using a best guess or inference based on available evidence. A deductive approach is applied for existing theory testing and an inductive approach is generally used in developing a theory or in research areas with lesser research on a topic. An abductive approach generally begins with a surprising fact and moves between deductive and inductive approaches for finding the most likely explanation (ibid). A deductive research approach is typically used in scientific examinations [32]. The inference from a deductive approach is guaranteed to be true, whereas the inference from inductive and abductive approach are 'probably true' and 'best guess' respectively.

The research philosophies of interpretivism (interviews, ethnography and grounded theory) and post-modernism (discourse analysis and visual methods) are used for pure qualitative evaluations. Critical realism (archival research and historical analysis) and pragmatism (any strategy) take an abductive approach and are used for quantitative and/or qualitative evaluations. Positivism primarily reflects the philosophical stance of a natural scientist [31]. Its ontology is based on objectivist assumptions that "entities are observed, atomistic events, existing external to social actors, therefore only observation and empirical data may be referred to as 'credible'" (ibid). Knowledge is acquired by observation and finding event regularities that are based on law-like, functional and causal relations. Positivism uses a deductive approach is used for pure quantitative evaluations (experiments, surveys, etc.).

The present research is a 'quantitative' assessment of low-carbon technology and energy vector combinations for future inter-continental passenger aircraft. Considering the above, the research philosophy of 'positivism' is relevant and is thus used in this research, which uses deductive approach for a quantitative research. In the context of the present research, each main chapter (*Chapter 3-6*) uses a mono quantitative method (numerical experiments). Overall, this thesis uses multi-method quantitative method towards the research aim and objectives.

The overall process or thesis information flow schematic is provided in Figure 2, where each of the research objectives discussed previously are addressed in individual chapters. In terms of progress since ESA, the efforts comprised of research on Chapter 1-5 and its documentation. The drafts of Chapter 1-5 have undergone two cycles of review from both supervisors. The research for Chapter 6 and its documentation will be undertaken in the remaining PhD timeline. Simultaneously, the research from the drafts of Chapter 3-5 are expected to be submitted for Journal publication. The table of contents of the thesis is included in sub-section 7.

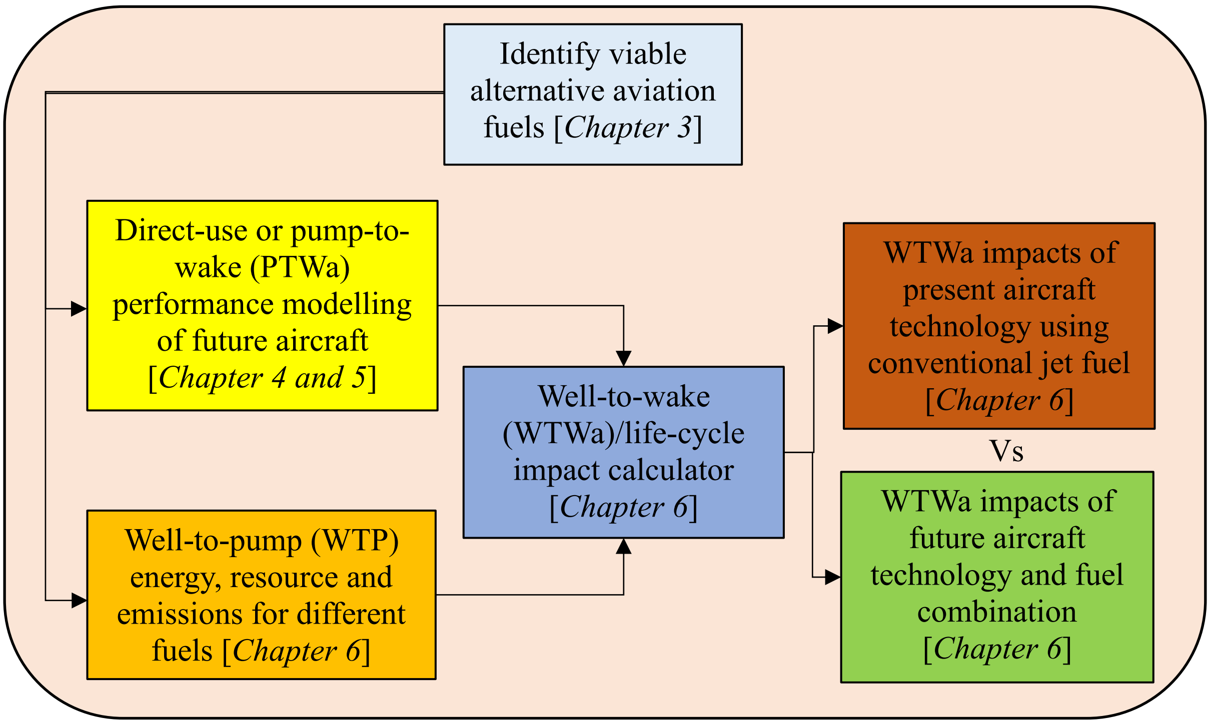

Figure 2. Schematic of the overall process or thesis information flow

4.1 Chapter 1: Introduction

Chapter 1 of the thesis introduces the problem at hand with background information, research aim, scope and objectives. This chapter is 95% complete approximately.

4.2 Chapter 2: Literature review

Chapter 2 includes a comprehensive literature review along with a summary of this review. This chapter is attached as for reference and is approximately 95% complete.

4.3 Chapter 3: Comparative performance evaluation of alternative fuels

A comparative assessment of the performance characteristics of the six alternative fuels is conducted using the standard Breguet's range equation (equation 1) in *Chapter 3*. Such an evaluation is missing in the literature. These alternative fuels include fuels such as synthetic jet fuel (fossil fuel based, biomass based and power-to-liquid), liquid hydrogen (LH_2), liquid natural gas (LNG), liquid ammonia (LNH_3), ethanol and methanol. The Breguet's range equation is a fundamental equation in aeronautics governed by multiple aspects of an aircraft such as aerodynamics, propulsion, and structures.

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

The Breguet range equation is applicable to cases where the overall efficiency (η_{o}), lift to drag ratio (*L/D*), and flight velocity are constant over the flight (example cruise condition). Thus, for cruise, W_{initial} and W_{final} in equation 1 are the aircraft weights at the beginning and end of cruise. The parameter *h* in equation 1 represents the lower calorific value of the fuel (gravimetric energy density), *R* is the range and *g* is acceleration due to gravity. Each parameter/variable of equation 1 i.e. *h*, *L/D*, η_{o}, W_{initial} and W_{final} are different for different fuel cases. The range/distance travelled is assumed to be equal to the cruise range. Viable alternative fuel(s) for inter-continental travel are identified through *Chapter 3* from a range of options. The Breguet's range equation is validated before it is used for the estimation of the performance characteristics of the alternative fuels. This chapter is 95% complete approximately.

4.4 Chapter 4: Engine modelling and validation

Chapter 3 of the thesis reveals viable alternative aviation fuels. The identified alternative fuels are considered for further detailed analysis in *Chapter 4* and *Chapter 5*. In both *Chapter 4* (engine modelling) and *Chapter 5* (aircraft modelling), conceptual design process is used which is a low-order (low-fidelity) modelling stage. Though the conceptual design phase involves low-order computations, it provides realistic design information. Moreover, the preliminary and detailed design phases, which are subsequent to the conceptual design phase, are computationally expensive and require integrated efforts of multiple discipline-specific specialists. Therefore, considering the above, in this research the design of aircraft engine and aircraft are restricted to the conceptual design phase. An advanced and/or novel aircraft and engine technology of the future is used. In *Chapter 4* engine modelling (design and optimization) and validation is presented. The engine modelling is along the lines of the standard design and optimization scheme. This chapter includes the conceptual design methodology for engine performance simulation at on-design and off-design points for conventional jet fuel and identified alternative fuels (separately) along with validation cases that are helpful to build a confidence in the engine model. The engine design and optimization scheme used in this work is along the lines of the schematic of Walsh and Fletcher [33] as it is more holistic and specific to the conceptual engine design phase as compared to the engine design schematic of Mattingly [34]. The engine performance modelling is done in a commercial software called 'GasTurb 13'. This chapter is 95% complete approximately.

4.5 Chapter 5: Aircraft operational energy consumption modelling

Chapter 5 includes the aircraft energy consumption modelling which is part of the conceptual aircraft design phase according to the defined scope. The energy consumption modelling is based on the standard aircraft weight sizing process/methodology provided by Raymer [35] and Roskam [36] for the conceptual aircraft design phase. This chapter addresses the design challenges associated with storing a special fuel like liquid hydrogen (in a future aircraft concept) which has 2.78 times the gravimetric energy density as that of conventional jet fuel but the volumetric energy density of the conventional jet fuel is 4.1 times as that of liquid hydrogen. The results of *Chapter 4* are used in *Chapter 5* for predicting the performance of future large-twin aisle aircraft concept powered by conventional jet fuel and identified alternative fuels (separately). The analysis does not conduct any structural and stability examination. This chapter is 95% complete approximately.

4.6 Chapter 6: Life-cycle effects of aircraft performance

In *Chapter 6*, life-cycle approach is considered that requires results of *Chapter 6* towards aircraft's use phase energy and emissions. In addition to the results of *Chapter 5* (for estimating use phase emissions), GREET 2020 model of Argonne National Labs, USA, is primarily used for obtaining the manufacturing phase information for different fuels and their manufacturing pathways, that enables the estimation of GHG emission, and socio-environmental impacts including non-CO_2 climate impacts, air quality, water use, resources and land-use. Though GREET model provides a comprehensive data of multiple pathways and feedstocks for producing different fuel, the analysis is geographically limited to USA. Lastly, Chapter 7 concludes the thesis with discussion on findings of the thesis and its implications/interpretation for future technology development and policy making. This chapter is 0% complete.

5. Results to date

5.1 Chapter 3 results

The performance characteristics of Airbus A350-1000 aircraft modified for the use of alternative fuels (for same payload of 34,770 kg [366 passengers-payload]) is listed in Table 1. These are obtained using the Breguet's range equation (*Chapter 3*). It can be observed from Table 1 that only 100% SPK and LH_2 powered aircraft are able to fly same distance as that of the Jet-A aircraft (baseline) within the limit of aircraft maximum take-off weight (MTOW) (of 316 ton). Since other alternative fuels have lower 'h' as compared to Jet-A, higher quantity of fuel would be required (to be carried) on the aircraft for enabling the same range as that of the Jet-A aircraft. This also increases the operating empty weight (OEW) of the aircraft and resultantly the gross take-off weight (GTOW). Since the GTOW is structurally limited by MTOW bound, limited fuel and corresponding OEW can be supported for a given aircraft (MTOW defined).

Table 1. Airbus A350-1000 performance characteristics using alternative fuels for passenger payload of 34,770 kg (366 passengers)

Fuel	h/g (km)	OEW (kg)	$W_{f,total}$ (kg)	GTOW (kg)	Fuel in fuselage tank (kg)	ΔL (m)	L/D	R (km)
Jet-A	4,404	155,129	126,101	315,999	-	-	18.63	13,869
100% SPK	4,496	155,314	123,320	313,404	5,178	0.25	18.57	13,869
LH_2	12,233	183,371	50,375	268,516	50,375	26.87	16.09	13,869
LNG C1	5,097	187,239	93,990	315,999	93,990	8.4	18.2	10,895
LNG C2	5,097	205,161	76,068	315,999	76,068	6.77	18.48	8,517
LNH_3	1,896	183,605	97,624	315,999	97,624	5.05	18.34	3,478
Methanol	2,029	155,191	126,037	315,999	1,809	0.08	18.52	5,943
Ethanol	2,773	155,202	126,027	315,999	2,111	0.1	18.57	8,421

It is to be noted that since LH_2 has 2.78 times high gravimetric energy density than Jet-A the total fuel weight ($W_{f,total}$) carried at the mission start is less. The volumetric energy density of the conventional jet fuel is 4.1 times as that of LH_2 fuel. The lower volumetric energy density of LH_2 fuel increases the fuselage length by 26.87 m which penalizes the fuselage weight and L/D ratio. For a high energy dense LH_2 fuel there is a net reduction in the aircraft GTOW of 15%. For 100% SPK fuel, the extra fuel (in addition to the wing tank) required considering slightly lower volumetric energy density as compared to Jet-A, to meet the flight range of Jet-A aircraft within the MTOW limit of 316 ton, is small as compared to the fuel that fits in the wing tanks. Therefore, the increase in fuselage length is 0.25 m which has an insignificant impact on the (wetted area) *L/D* performance.

Table 2. Specific energy consumption (SEC) performance of viable fuels for inter-continental travel

Fuel	Payload (kg)	h (MJ/kg)	Fuel consumed (kg)	R (km)	SEC (MJ/t-km)
Jet A	34,770	43.2	113,491	13,869	10.17
100% SPK		44.1	110,988	13,869	10.15 (-0.17%)
LH_2		120	45,338	13,869	11.28 (+10.97%)

Table 2 shows the specific energy consumption performance of viable fuels for inter-continental travel. It can be observed that 100% SPK offers an insignificant improvement (of 0.16%) in energy consumption as compared to Jet-A. On the other hand LH_2 aircraft consumes more energy (~11%) than Jet-A aircraft. This is due to the fact that the poor volumetric energy density performance of LH_2 fuel compared to Jet-A and higher OEW due to cryogenic systems requirement, results in longer and heavier fuselage (negative impact on *L/D*). The hydrogen aircraft is considered for further design analysis due to its impact on aircraft design characteristics (additional fuselage requirement that affects performance).

The A350-1000 aircraft (366 passengers) is a single decker aircraft [37] and is similar to a Boeing 777-200 LR aircraft (301 passengers) for a 3-class configuration [38]. The significant difference between the two vehicles is that A350-1000 aircraft (72.25 m) is longer than Boeing 777-200 LR aircraft (63.7 m) for accommodating more passengers. The aim and scope of this research is the evaluation of technology and alternative fuels for a sustainable 300 passenger intercontinental aircraft as outlined in sub-section 3. As observed for the A350-1000 aircraft, fuselage length is a sensitive parameter for LH_2 aircraft which negatively impacts aircraft performance. The passenger seating of a Boeing 777-200 LR aircraft (301 passengers) for a 3-class configuration can be applied to A350-1000 aircraft (366 passengers 3-class configuration). This would enable use of approximately 8 m of fuselage length (i.e. corresponding volume) A350-1000 aircraft for storing LH_2 tanks and additional need of LH_2 tanks can be accommodated via increase in aircraft fuselage length.

The fuselage/fuel tank volume is proportional to the square of the fuselage diameter. So far, through this research it is observed that fuselage length is a significant aspect for hydrogen aircraft because of its low density as compared to Jet-A. Considering the above points, very large aircraft like A380-800 that has a double-decker architecture or large fuselage diameter has the potential to reduce the increase in fuselage length for a hydrogen powered aircraft. For this aircraft, two cases are analysed. The first case is the actual A380-800 aircraft with full passenger payload (486 passengers in a 3-class configuration). The second case is the A380-800 aircraft modified for seating 312 passengers powered by LH_2. These modifications are important particularly for utilizing the aircraft volume for installing hydrogen tanks. Additionally, this is a double decker aircraft so the reduction in seating has to be done carefully. Overall, 10.41 m of the aircraft fuselage length is available for the installation of LH_2 tanks after the said modification.

Table 3. Characteristics of different aircraft (Jet-A and LH_2) at design point

Fuel type	Max. passenger	OEW (kg)	$W_{f,total}$ (kg)	GTOW (kg)	SEC (MJ/t-km)	L (m)	L/D	R (km)
				A350-1000				
Jet-A	366	155,129	126,101	315,999	10.17	72.25	18.63	13,869
LH_2	366	183,371	50,375	268,516	11.28	99.12	16.09	13,869
LH_2	301	178,284	47,645	254,524	12.74	89.67	16.43	14,125
				A380-800				
Jet-A	486	270,364	252,465	569,000	70.4	13.76	18.94	15,449
LH_2	312	309,625	78,440	417,705	84.43	20.41	17.07	14,000

Table 3 shows the design characteristics of different aircraft (Jet-A and LH_2) at design point considered in this research. The aircraft now becomes a ‘fixed’ aircraft i.e. its length, maximum fuel capacity, etc. cannot change. In real world applications, aircraft do not always operate with full design payload capacity, design range and/or full fuel tank. For example, with a full fuel tank and reduced payload (compared to design payload), the aircraft can fly greater distance compared to the design range. This is known as the off-design performance of the aircraft. In this research, the performance of each aircraft is evaluated for typical range and payload combinations for intercontinental flights. Figure 3 and Figure 4 show the specific energy consumption (SEC) comparison of different A350-1000 and A380-800 aircraft fuel cases respectively at different flight range and payload combinations. The nomenclature for the legend is as follows: ‘fuel case’, ‘actual passengers’/‘maximum passenger (PAX) seating’. Same nomenclature is followed throughout this report. From both these figures it is observed that for the Jet-A case there is a minimum point observed, whereas for the LH_2 aircraft the specific energy consumption keeps on decreasing within the aircraft’s off-design range (as expected). For a given aircraft, increasing the passenger count improves the SEC (or efficiency) as expected. For a given hydrogen aircraft case that has same maximum passenger capacity and actual passengers as that of the corresponding Jet-A case, the efficiency of the hydrogen aircraft improves with increasing range. On an absolute scale, the hydrogen aircraft consumes more energy than Jet-A aircraft at all range-payload combinations. Of the 3 LH_2 aircraft (A350-1000 366 PAX and 301 PAX, and A380-800 312 PAX) for different range-payload combination, using the A380-800 312 PAX aircraft would cost the airlines/passengers more as compared to A350-1000 366 PAX case. Considering only the energy consumption, across all cases, hydrogen aircraft consume more energy than their respective baseline Jet-A aircraft, due to increase in OEW.

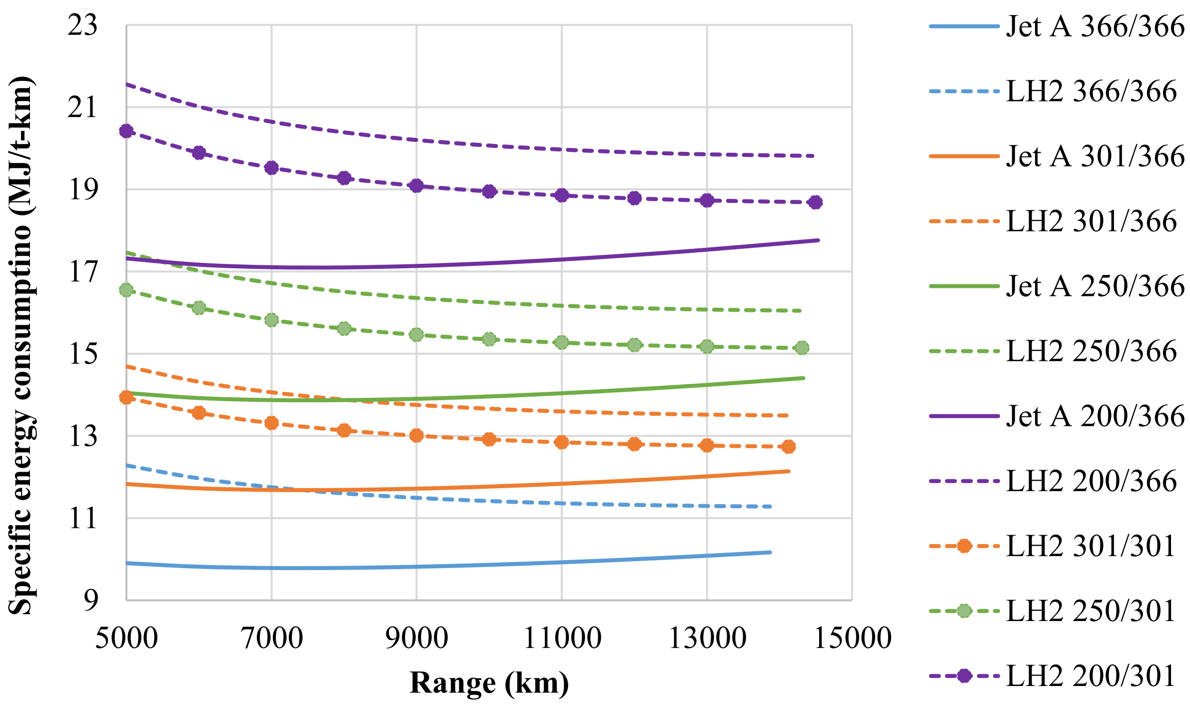

Figure 3. Specific energy consumption comparison of different A350-1000 aircraft fuel cases at different range and payload combinations

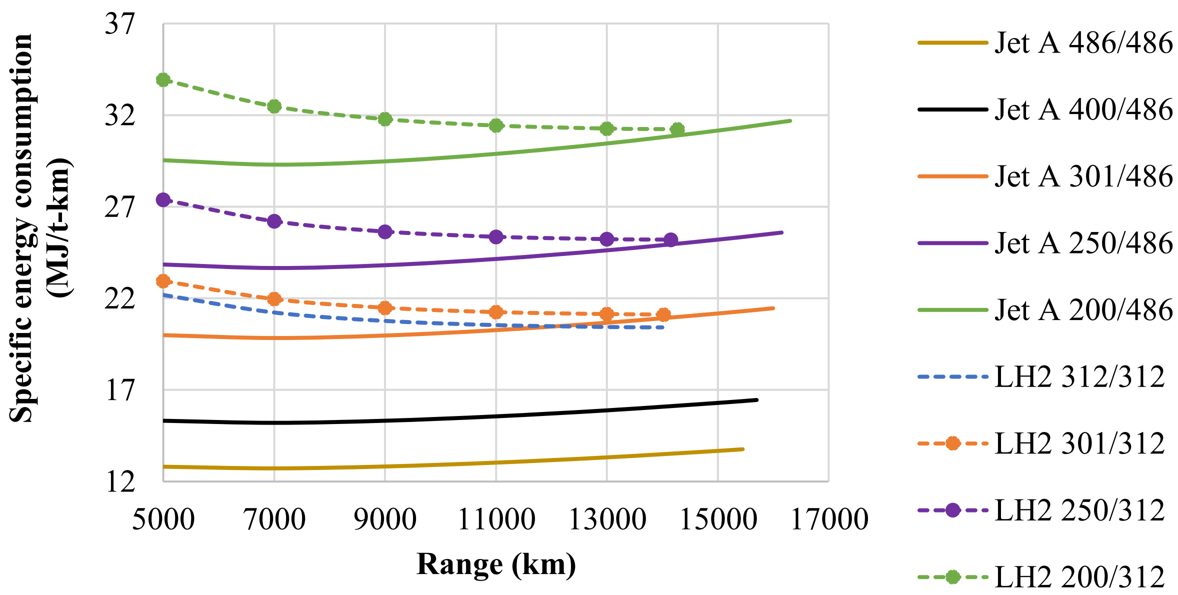

Figure 4. Specific energy consumption comparison of different A380-800 aircraft fuel cases at different range and payload combinations

5.2 Chapter 4-5 integrated results

The integrated results (main findings) of *Chapter 4* and *Chapter 5* are discussed next. Figure 5 provides the pictorial representation of the blended wing body (BWB) aircraft. It is to be noted that Jet-A, 3 cases of LH_2 and 3 cases of SPK aircraft have the same outer BWB frame/skin as illustrated by Figure 5. The aircraft length is estimated to be 35 m and the wetted area is calculated to be 2,132 m^2 (22,944 ft^2) using the SolidWorks 2019 geometric model. The aircraft span is 76.2 m.

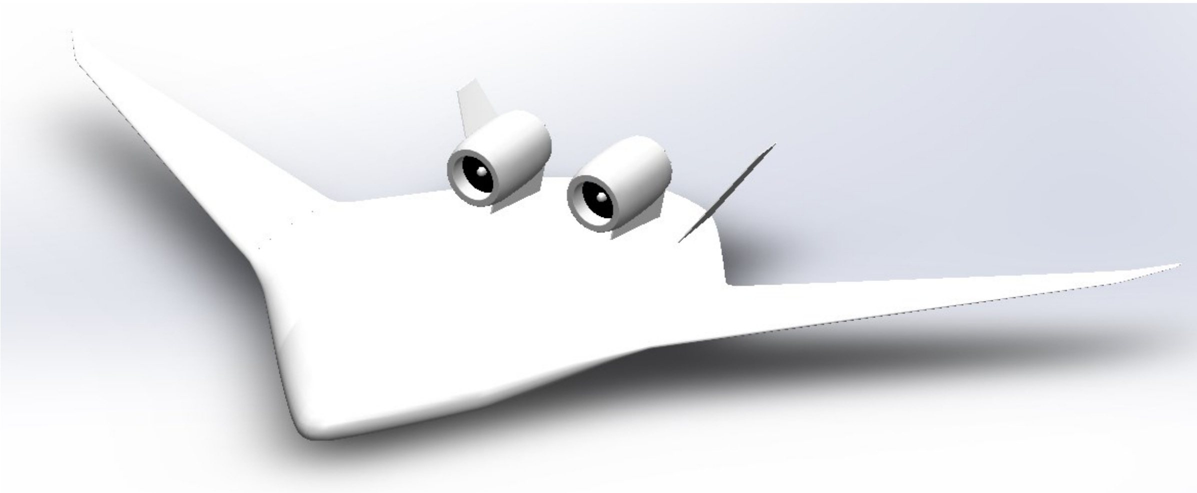

Figure 5. Geometric model of BWB aircraft

It can be observed from Table 4 that the thrust-to-weight (T/W) ratios at sea level static (SLS) and top-of-climb (TOC) for blended wing body (BWB) LH_2 aircraft tend towards the T/W ratios of BWB-GTF Jet-A aircraft at SLS and TOC, from case 1 to case 3 (from the unoptimized to the optimized aircraft). In all three cases of BWB LH_2 aircraft the minimum required T/W at SLS and TOC are met, for a flight to be possible with the same airframe used for Jet-A BWB aircraft (and NASA N+2 BWB-GTF 301 passenger [PAX] aircraft).

The NASA N+2 BWB-GTF 301 PAX (Jet-A) aircraft provides 47% reduction in block fuel energy consumption as compared to Boeing 777-200LR, which is known from Nickol et al. [39] study. The Jet-A BWB aircraft is (1.74%) more efficient as compared to NASA N+2 BWB-GTF 301 PAX (Jet-A). This energy-efficiency improvement is attributable to TSFC improvement, and engine weight reduction that reduces the GTOW.

Referring to Table 4, the Jet-A BWB aircraft provides 47.88% reduction in the block fuel energy consumption as compared to Boeing 777-200LR. The performance of BWB LH_2 aircraft is better than both NASA N+2 BWB-GTF 301 PAX (Jet-A) aircraft and Jet-A BWB aircraft (present study). Case 1, 2 and 3 of BWB LH_2 aircraft provide 51.69%, 52.55% and 53.49% reduction, respectively, in the block fuel energy consumption as compared to Boeing 777-200LR. It is important to note that the LH_2 fuel tank systems fit inside the BWB aircraft primarily because of the consideration of future aircraft technology that significantly reduces the fuel weight and fuel volume to be carried on the aircraft. For example: as discussed above, BWB LH_2 aircraft (all 3 cases) provides energy-efficiency improvement of approximately

50% as compared to Boeing 777-200LR. Had there been no energy efficiency improvement due to the use of aircraft technology, the LH_2 fuel volume required would be approximately twice the volume of fuel required by the current BWB LH_2 aircraft cases. The use of future aircraft technology (engine and airframe) enables successful and efficient use of LH_2 fuel in the aircraft. Compared to the Jet-A BWB aircraft, BWB LH_2 aircraft case 1, 2 and 3 provide 7.31%, 8.97% and 10.76% reduction, respectively, in the block fuel energy consumption. As discussed before, the improvement in the block fuel energy consumption in all 3 cases of BWB LH_2 aircraft is primarily due to the improved TSFCs and due to the aircraft weight reduction. In case 2 and 3 of BWB LH_2 aircraft the reduction in the thrust requirement [leading to engine weight reduction and therefore the reduction of aircraft gross take-off weight (GTOW)] is an additional reason for the improved energy efficiency. It was observed earlier that tube-wing LH_2 aircraft require increase in fuselage length to accommodate LH_2 fuel tanks which negatively impacts L/D and therefore the aircraft energy consumption. This negative impact is not observed for BWB because of their higher internal volume that enable storage of hydrogen tanks.

Table 5 provides the performance comparison of Boeing 777-200 LR and future aircrafts [Jet-A BWB aircraft and BWB SPK aircraft (all 3 cases)] over one flight mission. All three BWB SPK cases have similar performance metrics as that of BWB Jet-A aircraft. BWB 10% SPK is as efficient as BWB Jet-A aircraft, and BWB 50% SPK and BWB 100% SPK cases have insignificant energy efficiency improvement of 0.1% and 0.19% respectively. Additionally, for the 100% SPK BWB aircraft there is an insignificant increase in the OEW (of 19 kg in fuel tank weight) to accommodate slightly less dense (100% SPK) fuel than Jet-A. It is to be noted that 100% SPK is not a drop-in fuel.

Table 4. Performance comparison of Boeing 777-200 LR and future aircrafts [Jet-A BWB aircraft and BWB LH_2 aircraft (all 3 cases)] over one flight mission for 301 PAX

Aircraft range: 13,890 km (Current scenario) [39]		
Aircraft	**Jet A block fuel consumption (kg)**	**Jet A block fuel energy consumption (TJ)**
Boeing 777-200LR	125,705	5.43

Aircraft range: 13,890 km (Future scenarios)						
Parameters	**Units**	**Nickol et al. [39]**	**Jet-A BWB aircraft**	**BWB LH_2 aircraft**		
				Case 1	**Case 2**	**Case 3**
Gross take-off weight (GTOW)	kg	242,441	236,398	195,325	194,177	192,677
Operating empty weight (OEW)	kg	114,907	110,150	117,505	116,790	115,760
GTOW / $GTOW_{NASA}$	-	***1***	***0.975***	***0.806***	***0.801***	***0.795***
Block fuel consumption	kg	66,683	65,523	21,863	21,473	21,049
Block fuel energy	TJ	2.88	2.83	2.62	2.58	2.53
Block fuel energy reduction as compared to Boeing 777-200LR	%	47%	47.88%	51.69%	52.55%	53.49%
Block fuel energy reduction as compared to Jet-A BWB aircraft	%		-	7.31%	8.97%	10.76%
$(L/D)_{cruise}$	-	23.7	23.7	22.51	22.45	22.36
Block fuel weight/total fuel weight	-	0.9	0.9	0.9	0.9	0.9
Thrust to weight ratio (SLS)	-	0.252	0.262	0.318	0.277	0.276
Thrust to weight ratio (TOC)	-	-	0.04851	0.058	0.0487	0.0489

Table 5. Performance comparison of Boeing 777-200 LR and future aircrafts [Jet-A BWB aircraft and BWB SPK aircraft (all 3 cases)] over one flight mission for 301 PAX

Aircraft range: 13,890 km (Current scenario) **[39]**

Aircraft	Jet A block fuel consumption (kg)	Jet A block fuel energy consumption (TJ)
Boeing 777-200LR	125,705	5.43

Aircraft range: 13,890 km (Future scenarios)

Parameters	Units	Nickol et al. [39]	Jet-A BWB aircraft	BWB SPK aircraft		
				10%	50%	100%
Gross take-off weight (GTOW)	kg	242,441	236,398	236,241	235,601	234,798
Operating empty weight (OEW)	kg	114,907	110,150	110,150	110,150	110,169
GTOW / $GTOW_{NASA}$	-	1	0.975	0.974	0.972	0.968
Block fuel consumption	kg	66,683	65,523	65,382	64,805	64,065
Block fuel energy	TJ	2.88	2.83	2.83	2.83	2.82
Block fuel energy reduction as compared to Boeing 777-200LR	%	47%	47.88%	47.89%	47.93%	47.97%
Block fuel energy reduction as compared to Jet-A BWB aircraft	%		-	0.02%	0.095%	0.187%
$(L/D)_{cruise}$	-	23.7	23.7	23.7	23.68	23.656
Block fuel weight/total fuel weight	-	0.9	0.9	0.9	0.9	0.9
Thrust to weight ratio (SLS)	-	0.252	0.262	0.262	0.263	0.264
Thrust to weight ratio (TOC)	-	-	0.04851	0.04854	0.04866	0.04883

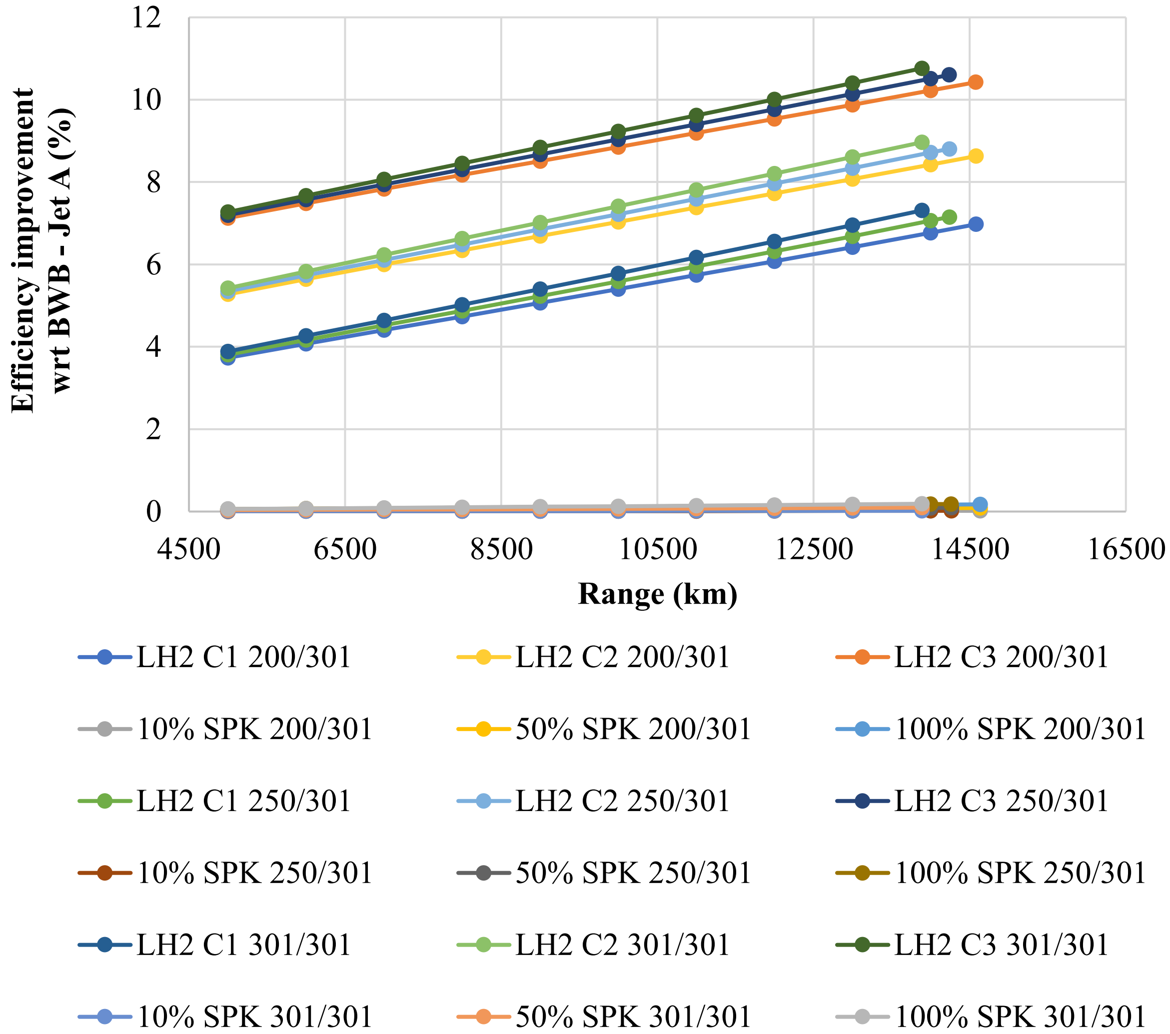

Figure 6. Energy efficiency improvement of BWB powered by different fuel cases as compared to Jet A BWB aircraft for varying range and payload combinations

Figure 6 demonstrates the energy efficiency improvement of BWB powered by different fuel cases as compared to Jet A BWB aircraft for varying range and payload combinations. For a given fuel case, with increasing payload, the maximum range that can be travelled decreases. Additionally, for a given fuel case, increasing the payload improves the energy efficiency compared to a Jet-A BWB aircraft. Moreover, for a given fuel case and payload, the energy efficiency improves with increasing range compared to a Jet-A BWB aircraft. This increase in energy efficiency is observed prominently for all three cases of BWB LH_2 aircraft compared to the Jet-A BWB aircraft. The BWB LH_2 case 3 (C3) aircraft is the most efficient aircraft at all range and payload combinations compared to the Jet-A BWB aircraft.

6. Conclusions

It was observed that only 100% SPK and LH_2 powered aircraft are feasible to fly intercontinental distance as that of the Jet-A aircraft (baseline) within the limit of MTOW. This analysis was done using the conventional tube-wing aircraft architecture. The 100% SPK aircraft provides insignificant energy efficiency improvement. On the other hand LH_2 aircraft consumes more energy than Jet-A aircraft. This is due to the fact that the poor volumetric energy density performance of LH_2 fuel compared to Jet-A and higher OEW due to cryogenic systems requirement, results in longer and heavier fuselage (negative impact on *L/D*). However, for a high energy dense LH_2 fuel there is a net reduction in the aircraft GTOW (order of approximately 20%). Overall, for a tube-wing aircraft it was observed that hydrogen aircraft consumes more energy than the Jet-A aircraft for all range and payload combinations considered in this research.

The SPK and LH_2 fuel were considered for further analysis in a future aircraft technology i.e. a BWB aircraft powered by ultra-high bypass ratio turbofan engines. Overall, the advanced aircraft has ~50% improved energy efficiency as compared to the Boeing 777-200LR aircraft. Using different blends and 100% SPK fuel in BWB aircraft improves the energy efficiency insignificantly as compared to Jet A BWB for all range and payload combinations. Using LH_2 fuel in the BWB improves the energy efficiency by 4-11% as compared to the Jet A BWB aircraft for different range-payload combinations. For the tube-wing LH_2 aircraft it was observed there is an increase in fuselage length to accommodate LH_2 fuel tanks which negatively impacts L/D and therefore the aircraft energy consumption. This negative impact is not observed for the future aircraft technology/BWB because of their higher internal volume that enable storage of hydrogen tanks. The use of future BWB aircraft technology (engine and airframe) enables successful and efficient use of LH_2 fuel in the aircraft.

7. Proposed thesis structure

Based on the contents of thesis chapters discussed in sub-section 4, the table of contents of the thesis is as follows:

8. Plan

8.1 Publication plan

The research efforts of Chapter 3 could potentially contribute as a standalone journal article (#1). The integrated research efforts of Chapter 4 and Chapter 5 could potentially contribute as a journal article (#2). The research efforts of Chapter 6 could potentially contribute as a standalone journal article (#3). The respective titles of the three potential journal articles are included next in the completion plan.

8.2 Completion plan

<table>
<tr><th colspan="2" rowspan="2">Activities*</th><th colspan="4">2020</th><th colspan="4">2021</th></tr>
<tr><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th></tr>
<tr><td rowspan="9">Year 3</td><td>Chapter 1-5 draft submitted to supervisors for review</td><td bgcolor="gray"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>LSR report draft</td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>LSR</td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td></td><td></td><td></td></tr>
<tr><td>Revision of Ch 1-5 based on review comments</td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Use-phase emissions calculation for aircraft powered by different fuel</td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td></td><td></td><td></td></tr>
<tr><td>Life-cycle impacts comparison for aircraft powered by different fuel</td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td></tr>
<tr><td>Journal article 1 (Proposed topic: Comparative fuel performance evaluation of different alternative fuels for long-range subsonic aircraft)</td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td></td><td></td><td></td></tr>
<tr><td>Journal article 2 (Proposed topic: Conceptual design-sizing of long-range subsonic blended wing body aircraft with comparative fuel performance: Jet-A v/s synthetic fuel v/s liquid hydrogen)</td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td></td><td></td></tr>
<tr><td>Journal article 3 (Evaluating the potential of advanced technology and alternative fuels towards mitigating aircraft’s social and environmental impacts) using fuel life-cycle analysis</td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td></tr>
<tr><td colspan="10">* Conference travel/submission not included due to travel uncertainty</td></tr>
</table>

Activities*	Year 3			Year 4					
	2021								2022
	Apr-May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan
Ch 6-7 drafting									
Ch 1-7 revisit for coherent writing									
Submit the first draft - supervisor review and feedback									
Supervisor review									
Viva examination									
Thesis correction									
Buffer delayed									
* Conference travel/submission not included due to travel uncertainty									

More information:

First author’s other research work can be found in [40]–[70].

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