

CRANFIELD UNIVERSITY

SARATH SASI

Advanced Turbofan Architectures with Alternative Fuels

School of Aerospace, Transport and Manufacturing
Aerospace Engineering

PhD

Academic Year: 2020 - 2023

Supervisor: Dr. Ioannis Roumeliotis
Associate Supervisor: Dr. Christos Mourouzidis
October 2023

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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD

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ABSTRACT

Aviation at present is required to reach net zero carbon emissions by 2050. An effective method to reduce aviation's carbon footprint with immediate effect is to switch to alternative fuels. This thesis explores novel alternative fuels that could be used for future civil aviation and investigates their impacts on turbofan design to aid in research and development of future turbofan engines operating with alternative fuels. Investigations have been conducted in a systematic manner by adopting an appropriate methodology to answer the identified research questions. The proposed novel alternative fuels for civil aviation consists of seven fuels namely Hydrogen, Ammonia, Methane, DME, Butane, Butanol and Octane with SAF as an additional drop in fuel.

The potential impacts and design opportunities for turbofan engines when operating with the proposed alternative fuels is highlighted through a preliminary turbofan design space exploration study. Maximum impacts in the design space are observed for zero carbon fuels Hydrogen and Ammonia. They offer 3% and 6% ESFC benefits respectively against kerosene with up to 20K and 40K peak cycle temperature reduction at take-off.

The potential impacts on turbofan engine size and weight when operated by alternative fuels is brought to light through this research. Maximum impacts on engine size, weight and temperature are observed for zero carbon fuels Hydrogen and Ammonia. The maximum benefits in weight and take-off temperatures are 20% and 164K respectively for Ammonia cycles whereas for Hydrogen cycles, it is 6% and 64K respectively.

The potential role that aircraft mission range can play in affecting the turbofan engines powered by alternative fuels is showcased in this thesis. Hydrogen SMR and LR aircraft leads to BPR increment up to 31.7% and 61.5% respectively considering a retrofitted style Hydrogen aircraft application.

The potential role of various fuel conditioning strategies and thermal power requirements in affecting turbofan designs highlighted through this research work indicates fuel conditioning to be a major design driver for future turbofan engines operating with alternative fuels. For the investigated LR thrust class application, Hydrogen, Methane and Ammonia requires up to 3 MW, 2.28 MW and 2.2 MW of thermal power to condition the fuel respectively.

Finally, the thesis explores the feasibility of utilising Ammonia as a Hydrogen carrier in aviation and highlights certain challenges at mission level and turbofan design implications. For the investigated LR thrust class application, the amount of thermal power required to crack Ammonia into Hydrogen for the Hydrogen turbofan engines can be up to 25 MW which is interestingly an order of magnitude higher than the fuel conditioning requirements of Hydrogen, Methane and Ammonia.

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LIST OF ABBREVIATIONS

ACARE	Advisory Council for Aeronautics Research in Europe
Al	Aluminium
Ar	Argon
ASTM	American Society for Testing and Materials
B	Boron
B ₅ H ₉	Pentaborane
BPR	Bypass Ratio
CEA	Chemical Equilibrium with Applications
CH ₃ NO ₂	Nitromethane
CO ₂	Carbon di oxide
C _p	Specific heat capacity at constant pressure
CSPK	Camelina Synthesized Paraffinic Kerosene
cSt	Centistokes
CTL	Coal To Liquid
DEE	DiEthylEther
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DME	DiMethylEther
EI	Emission Index
EIS	Entry Into Service
EOR	End Of Runway
ERF	Effective Radiative Forcing
ESFC	Energy Specific Fuel Consumption
EU	European Union
FAR	Fuel to Air Ratio by mass
FLOPS	Flight Optimisation System
FPR	Fan Pressure Ratio
GI	Gravimetric Index
GTL	Gas To Liquid
GWP	Global Warming Potential
H/C	Hydrogen – Carbon atomic ratio
H ₂ O	Water vapour

HEFA-SPK	Hydrotreated Esters and Fatty Acids – Synthesized Paraffinic Kerosene
HEX	Heat Exchanger
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPC	Intermediate Pressure Compressor
IPCC	International Panel on Climate Change
IPK	Iso Paraffinic Kerosene
IPT	Intermediate Pressure Turbine
ISA	International Standard Atmosphere
JSPK	Jatropha Synthesized Paraffinic Kerosene
KE	Kerosene
L + fuel name	Liquified form of that fuel (Liquid state)
LB ₂ H ₆	Liquid Diborane
LCH ₄ /CH ₄	Liquid Methane / Methane
LED	Light Emitting Diode
LFL	Lean Flammability Limit
LH ₂ /HY	Liquid Hydrogen / Hydrogen
LHV	Lower Heating Value
LNG	Liquified Natural Gas
LNH ₃ /NH ₃	Liquid Ammonia / Ammonia
LPG	Liquified Petroleum Gas
LPT	Low Pressure Turbine
LR	Long Range
LTAG	Long Term Aspirational Goal
M _a	Axial Mach number
MCL	Maximum Climb
MCR	Mid-Cruise
Mg	Magnesium
MTO	Maximum Take-Off
MTOW	Maximum Take-off Weight

N ₂	Nitrogen
N ₂ H ₄	Hydrazine
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NGV	Nozzle Guide Vanes
nm	Nautical Mile
NO _x	Oxides of Nitrogen
NTU	Number of Transfer Units
O ₂	Oxygen
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
OPR	Overall Pressure Ratio
P30	High pressure compressor exit pressure
PAX	Passengers
PR	Pressure Ratio
PROOSIS	Propulsion Object Oriented Simulation System
R	Universal gas constant
RFL	Rich Flammability Limit
SAF	Sustainable Aviation Fuel
SFC	Specific Fuel Consumption
SLS	Sea Level Static
SMR	Short Medium Range
SPK	Synthesized Paraffinic Kerosene
T30	High pressure compressor exit temperature
T40	Combustor outlet temperature
T41	Turbine rotor entry temperature
TET	Turbine Entry Temperature
TOC	Top Of Climb
TOW	Take-Off Weight
U	Blade linear velocity
UHBR	Ultra High Bypass Ratio
V	Flow velocity
W	Inlet Mass flowrate

WAR	Water to Air Ratio
W_{core}	Core inlet mass flow rate
wt	Weight
X	Mole fraction
ϵ_{HEX}	Heat exchanger effectiveness
η_{is}	Isentropic efficiency
η_{poly}	Polytropic efficiency
γ	Gamma (Ratio of heat capacities at constant pressure to constant volume)
η_{prop}	Propulsive Efficiency
η_{therm}	Thermal Efficiency

1 INTRODUCTION

1.1 Background

Aviation industry is required to cut down its carbon emissions to reduce global warming. Various targets set in the past to present around the world showcases the continuous efforts of the industry to be more environmentally friendly. In 2011, ACARE set goals for the reduction of aviation CO₂ emissions by 75% and NO_x emissions by 90% relative to the year 2000 values [1]. In 2018, the IPCC report 'Global Warming of 1.5°C' indicated that by 2050, global CO₂ emissions must reduce to net zero to avoid unrecoverable climate change [2]. In 2019, the EU commission implemented the Green Deal 2050 aiming for net zero emissions by 2050 across all industries and sectors including aviation [3]. In the UK, Jet Zero Council launched in 2020 aiming to deliver net zero aviation by 2050 [4] with an ambitious goal of achieving the first zero-emission commercial transatlantic passenger flight by 2025.

In 2021, IATA member airlines agreed to transition their operations to net zero carbon emissions by 2050 to limit global warming to 1.5°C [5].



Figure 1-1: Fly Net Zero commitment by IATA member airlines [5]

In 2022, ICAO adopted LTAG (Long Term global Aspirational Goal) to achieve net zero carbon emissions for international aviation by 2050 [6].



Figure 1-2: ICAO LTAG commitment for international aviation [6]

In September 2020, AIRBUS announced Hydrogen aircraft concepts as shown in Figure 1-3 in response to tackle the emissions impact and achieve sustainable aviation.



Figure 1-3: AIRBUS ZEROe concepts using liquid Hydrogen [7]

The air traffic is forecasted to grow at the rate of 3.6% per annum for the next 20 years (2023-2042) as reported by AIRBUS global market forecast [8]. The growth in air traffic is a positive sign when thinking in terms of economic development and prosperity. However, it can be concerning when its thought from an environmental point of view since increasing air traffic suggests that the fossil fuel energy consumption and its related pollution levels will rise in the future. This will lead to aviation being tagged as 'non-sustainable'. To make aviation more sustainable in the future and help address the recent net zero emissions target, alternative fuels are investigated in this PhD project.

The EU commission has listed potential alternative fuels for aviation which includes Bio-jet fuels, Electro-jet fuels, liquefied Methane, Hydrogen and Ammonia [9]. Although not yet for aviation, it's interesting that the United States

department of energy has listed Biobutanol, DME, Methanol, Renewable Gasoline, and Ammonia as emerging alternative fuels [10].

When the emissions contributed from aircraft class are considered namely regional, narrowbody and widebody, narrowbody constituted 51% of total CO₂ emissions in 2019. This is followed by 42% for the widebody and only 7% for the regional passenger aircraft [11]. As a result, to make a significant and immediate impact on the carbon emissions, alternative fuels must be applied to aircraft classes that's capable of transporting larger passengers.

Today, the propulsion system that the narrowbody and widebody utilises, is the turbofan engine. Hence, it is imperative that the impact of alternative fuels on turbofan engines be investigated for aiding in the design and development of next generation of turbofan engines operating on alternative fuels.

1.2 Research scope

The research focuses on the application of alternative fuels to civil turbofan engines. The general scope of the project is to explore the civil turbofan engine cycle design space for novel fuel types. The target area of the application is in the range of thrust class greater than 130 kN SLS. As such the project was divided into 3 phases that included mainly:

1. Phase 1: Selection of candidate fuels for further study in the project through a systematic selection process.
2. Phase 2: Conventional turbofan cycle design evaluations using the selected candidate fuels.
3. Phase 3: Advanced cycle design evaluations using the candidate fuels as the cold source for heat exchange.

1.3 Main aim & objectives

The main aim of this research is to explore the impacts of novel alternative fuels on turbofan engine designs.

The objectives to accomplish this goal are as follows:

1. Identify alternative fuels in a systematic manner for further investigations in the research. The selection of novel fuels must be performed for aviation application purposes.
2. Demonstrate the turbofan engine cycle design space for the identified fuels. The evaluation must be performed for the same thrust requirements enabling fair evaluation of the design impacts.
3. Quantify the impact of the identified fuels on turbofan engine weights. Demonstrate the same in terms of turbofan size. All the assessments must be for the same thrust requirements.
4. Establish the design opportunities for turbofan engines powered by the identified fuels considering their practical implementation for aviation through an aircraft mission assessment.
5. Determine the fuel conditioning requirements for the identified fuels and investigate the impact of fuel conditioning on turbofan cycle design.

1.4 Research contribution and industrial relevance

This research has brought to light significant knowledge about the impacts on turbofan engine when transitioning to novel alternative fuels for civil aviation. Consequently, the novel contributions to knowledge and the associated industrial relevance to influence the decision making for future design and development of turbofan engines operating with alternative fuels, are as follows:

- ❖ Preliminary turbofan design space exploration study identified potential turbofan design possibilities when using novel alternative fuels. The study provides new knowledge on novel fuels (Octane, Butane, Butanol, DME, Methane, Hydrogen, Ammonia) applied to turbofan design space. The TURBOMATCH software is updated with these fuels. With this study, it came to the realisation that there exists possibility to have both thermally

efficient turbofan cycles and lower core operating temperatures at the same time. This is particularly important since different fuels can lead to different levels of NO_x emission characteristics and hence, the lower core operating temperature cycle capability allows the designer to negotiate for NO_x emissions if required, without penalising thermal efficiency.

- ❖ Turbofan engine size and weight estimation phase of the study drove the updating of the ATLAS software to handle novel alternative fuels. The size and weight estimation study identified the weight impact various cycle design strategies could offer when operating with alternative fuels. This knowledge is important and could act as a lever to negotiate for any additional fuel system weights that maybe needed to use these fuels in the future.
- ❖ Integrated engine aircraft performance phase of the study enabled the realisation of the potential role aircraft mission range can play in the core resizing opportunities for turbofan engines powered by alternative fuels. Currently, with the aviation industry aiming to certify the use of 100% blends of SAF in pursuit of net zero targets, the study showcases that 100% SAF blends offer opportunities for redesign of turbofan engines. With the industry aggressively putting efforts to bring Hydrogen powered aircraft into mainstream aviation, the study highlighted the importance to increase the fan size (reduce specific thrust) to improve fuel burn of Hydrogen aircraft regardless of the cryogenic tank technology. The cryogenic tank technology is found to be one of the major design drivers for future Hydrogen powered turbofan engines.
- ❖ The fuel conditioning assessment provided insights into the potential working state of the novel alternative fuels under the turbofan operating conditions. The study also identified that other than Hydrogen, Methane and Ammonia, heating the rest of the alternative fuels to required conditions can be done in a similar fashion like conventional Jet A. When

the engine is required to provide energy/power to condition the fuel, the study highlighted the potential implication of several strategies on cycle design and thermal efficiency which can be of value to the industrial partner. It also indicates that fuel conditioning using the engines can be another major design driver for the future turbofan engines using Hydrogen, Methane and Ammonia. The study throws light to the fact that even after using the turbofan engines as energy/power source to condition the fuel, the design still resulted in smaller compact cores. The pursuit of improving the range performance of Ammonia aircraft using the Hydrogen contained it led to the realisation of significant thermal energy requirements, impacts on the turbofan engine and challenges at mission level. This hints that it may very well be worth to go ahead with an aircraft using Ammonia as fuel without any cracking as compared to one that uses Hydrogen that's cracked from Ammonia.

Some of the outcomes of this research have resulted in a conference publication titled '*Impacts Of Alternative Aviation Fuels On Engine Cycle Design And Aircraft Mission Capability*' at the ASME Turbo Expo, USA, 2023. DOI: <https://doi.org/10.1115/GT2023-101114>

Based on this thesis research, a research article titled '*Ammonia For Civil Aviation*' has been submitted to the International Journal of Hydrogen Energy.

1.5 Thesis structure

The main chapters of the thesis have been organised in the following order:

- Chapter 2 provides the reader an overview of the current state-of-the-art studies on alternative fuels for aviation. The chapter mainly aims to highlight the research gaps which this thesis aims to tackle.

- Chapter 3 details the reader about the methods with which the technical investigations proceeded. It provides an overview of the general methodology adopted to assess the impacts of alternative fuels on turbofan engines. First, the rationale and methods for the generation of candidate list of alternative fuels is explained. Second, the fuels integration into TURBOMATCH [12] software is discussed followed by the methods adopted to perform the engine cycle design space exploration. Third, the rationale and methods adopted to introduce novel fuels into ATLAS [13] software is described along with the 3-point turbofan cycle design methodology utilised for investigating the test cases where applicable. Fourth, the methodology for the integrated engine-aircraft assessment is described. The methodology for the mission capability assessment is discussed along with the approach used to assess the environmental impact. Finally, the methods adopted to determine the fuel conditioning requirements is discussed along with the various techniques to condition the fuel using the engine as the power/energy source. The details about the methodology to perform cycle design with fuel conditioning is also described.
- Chapter 4 establishes the main results of the work which are discussed and analysed in detail.
- Chapter 5 provides a summary of the research work with key learnings from the findings. The chapter ends with future work as a list of recommendations.

2 LITERATURE REVIEW

2.1 Theoretical background

2.1.1 Turbofan engine cycle design and performance

Since this project focuses on the turbofan engine cycle design for alternative fuels, it is important to provide the reader, a brief overview of the importance of cycle design and performance. This is because engine design basically starts with a cycle design. There are several textbooks that discuss gas turbine design and performance at a fundamental level. The very famous textbooks of these include the ones by Saravanamuttoo [14] and Walsh & Fletcher [15]. On aero engine optimisation, Guha [16] highlights important aspects relevant to civil high bypass turbofan engines with regards to minimising SFC i.e. optimised design. He points out that there exists one FPR for the optimum jet velocities ratio (bypass cold velocity to core hot velocity) to minimise the SFC for a given BPR, T40, OPR and specific thrust when it comes to civil turbofan engines.

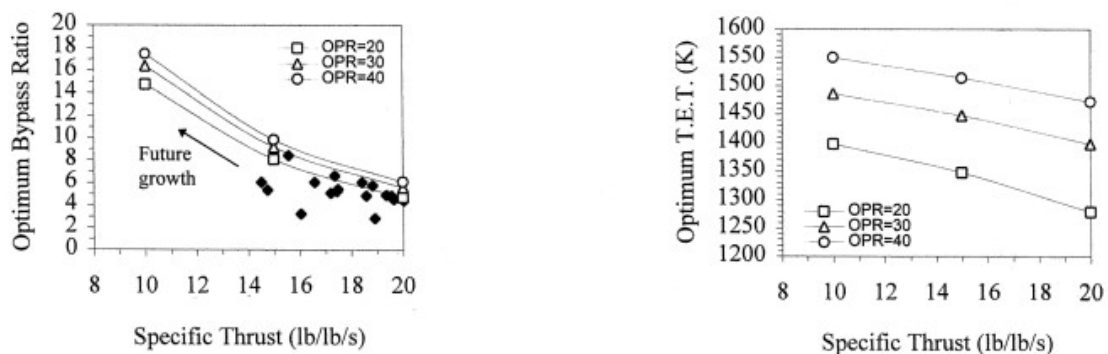


Figure 2-1: Trends of BPR and T40 with OPR and specific thrust for a single operating point at cruise using kerosene fuel [16].

From the right-hand side image of Figure 2-1, it is seen that as T40 increase for a given OPR, the specific thrust decrease. This is counterintuitive since one will expect the specific thrust to increase. An important variable that drives this trend is the BPR which is shown on the left-hand side image. It is observed that as specific thrust is reduced, the optimum BPR and T40 increase. These numbers further increase with increase in OPR. It is also worth noting that the FPR is optimised at every point. For civil turbofan engines, the trend is moving towards

lower specific thrust designs with larger fan diameters and higher OPRs. This can be confirmed by the engine specification noted for the recent state of the art Rolls-Royce UltraFan™ turbofan demonstrator [17] having a fan size of 3.5m and OPR~70.

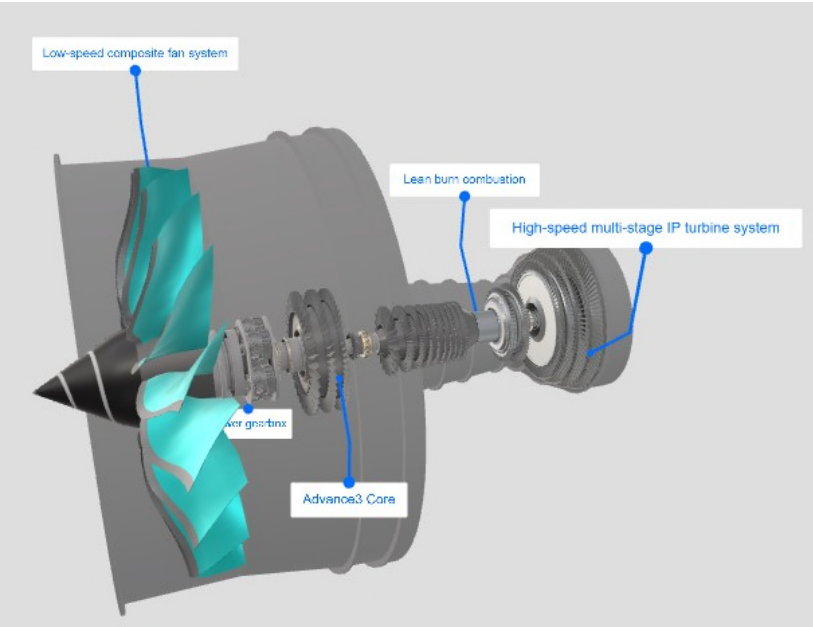


Figure 2-2: Rolls Royce UltraFan™ representation [18]

Figure 2-2 showcases the large composite based fan, a power gearbox behind it, a compression system with pressure ratio split leaning towards the HPC side and with multistage HP and IP turbines.

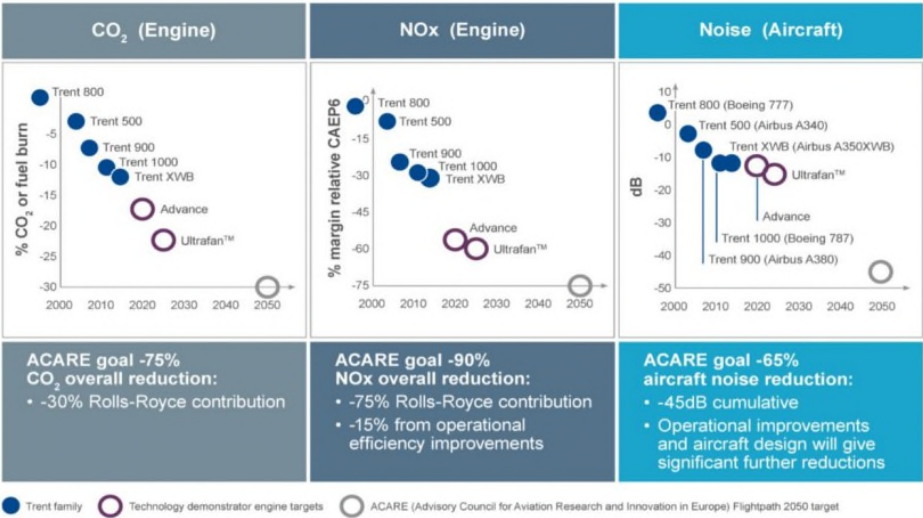


Figure 2-3: Improvement targets for UltraFan™ compared to Trent engines [19]

Figure 2-3 showcases the 25% fuel burn improvement target among others (NO_x and Noise) for the UltraFan™ engine against a first generation Rolls Royce Trent engine, based on the CleanSky2 technology evaluator technical report.

Civil turbofan engine cycles are designed to operate efficiently on the most critical operating points during the flight mission. These points are cruise, top of climb and take-off. This has been described clearly in the works of Mourouzidis [20] where he designs turbofan cycles based on these operating points that's targeted for a kerosene based UltraFan™ application.

Figure 2-4 from his works demonstrates the cycle design process based on these 3 operating points.

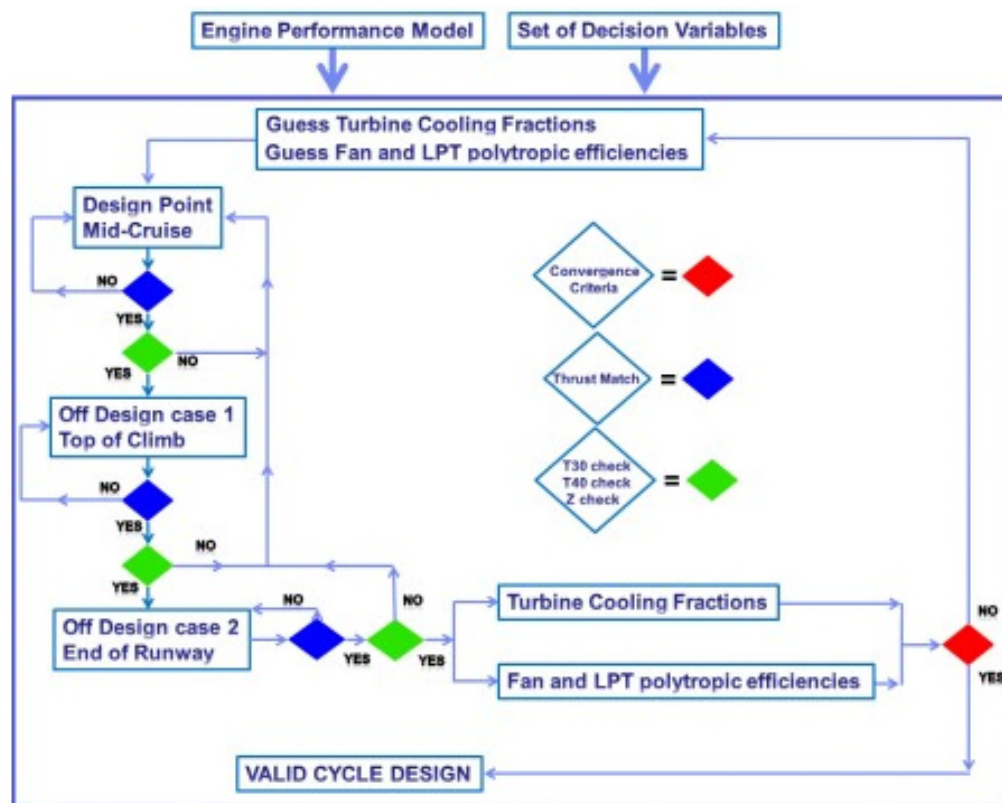


Figure 2-4: Cycle design process for UltraFan™ based application [20]

The mid-cruise is the design point of the turbofan cycle, and the other critical operating points top of climb and take-off (end of runway) are checked for satisfactory performance before selecting the turbofan cycle.

The fan is sized based on the top of climb mass flows as this operating point usually has the highest non-dimensional speeds, pressure ratios and flow capacities, and as a result, if more thrust is desired, then the fan size must be increased accordingly. Figure 2-5 from the works of Kyritsis [21] demonstrates this for a 2-spool turbofan engine.

It demonstrates the running lines from sea level static to end of runway operating point. It also demonstrates the running lines for constant altitude Mach flight which has two operating points top of climb and mid cruise. The top of climb operating point is at the end of the fan characteristic map denoting the maximum fan inlet Mach number. Note that the x-axis uses Mach number instead of flow capacity $\frac{W\sqrt{T}}{AP}$ to represent mass flow for a given engine inlet area.

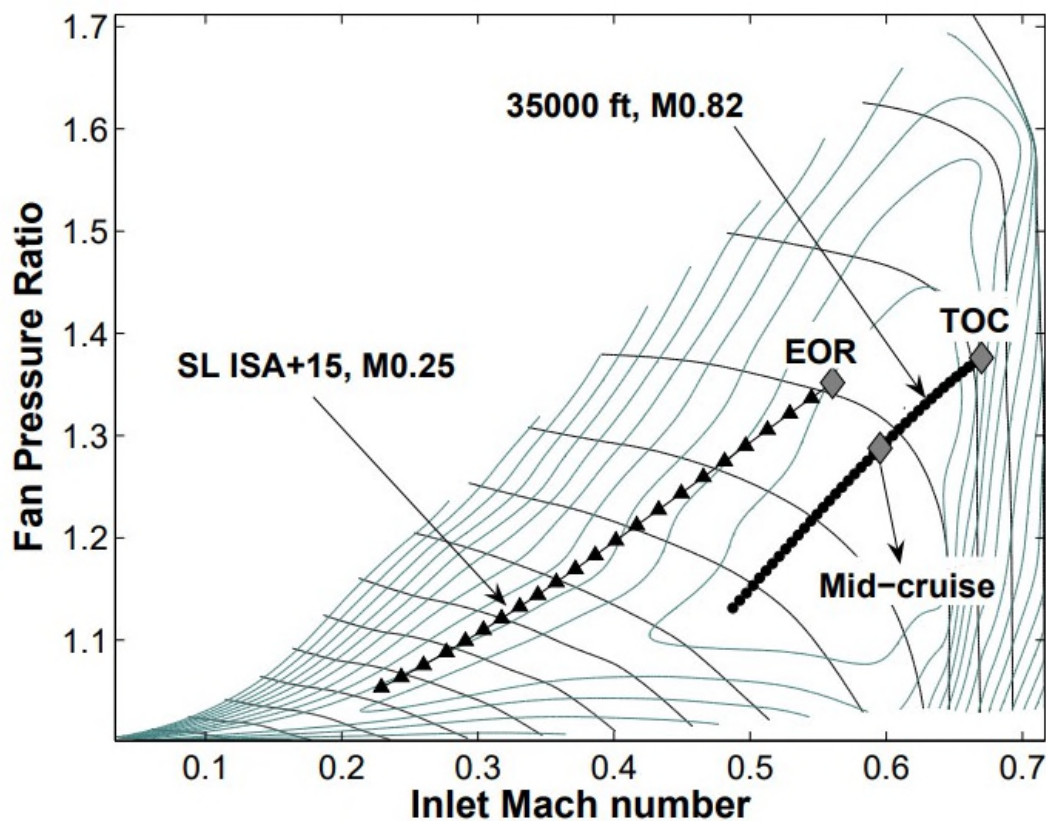


Figure 2-5: Fan operating points for a 2-spool turbofan engine [21]

As this PhD project deals with alternative fuels, the fluid properties are an important aspect for turbofan performance since combusting alternative fuels with

different chemistry leads to working fluids with different thermofluidic properties into the hot core section.

Sethi et al [22] and Kyprianidis et al ([23], [24]) highlight and discuss the importance of thermodynamic fluid properties modelling for gas turbine performance calculations. Their works demonstrate the uncertainty introduced by different fluid thermodynamic models and consequently, on the performance calculations. Sethi [25] has demonstrated the different fluid thermodynamic properties due the combustion of different fuels for the development of PROOSIS software.

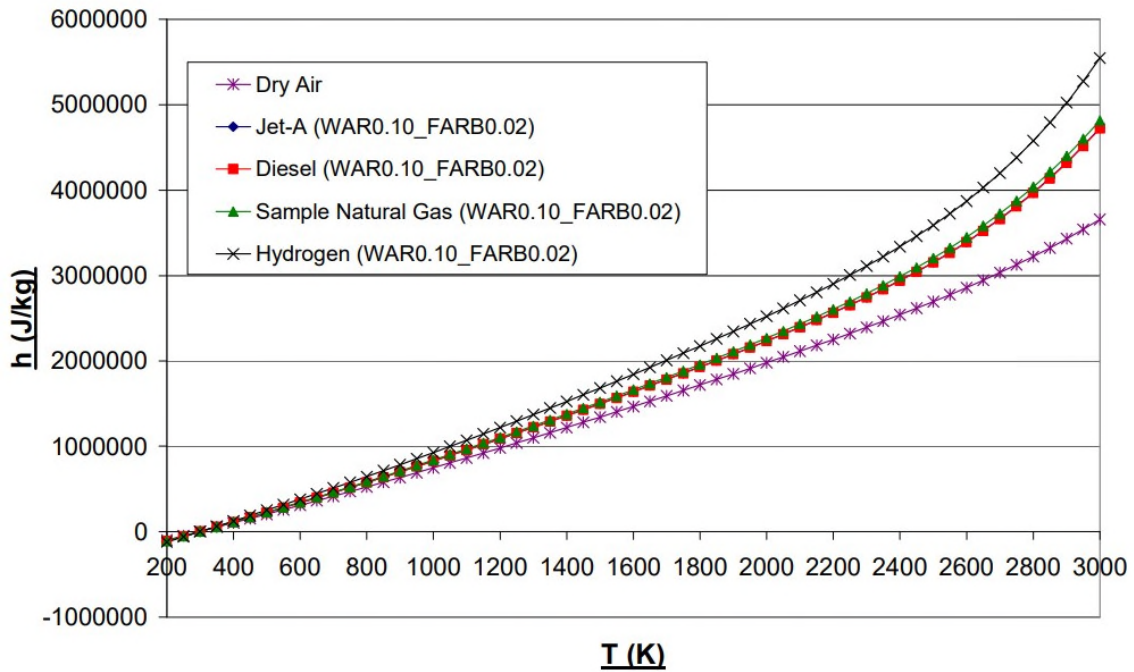


Figure 2-6: Variation of specific enthalpy of combustion products with temperature for different fuels in PROOSIS [25]

It is observed that the specific enthalpy of the working fluid is different for different fuels and the trends diverge for increasing temperatures. This is just a demonstration of a specific case for fixed fuel-air and water-ratio. Other fluid property effects are also demonstrated in the above reference such as entropy function, gamma, heat capacity, gas constant and dynamic viscosity.

Although not discussing about turbofan engines, Burnes and Camou [26] interestingly points out that for industrial gas turbine engines, higher hydrogen-carbon ratio hydrocarbon fuels leads to higher power output and thermal efficiency at full load as shown in Figure 2-7.

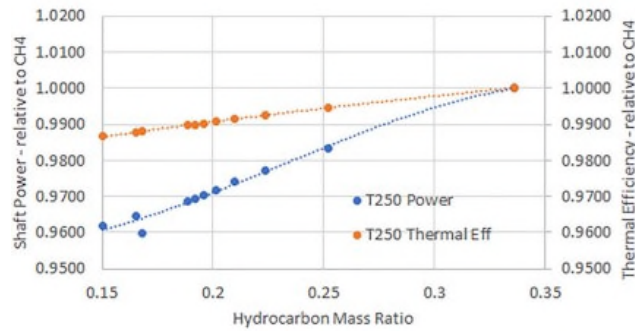


Figure 2-7: Effect of Hydrogen-carbon mass ratio with Methane fuel as baseline [26]

2.2 Alternative fuels for civil aviation

Lok et al [27] assess alternative fuels for aviation applied to a conventional tube and wing aircraft configuration with turbofan engines. The aircraft are designed for mission ranges from 2000 nm to 8500 nm. The alternative fuels investigated include Hydrogen, Natural Gas, Ammonia, Biofuel, and conventional Jet fuel.

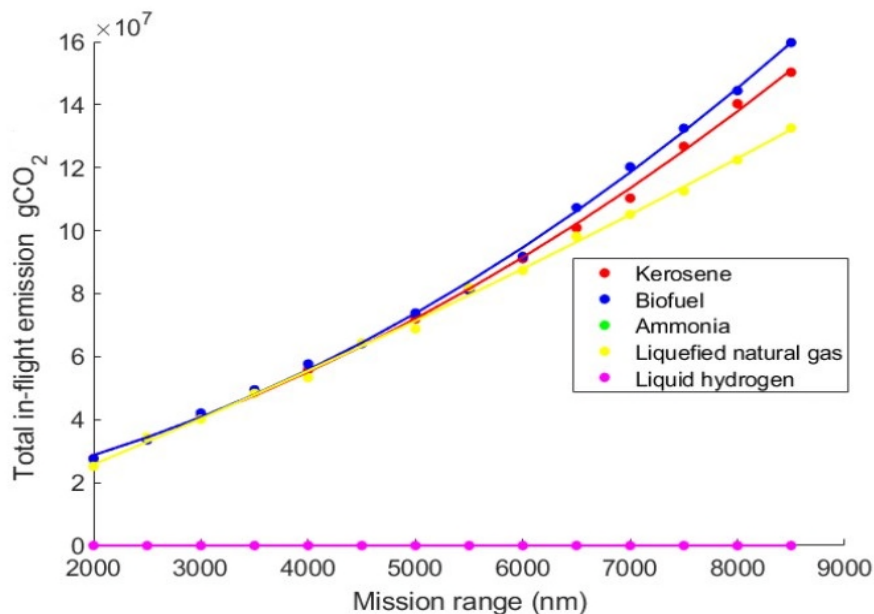


Figure 2-8: Total inflight CO₂ emissions for the sized aircraft [27]

Figure 2-8 presents the inflight emissions of the sized aircraft for these different ranges. It demonstrates that except for Hydrogen and Ammonia, the other alternative fuels emit CO₂. Natural Gas provides reduced carbon emissions relative to other hydrocarbon based fuels. It's interesting to note that the biofuel emits more carbon compared to the traditional kerosene based Jet fuel at longer ranges. This is due to the type of biofuel used that has a higher density and reduced LHV compared to kerosene. However, the turbofan engines used for the study are rubberised, meaning they are simply scaled to satisfy the aircraft requirements and does not provide more details on the turbofan engine cycle.

Otto et al ([28], [29]) performs a feasibility study of Ammonia as an aircraft fuel. It is assessed for an aircraft application of Boeing 737-8 powered by CFM LEAP-1B turbofan engines. It highlights the non-coking properties of Ammonia fuel, which enables it to be used as a heat sink for compressor intercooling. Ammonia is used as a Hydrogen carrier, where the Ammonia that's carried in the wings as a liquid is converted into Hydrogen before burning in the combustor using a catalytic converter. The comparable life cycle emissions of Ammonia and Hydrogen that includes combustion are highlighted in their works. However, a top-level mission assessment is missing without identifying any engine cycle design opportunities when operating with Hydrogen.

Jayant and Dan [30] assessed a turboprop and a narrowbody Hydrogen powered aircraft for EIS 2035. They reported that Hydrogen powered aircraft could contribute to aviation's 2050 climate goals depending on the adoption of the Hydrogen powered aircraft into the fleets. The study redesigns the aircraft to accommodate the Hydrogen fuel. Two cryogenic tank gravimetric efficiencies used for the assessments are 20% and 35%. The heavier tank aircraft (20% GI) led to higher energy consumption compared to the lighter tank aircraft (35% GI) for both category aircraft. However, the study scales the Hydrogen turbofan engines according to the aircraft thrust requirements, while maintaining the same thermodynamic cycle failing to explore opportunities for turbofan designs. It is also worth noting that the ESFC is kept the same as that of the kerosene variant.

The UK government initiative FlyZero project concluded that green liquid Hydrogen is the most viable zero-carbon emission fuel ([31], [32]). They have assessed Hydrogen powered aircraft concepts for EIS 2030 that includes regional, narrowbody and a mid-size category segment aircraft. Although the turbofan design characteristics in terms of BPR and fan size are provided for the narrowbody and mid-size category Hydrogen powered concepts, more details are not quantified to draw conclusions regarding the impact on the turbofan designs. Roadmaps are provided for technological advances to be made in the field Hydrogen powered gas turbines through to the year 2050.

Troeltsch et al [33] showcase a Hydrogen powered long range concept aircraft Hyliner 2.0 and compare it to the contemporary kerosene variant of EIS 2040. A tube and wing configuration using turbofan engines are used in the study. It demonstrates that Hydrogen variant provides significant emission benefits with 9% higher mission energy consumption. It employs advanced wing technologies and high aspect ratio wings but does not investigate the possibilities for the turbofan engines. This is because the geared turbofans used in the study are scaled for the thrust requirements of the concept aircraft.

Huete et al [34] propose a family of large airliners powered by Hydrogen as a technology introducer to decarbonise aviation in the near term. These airliners use turbofan engines as their propulsion system since they are first generation. It includes aircraft in the category of medium range, long range and extended range options covering distance from 3300 to 5500 nm. The turbofan engine is modelled after a 3-spool engine architecture. The cryogenic tank gravimetric efficiency of 45% is used for the assessments of the three concepts. Turbofan engines operating with Hydrogen are used for the concept generation and are designed based on the aircraft concept that requires the highest thrust. However, these are simply derated for the other concept variants that require less thrust and do not quantify/provide the turbofan cycle performance details to gain an understanding of the engine cycle design.

Rompokos et al [35] assessed LNG as an alternative aviation fuel and found environmental benefits in terms of CO₂ emissions reduction of up to 16% but

increased mission energy consumption per passenger mile due to the increased weight and drag of the aircraft. The aircraft is redesigned with LNG fuel for a distance of 2855 nm as design mission. It is modelled after a Boeing 737-800 style baseline airframe. Although the aircraft sizing is done using the turbofan engines operating with LNG fuel, no engine performance/design quantification is reported in the study to gain an understanding of LNG impact on turbofan design/performance.

Hoelzen et al [36] assess the economic aspects for aviation when green Hydrogen is used as an alternative fuel to reduce the climate impact. Economic evaluations are performed considering aircraft costs and uncertainties in fuel cost due to Hydrogen fuel infrastructure required. A short range and a medium range aircraft using Hydrogen turbofan engines are modelled to enable their assessments for EIS 2035. It highlights that the uncertainties in the economics of Hydrogen powered aviation are not only influenced by Hydrogen aircraft technology but also the setup of a green Hydrogen infrastructure and the resulting Hydrogen fuel costs. Given the fact that study is economical in nature, it is worth noting that no quantification corresponding to the Hydrogen powered turbofan cycles are provided apart from the cruise SFC and its overall efficiency.

Lammen et al [37] assess 3 categories of aircraft powered by Hydrogen fuel to reduce the emissions. These are regional, single aisle and twin aisle aircraft targeted for EIS 2035 onwards. The regional configuration is powered by a fuel cell. The single aisle variant has two configurations. One using Hydrogen burning turbofan and another using fuel cell power hybridising the turbofan. The twin aisle configuration is powered by a Hydrogen turbofan. The tank gravimetric efficiency for these aircraft categories were 30%, 35% and 37% respectively. When observing the variants utilising only turbofan engines, that is the single and twin aisle, the modelled engines are simply a switch from kerosene to Hydrogen accounting for fuel flow differences without any thermal efficiency changes. This leads to no knowledge of the impacts of Hydrogen fuel on turbofan cycle design.

Karpuk and Elham [38] assessed medium range Hydrogen powered aircraft against a contemporary kerosene variant employing future airframe technology

and ultra-high bypass turbofan engines. It is an aircraft conceptual design study. Interestingly, an over the wing turbofan configuration is used for the assessment as shown in Figure 2-9.

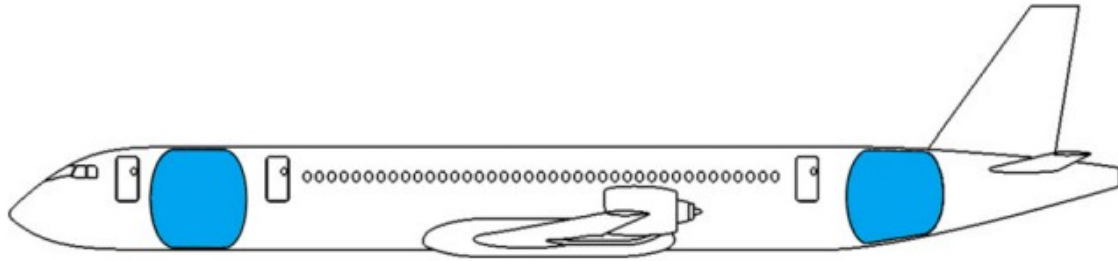


Figure 2-9: Over the wing turbofan configuration [38]

Green and blue Hydrogen are compared against the kerosene. It reports that green Hydrogen could provide 41 – 63% overall emission reductions whereas 21 – 26% is possible for blue Hydrogen, all compared to kerosene variant. Economically, blue Hydrogen seems to be more attractive compared to green Hydrogen due to fuel price differences. However, when it comes to turbofan engines using Hydrogen fuel, no quantification or impact of Hydrogen on UHBR turbofan engine is provided apart from the SFC reduction applied as part of the future technology.

Boehm et al [39] investigates fundamentally the effects of sustainable aviation fuel (SAF) on the energy efficiency on jet engines. A simple engine performance model involving the use of fuel system thermal model (FSTM) is used for the assessment as shown in Figure 2-10 and Figure 2-11 respectively.

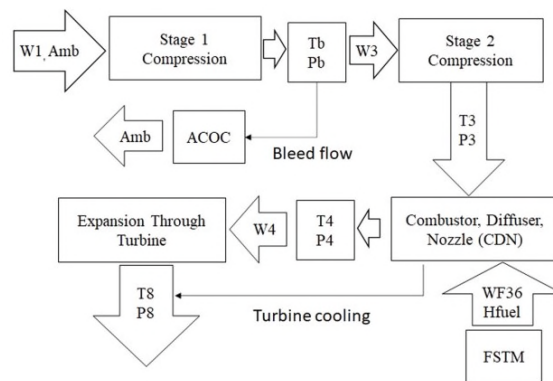


Figure 2-10: Simple engine performance model [39]

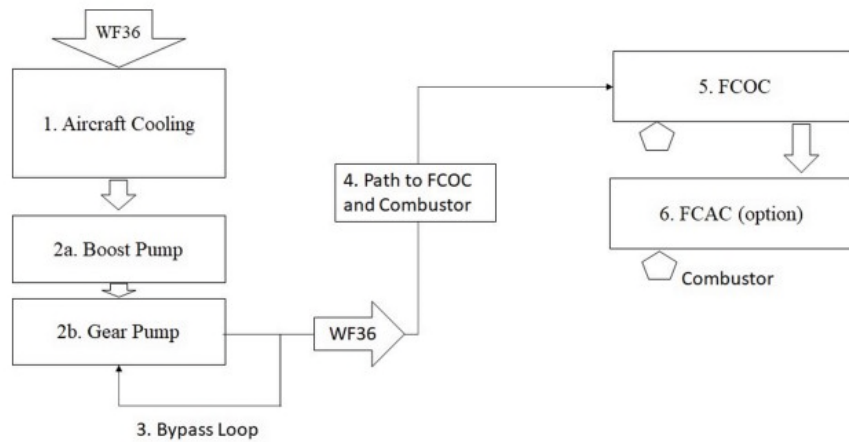


Figure 2-11: Fuel system thermal model (FSTM) [39]

The fuel will collect heat to cool the oil before being injected into the combustor. This study highlights the heat sink capability of sustainable aviation fuels to increase engine efficiency. This is because the thermal stability of these fuels are higher since these are certified for higher temperature of 325°C compared to 260°C for Jet A. Using this capability, one can reject more heat into the fuel and improve the waste heat recovered by the system. The study hints that SAF can be relied on more as a coolant when compared to Jet A and reduce the dependency on air oil coolers. The study claims 0.5% of efficiency benefit out of which 60% of it is from the higher thermal stability of the SAF. Although the results show potential, the study is performed only for only two operating conditions and demands further investigation with realistic turbofan cycles monitoring thrust and SFC changes.

Osigwe et al [40] investigate the effects of Hydrogen fuel for 3-spool turbofan engine due to its environmental benefits to reduce the emissions. The turbofan cycle performance is compared for fixed thrust requirements. Take-off and cruise TET benefit of 6°C and 9°C respectively are observed for Hydrogen powered turbofan engine compared to the kerosene variant. As expected, due to the difference in LHV, 64% SFC reduction is reported in the study. The study also showcases the possibility of having better HPT blade life (15%) with Hydrogen fuel which is assessed through a creep life estimation for fixed HPT geometry.

Although the study highlights the benefits of Hydrogen fuel, it does not discuss the potential turbofan design implications when considering the mission level performance of a Hydrogen aircraft.



Figure 2-12: The NASA DC8 research aircraft probing contrails from the DLR A320 burning sustainable aviation fuel blends [41]

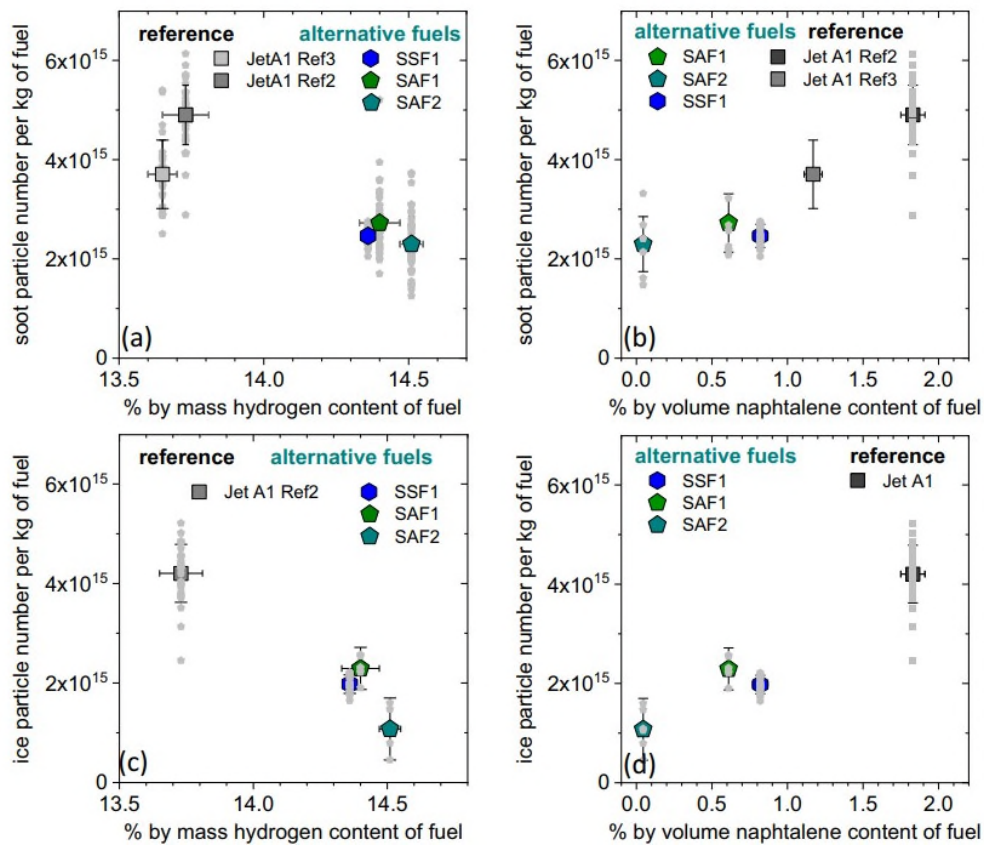


Figure 2-13: Soot and ice particle emissions per kg of fuel at cruise conditions for the reference Jet A1 fuels and for the low aromatic sustainable aviation fuel blends [41]

Voigt et al [41] provides details of DLR-NASA aircraft campaigns that measured exhaust and contrail characteristics of an Airbus A320 burning kerosene and low aromatic SAF blends. It provides evidence that burning low aromatic SAF provides a 50%-70% reduction in soot and as a result lower contrails leading to lower climate impact from adopting SAF compared to standard jet fuel.

Figure 2-12 showcases the research aircraft on the left chasing the test aircraft A320 on the right to measure the emissions.

Figure 2-13 showcases the trends of soot and ice crystal emissions obtained from the campaign. It clearly provides evidence that soot and ice emissions are lower for the blends compared to pure Jet A. Blending SAF with Jet A increases the overall Hydrogen content and reduces the aromatics involved. Although these are favourable attributes of SAF from an environmental perspective, there exists certain matters from a fuel systems perspective, at least for an older generation aircraft, that needs attention. These include systems that depend on fuel properties such as fuel metering, pumps and seals.

Rao et al [42] reviews Hydrogen and Natural gas/Methane for aviation. It highlights certain advantages and disadvantages of using them for aviation. When it comes to Hydrogen fuel, the advantages are as follows:

- High energy per kilogram (almost three times compared to kerosene)
- No inflight CO₂ emissions.
- No soot, CO, unburnt hydrocarbon (UHC) and volatile organic compounds
- Potential to reduce NO_x emission from combustion
- Usage of cryogenic heat sink to boost the thermal efficiency of the turbofan engines
- Can be used in conjunction with fuel cells and electrical motors.
- Wide combustion range and flammability limit.

The disadvantages of Hydrogen fuel are as follows:

- Poor energy per volume (approximately requires 4 times more volume compared to kerosene for the same energy)

- Cannot be stored inside the wings but only the fuselage or in the underwing pods
- Requires cryogenic storage or pressurised tanks
- Airport logistics could be difficult.
- Water emissions are very high especially water being a greenhouse gas at higher altitudes (>10km)
- Hydrogen has propensity to leak and tends to flashback during combustion in a gas turbine.

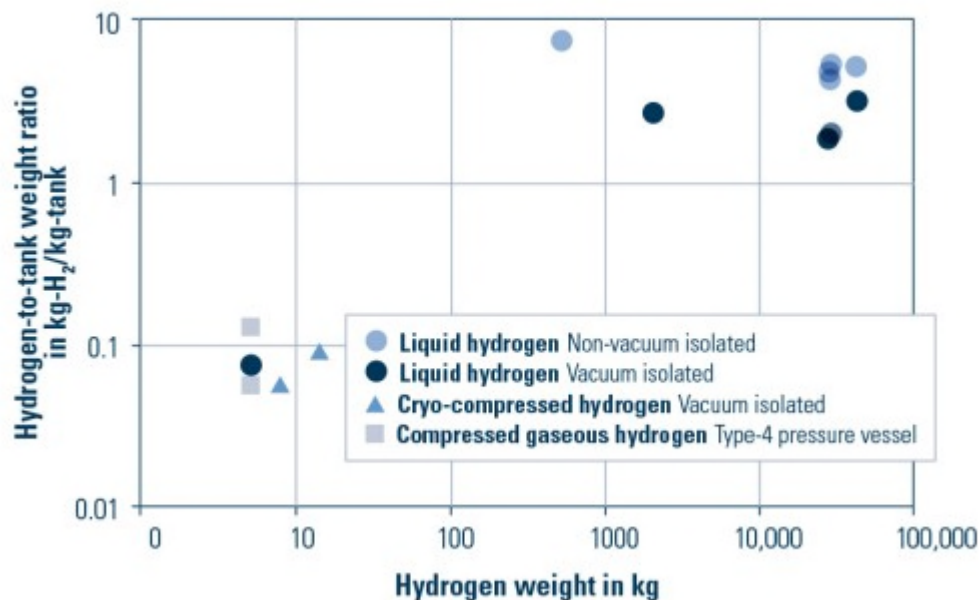


Figure 2-14: Comparison Hydrogen tank weights based on different storage technology [42]

Figure 2-14 showcases the tank weights arising from the usage of different Hydrogen tank storage technologies. It is observed that the liquid Hydrogen storage technology leads to lower tank weights compared to compressed gaseous Hydrogen storage technologies.

When it comes to using Natural gas/Methane for aviation, there exists certain advantages as follows:

- Higher energy per kilogram and better combustion properties compared to kerosene
- Burning Methane reduces CO₂ emissions by 25%. Particulate emissions are reduced substantially while eliminating sulphate emissions.
- The heat sink capability can be used beneficially for intercooling, bleed air cooling to enhance the thermodynamic efficiency of the engine.

The disadvantages of using it are:

- The storage requires the use of pressurised tanks and insulation which increases the OEW of the aircraft.
- Methane slip during utilisation can lead to increased global warming as Methane itself is a potent greenhouse gas with effects approximately 34 times compared to CO₂ emissions over a 100 year period.

Lee et al [43] quantifies the impacts of aviation to global climate change from the year 2000 to 2018.

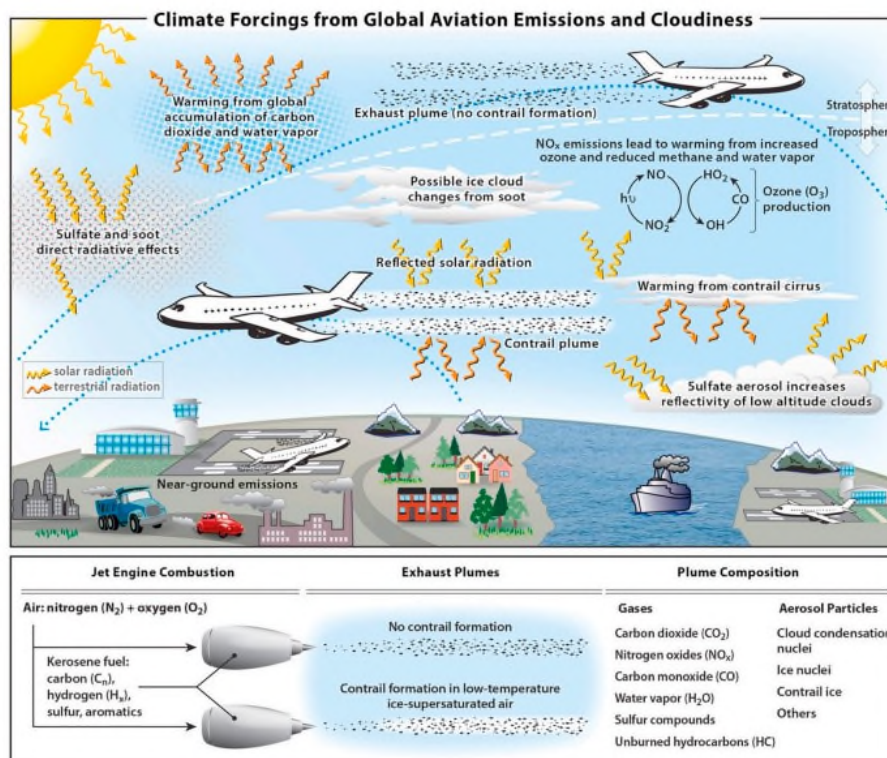


Figure 2-15: Schematic overview of the processes by which aviation emissions can affect the climate system [43]

Figure 2-15 provides a good illustration of the various complex processes involved that causes the warming of the planet. It shows how NO_x emissions leads to warming through Ozone production, how contrails reflect radiative forcings in and out of the planet and the effects of soot radiative forcings among other factors.

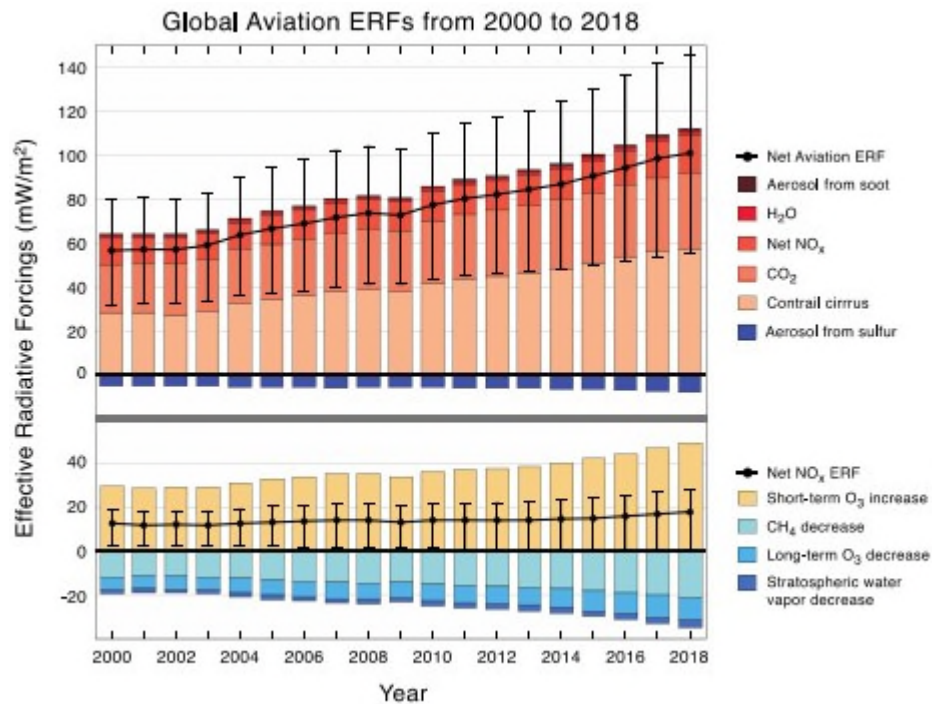


Figure 2-16: Timeseries of ERF values from 2000 to 2018 due to aviation induced emissions [43]

Figure 2-16 showcases the increasing trends of net radiative forcings over the period 2000 to 2018 due to the aviation emissions. It also showcases that the NO_x induced net effect also leads to warming over this period of time. It is worth noting that the contrail radiative forcings (non-CO₂) are bigger proportion compared to the CO₂ forcings in the total buildup for ERF.

Pregger et al [44] provides details about state of the art regarding future fuels researched in Germany for application in space, energy, transportation and aviation industry. The synthetic fuels researched are entirely produced from renewable sources of energy. When looking at the aviation fuels, only drop in fuels are discussed, citing reasons such as stringent safety and performance

requirements with no modification of any subsystem or infrastructure for direct use.

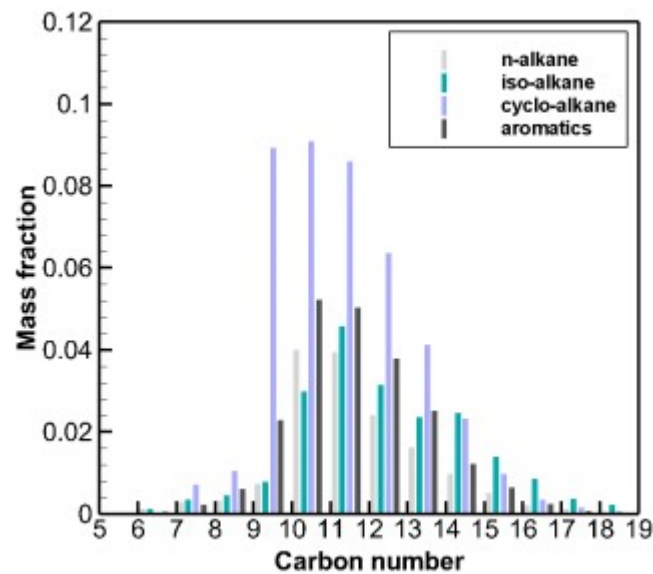


Figure 2-17: Detailed fuel composition of a typical crude oil-based Jet A-1 [44]

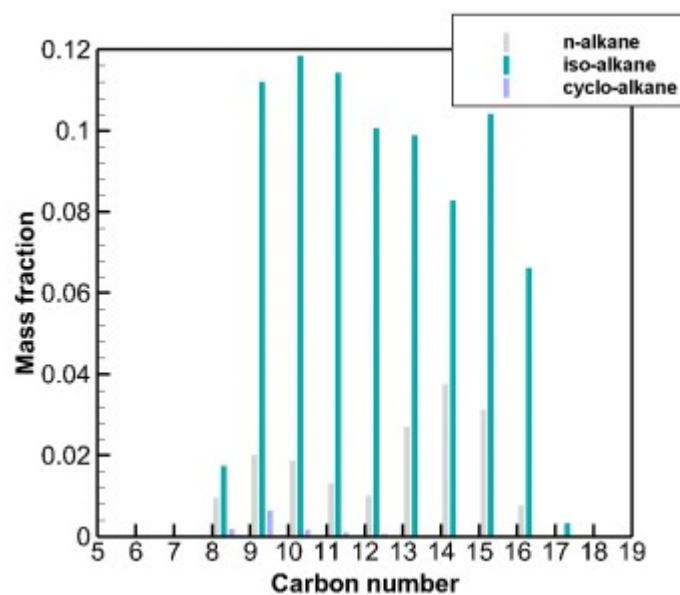


Figure 2-18: Detailed fuel composition of a HEFA-SPK fuel [44]

From Figure 2-17 and Figure 2-18, the main differences in composition between a typical crude oil based Jet A-1 fuel and synthetic HEFA-SPK is demonstrated. HEFA-SPK consists mainly of alkanes (paraffins) and very less aromatics (cyclo-alkanes) whereas Jet A-1 include high concentrations of aromatics along with

alkanes. Aromatics is known to be an important precursor to soot production. Although different to aviation, in road transportation, it is reported that oxygenated fuels such as alcohols and ethers are known to burn much cleaner and reduce the particulate matter emissions. Oxygenated fuels revealed a high particulate emission reduction potential due to the oxygen content in the fuel molecular structure. Butanol is reported to have more complete combustion due to its oxygen content and reduce soot formation. Ethers are also reported to reduce soot emissions due to the lack of C-C compounds and high oxygen content.

Derwent [45] reviews the impact of Hydrogen slip into the atmosphere. The review is conducted as part of the strategy to decarbonise heating in the UK using Hydrogen. The review identified that Hydrogen can take part in atmospheric chemical reactions that can lead to global warming. In the upper atmosphere, Hydrogen can slow down the ozone recovery while in lower atmosphere, it can lead to increased methane and ozone levels. It reports 4.3 megatonnes of CO₂ equivalent emissions for 1 megatonne of Hydrogen released over a 100 year time horizon.

Goldmann et al [46] discusses about electrofuels for aviation, a term assigned to synthetic fuels produced from renewable power. It highlights various synthesis pathways for the sustainable production of these fuels along with their physico-chemical properties.

Figure 2-19 showcases various pathways by which fuels from renewable power can be produced. Renewable Methane can be produced from green Hydrogen and CO₂ using process called Methanation by the Power to Gas pathway. Renewable liquid fuels can be produced from green Hydrogen and CO₂ to make syngas (H₂+CO) which is further used in Fischer-Tropsch process to make long chain hydrocarbon fuels. Renewable Ammonia can be produced using green Hydrogen and atmospheric nitrogen using process called Haber-Bosch. An electrochemical pathway also exists where CO₂ is electrochemically reduced directly into hydrocarbons such as Methane, Ethane, or Methanol for example.

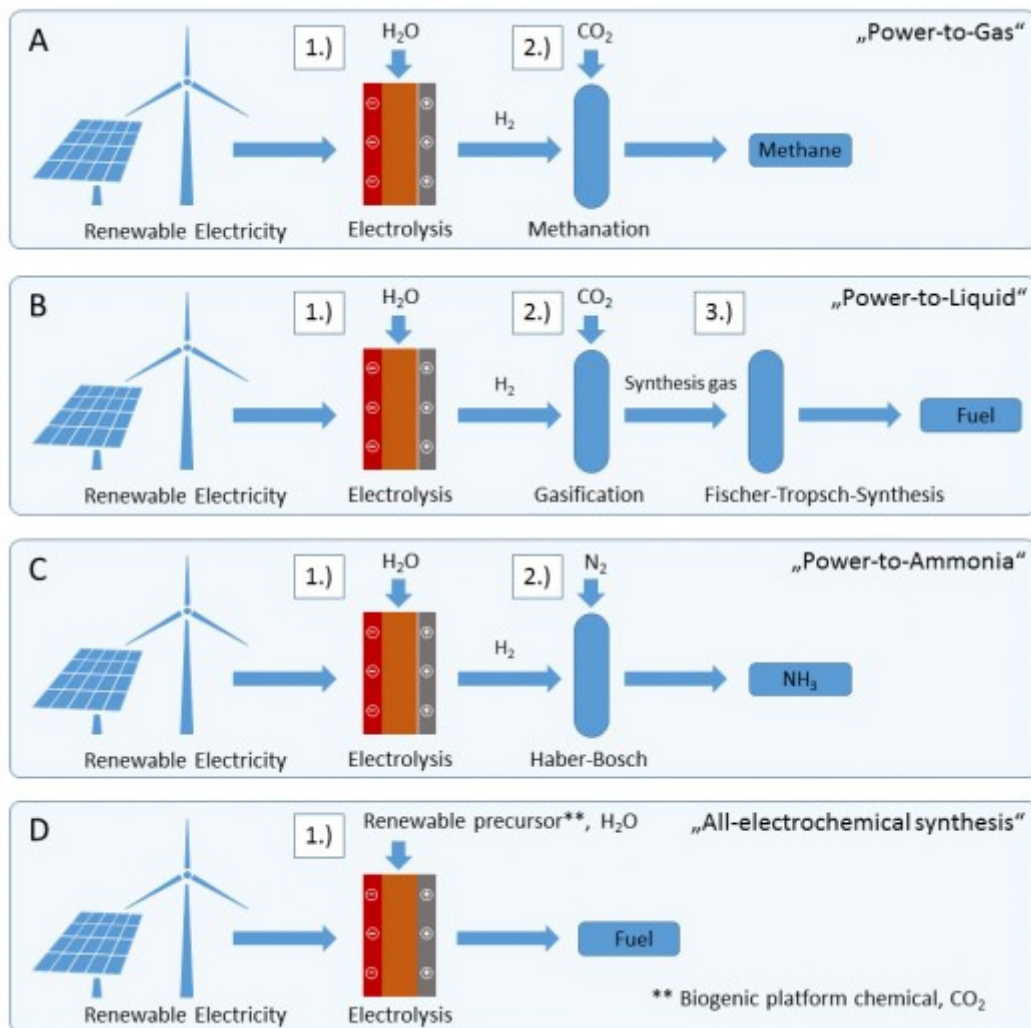


Figure 2-19: Schematic illustration of the “power-to-X” technologies [46]

Alternative fuels such as Octane, Methanol, Methane, Hydrogen and Ammonia are discussed for aviation. Impact of these fuels for a single operating point on the performance of the turbine of fixed geometry is discussed. It is found that usage of these fuels leads to increased power output from the turbine but however, with the consequence of increased shaft speeds as shown in Figure 2-20 and Figure 2-21. Ammonia is found to provide the highest turbine power output and leads to highest shaft speed. Although these are potential findings, the study does not quantify the impacts on the turbofan cycle and does not provide a mission level assessment.

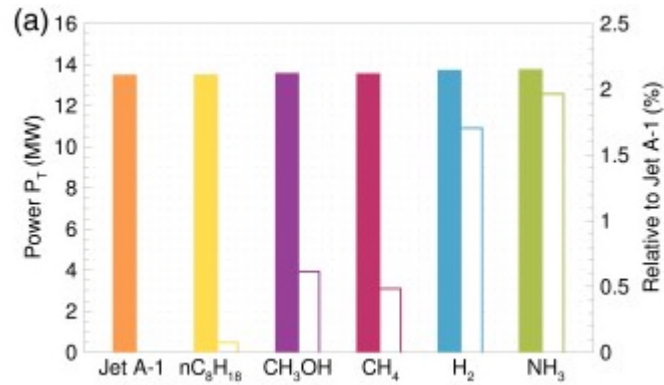


Figure 2-20: Comparison of turbine power output [46]

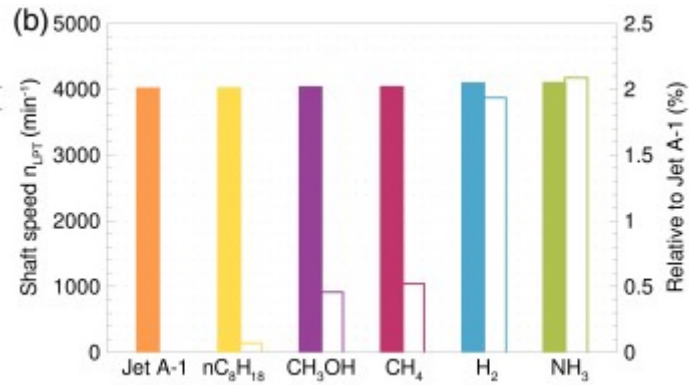


Figure 2-21: Comparison of shaft speed when using the fuels [46]

Gawron et al [47] performed experiments to measure the performance and emissions of a mini turbojet rig using blends of Jet A-1 and Butanol. A 10% blend of Butanol with Jet-A is investigated. Figure 2-22 showcases the test results of the experiment. It demonstrates that the thrust difference between the engine when operated with pure Jet A-1 and the blend is within 3%. When looking at the exhaust gas temperature differences, the differences are within 2%. Figure 2-23 demonstrates the reductions possible in CO and CO₂ emissions when operating with Butanol blends. It is reported that the differences in CO₂ emissions are up to 2% and CO emissions are up to 5%.

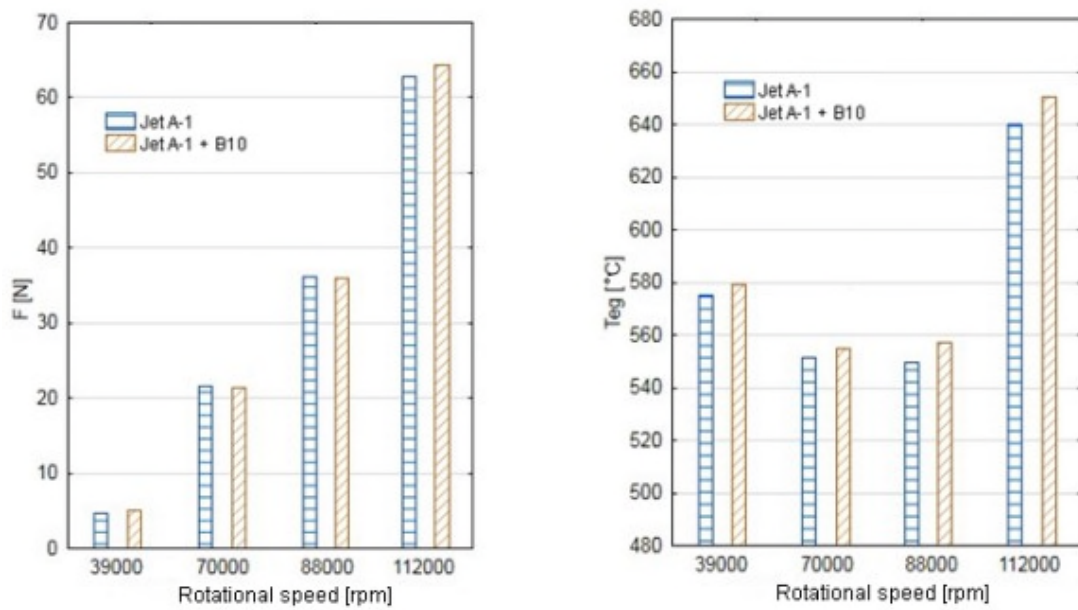


Figure 2-22: Thrust and exhaust gas temperature comparisons for different rpms [47]

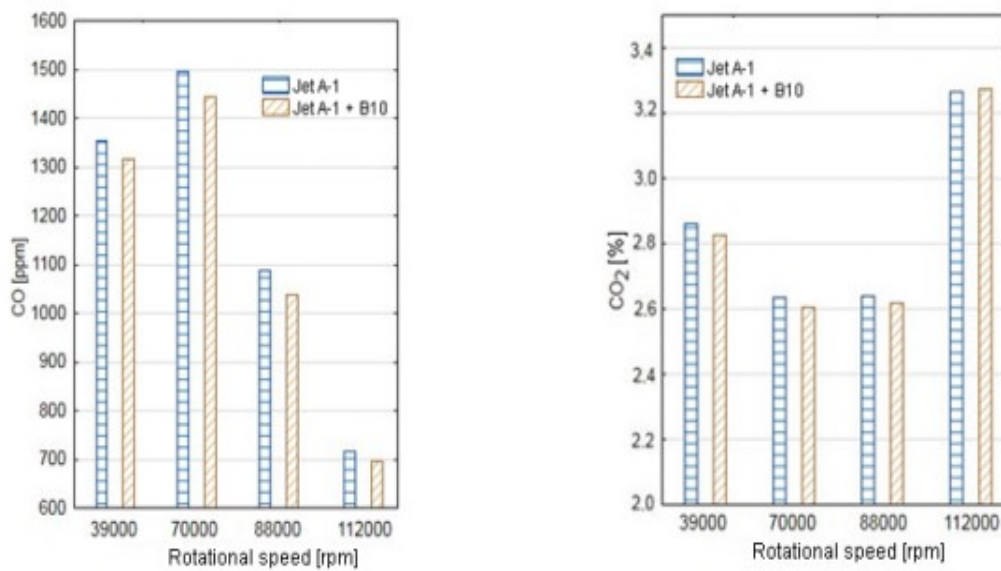


Figure 2-23: CO and CO₂ emissions comparisons for different rpms [47]

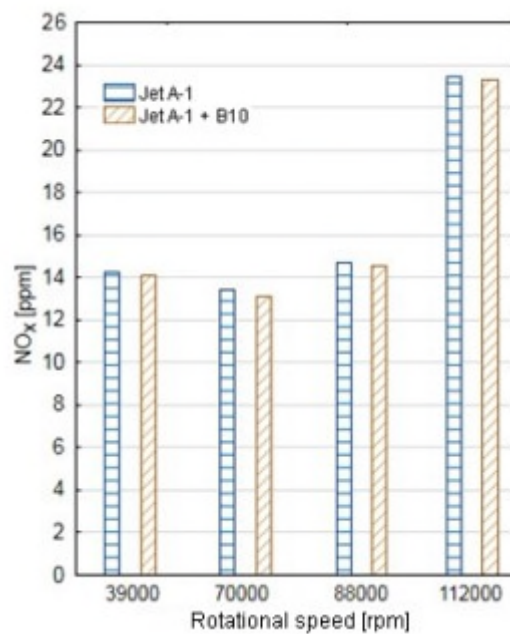


Figure 2-24: NO_x emissions comparison for different rpms [47]

Figure 2-24 demonstrates the NO_x emissions reduction possibility when operating with Butanol blends and the differences are within 2%. Although these tests are for miniature turbojet engine, the results appear to be promising in reducing emissions for turbofan engines.

Mazlan et al [48] assessed the effects of biofuel properties on aircraft engine performance. The effects are assessed for a single operating point at cruise. Two biofuels are assessed that are sourced from Jatropha and Camelina plants. The effect of heat capacity on engine thrust is demonstrated in Figure 2-25.

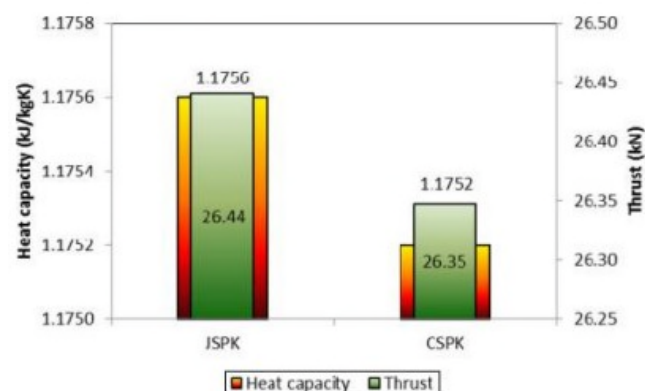


Figure 2-25: Effect of heat capacity on engine thrust for biofuels [48]

It showcases that higher the heat capacity, higher the thrust produced by the engine.

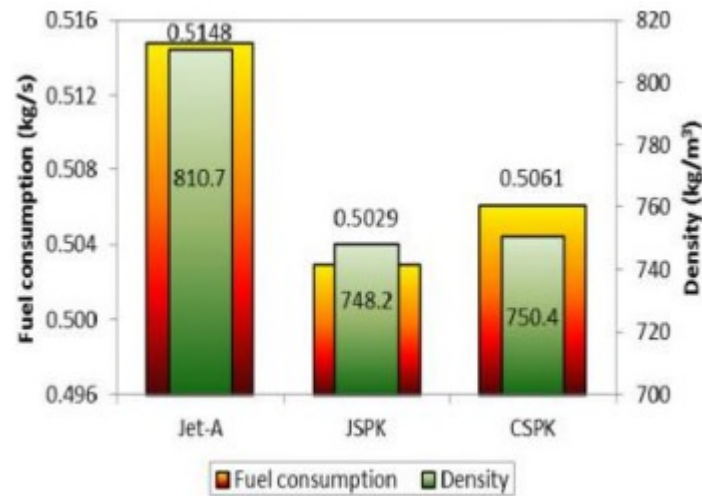


Figure 2-26: Effect of fuel density of biofuels on fuel consumption [48]

Figure 2-26 demonstrates the effects of density variations of biofuels on fuel consumption rates. The denser fuel CSPK showcases higher fuel flow rates which is linked to its reduced lower heating value (44 MJ/kg) while lighter JSPK showcases lower fuel flow rates due its higher LHV (44.3 MJ/kg).

Verstraete [49] assessed Hydrogen fuel for short, medium, and long range transport aircraft. The main idea was to investigate the energy efficiency of these aircraft compared to kerosene variant. The Hydrogen aircraft is redesigned maintaining the same passenger capacity with different wing area and wing loading. It is found that for long range aircraft (7560 nm), Hydrogen aircraft reduces mission energy burn up to 12%. For short range aircraft (2160 nm), 18% increased mission energy consumption is observed when switching to Hydrogen fuel mainly because the fuel requirements is less, and weight increase is high. For medium range aircraft (4860 nm), the mission energy burn for Hydrogen fuel is increased by 5% compared to kerosene variant. However, the study scales the turbofan engines to provide the required thrust for all the assessments, thereby not quantifying potential implications for the turbofan engine powered by Hydrogen.

Lokesh et al [50] assessed performance at aircraft mission level for three bio based jet fuels sourced from Jatropa, Camelina and Microalgae. These were assessed for 100% blends without blending with Jet A-1. The aircraft is representative for medium range category using a 2-spool turbofan engine.

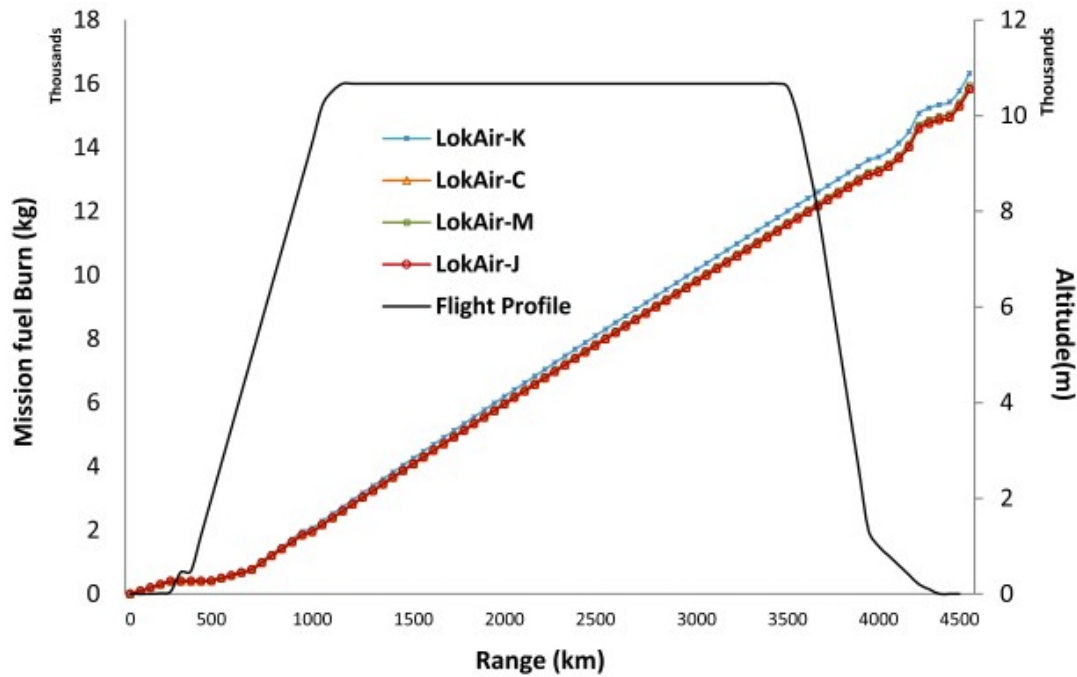


Figure 2-27: Mission fuel burn evolution when operating with various SAF [50]

Figure 2-27 demonstrates the fuel burn differences possible when operating with SAF. These differences can be attributed to the different LHVs of sourced SAF. It is reported that for the fixed aircraft mission range, fuel burn reductions of 3.8% were obtained for SAF sourced from Camelina and Jatropa whereas 3.1% reduction for SAF sourced from Microalgae. The study reported an overall life cycle carbon emissions saving up to 70% compared to conventional Jet A-1 fuel. However, when it comes to turbofan assessments using SAF, the study was performed for the same thermodynamic engine cycle as that of kerosene variant thereby not quantifying potential implications for the turbofan engine powered by SAF.

Zhuravlev [51] discusses the usage of alternative fuels in aviation. Liquid Hydrogen, Natural Gas and liquified Propane/Butane mixtures are discussed. It reports that liquified Propane/Butane mixtures require much less safety

requirements for the aircraft when compared to Natural gas. It provides information regarding the Tupolev -155 experimental airplane made to test liquid Hydrogen and Natural gas in the late 1980's. It is a trijet and only one engine was converted to work on the alternative fuel. The two other engines were operated on kerosene.



Figure 2-28: TU-155 airplane layout [51]

Figure 2-28 showcases the converted TU-155 airplane layout indicating the cryogenic tanks in blue colour to store the alternative fuel. Initially the test flight was made on liquid Hydrogen and then on Natural Gas. Demonstrations flights were made abroad in 1989 on the route of Moscow – Bratislava – Nice, 1990 in Hannover and in 1991 at Berlin. Although not jet aircraft, it's interesting to note the development of a helicopter Mil-8TG operating on Propane/Butane mixtures in the late 1980's as showcased in Figure 2-29.



Figure 2-29: Mil-8TG helicopter operating on Propane/Butane mixtures [51]

The helicopter engines can work on both kerosene and Propane/Butane mixtures. The storage tanks are pressurised capable of operating up to 1 MPa. The flight tests on Propane/Butane mixtures demonstrated no soot (clean exhaust) and no residue on the combustion chamber walls and turbine blades.

Mendez et al [52] assessed Butanol and their blends with Jet A experimentally on a mini gas turbine engine. 100% Butanol and their blends from 25% to 75% with Jet A were tested experimentally.

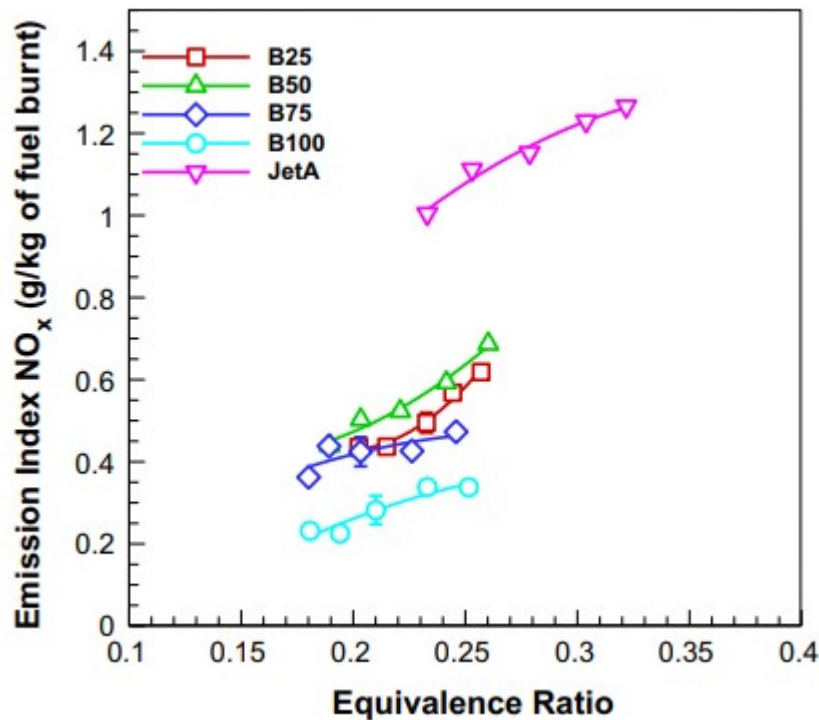


Figure 2-30: NO_x emission index for various blends [52]

Figure 2-30 demonstrates that Butanol and its blends with Jet A has a lower NO_x emission index. B25 for example means that 25% Butanol and 75% Jet A is used as a mixture. It is reported that due to the higher latent heat of vaporisation of Butanol, the combustion temperature is lower and as a result, the positive impact on NO_x reduction is noted.

Figure 2-31 showcases that CO emission reduction potential of Butanol and its blends when compared to Jet A. It is reported that the emissions are about 35% lower when compared to Jet A. This is explained by the presence of oxygen in

Butanol which tends to provide a more complete combustion and reduce CO emissions.

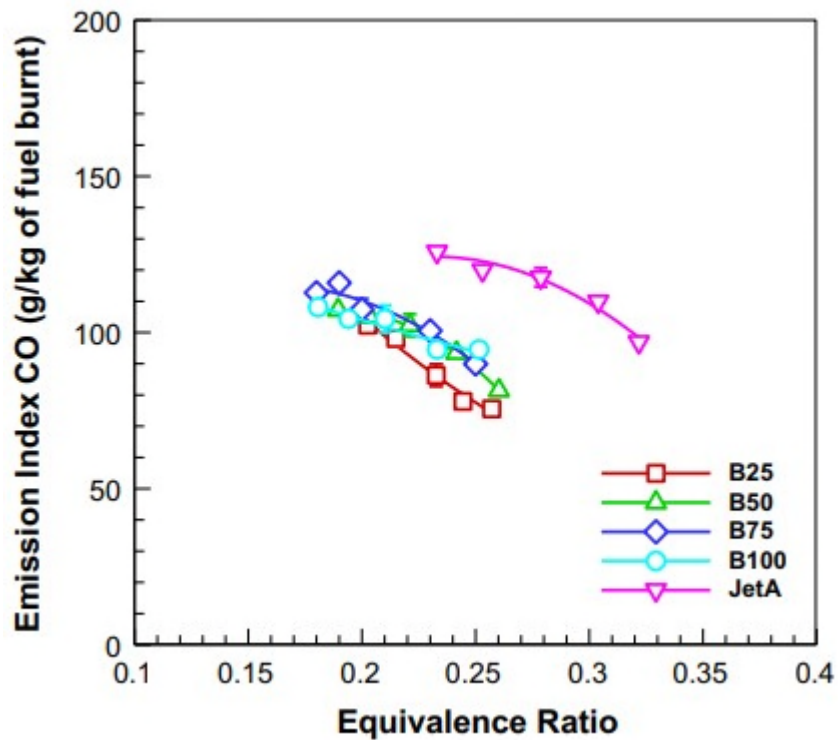


Figure 2-31: CO emission index for various blends [52]

This provides evidence of the favourable emission characteristics of using Butanol as a fuel for gas turbine engines.

Verstraete [53] investigated the potential of Hydrogen fuel for large long range transport aircraft (7500 nm and 380 pax). Figure 2-32 shows the schematic of aircraft assessed with tanks inside the fuselage at front and aft.

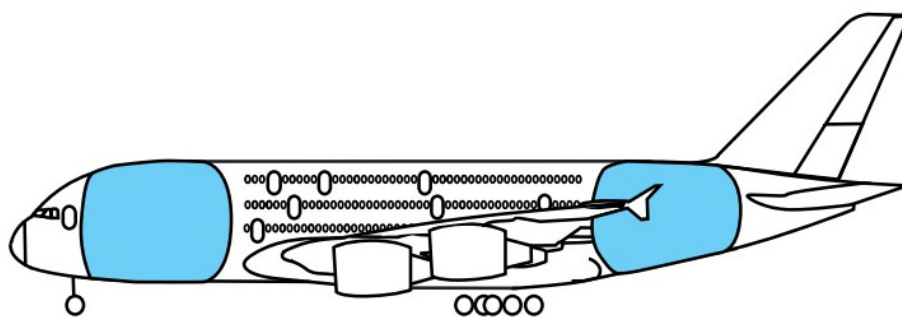


Figure 2-32: Large long range transport aircraft using liquid Hydrogen with cryogenic tanks [53]

It is found that the mission energy consumption reduces by around 11% for the Hydrogen powered aircraft when compared to the kerosene variant.

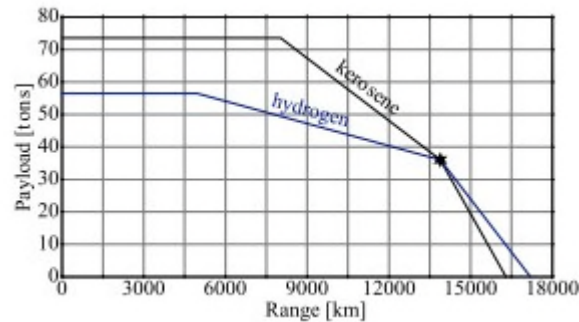


Figure 2-33: Payload range comparison between assessed Hydrogen and Kerosene aircraft [53]

Figure 2-33 shows that the Hydrogen aircraft is less competitive than the kerosene variant at ranges below the design range (*) as the payload capability is less. This is because the cryogenic tanks that is stored inside the fuselage reduces the volume of cargo hold and hence reduces the payload capability. However, at ranges above the design mission, there is a slight advantage in terms of ferry range. This is because the weight of the Hydrogen aircraft compared to kerosene aircraft is lower which results in higher range for maximum fuel capacity. The study, however, does not investigate the implications on Hydrogen powered turbofan engines as the study scales the engines to the required thrust values every time during the aircraft sizing.

Khandelwal et al [54] reviews the properties and traits of Hydrogen as a fuel for aviation. Certain interesting and important aspects of Hydrogen fuel discussed are mentioned herein briefly. Figure 2-34 shows the positive and negative aspect of Hydrogen relevant to aircraft application. The positive aspect is that Hydrogen contains 2.8 times more energy than kerosene for the same mass. As a result, this allows the Hydrogen aircraft to be lighter to carry the same energy as that of kerosene and theoretically result in a lighter airplane compared to kerosene aircraft for the same mission. However, the negative aspect is that Hydrogen requires 4 times the volume of kerosene to have the same energy on board due

the very low densities of liquid Hydrogen. As a result, the Hydrogen aircraft will be lighter but bulkier compared to kerosene aircraft.

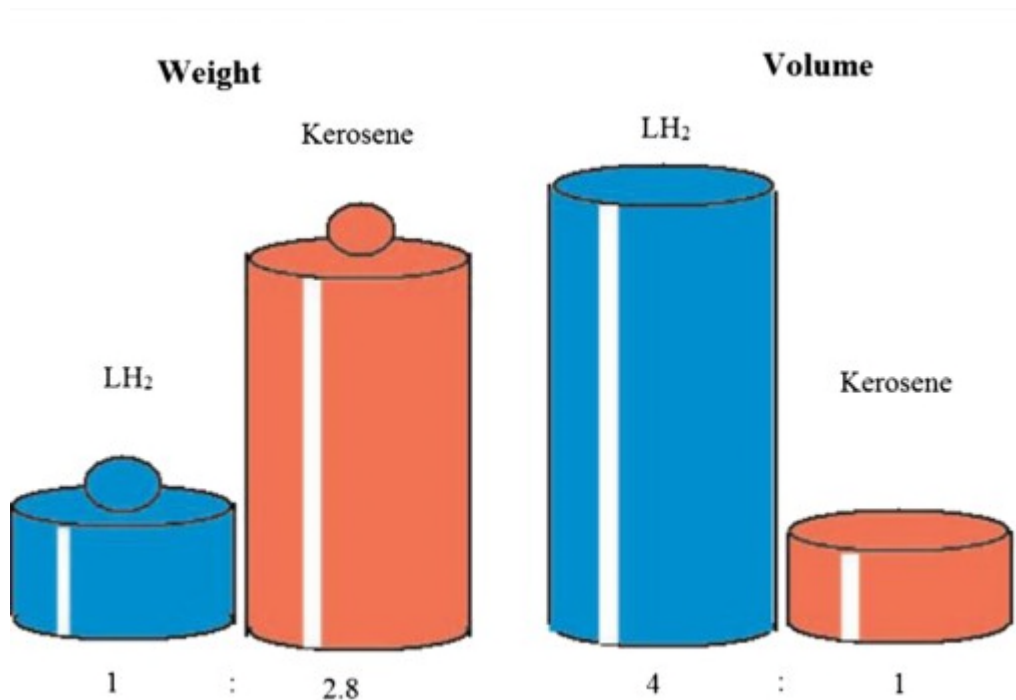


Figure 2-34: Weight and volume comparison of Hydrogen fuel with Kerosene [54]

It states that the flame temperatures of Hydrogen are higher compared to kerosene fuel at stoichiometry, however, due to Hydrogen's wider flammability limits, the equivalence ratio can be reduced to attain flames at lower temperatures as demonstrated in Figure 2-35. Since one can operate the combustor at lower flame temperatures with Hydrogen fuel, the thermal NO_x emission is believed to be lower. When it comes to safety aspects of operating with Hydrogen fuel, Figure 2-36 demonstrates real life effects of Hydrogen in an event of fuel leak and ignition. It is seen that the Hydrogen leak will continue to combust in a controlled manner until the tank is empty whereas the kerosene leak has engulfed the entire vehicle posing significant danger. Figure 2-37 shows that danger areas posed by Hydrogen fuel is significantly less when compared to other low carbon hydrocarbon fuels such as Methane and Propane mainly attributed to the fuel molecular weight differences.

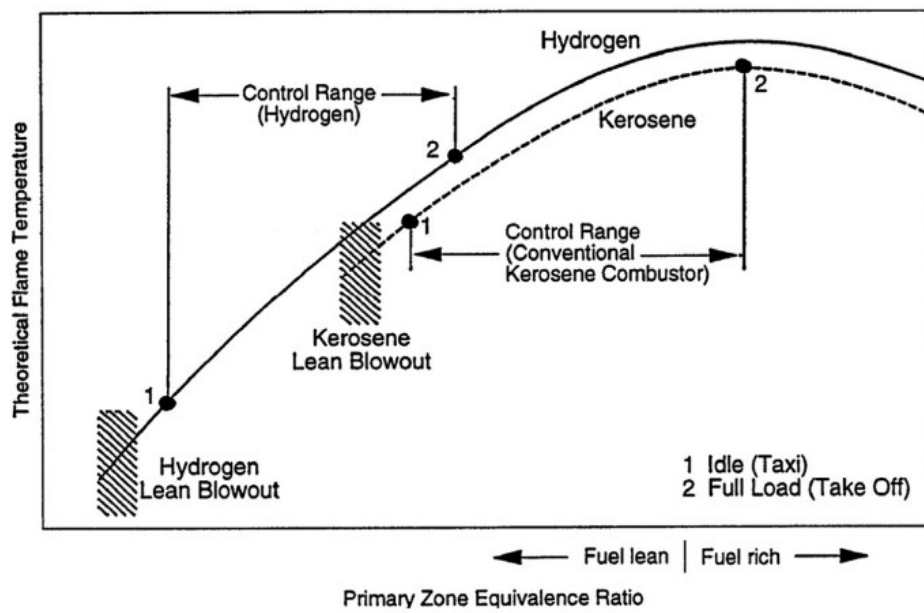


Figure 2-35: Flame temperature characteristics of Hydrogen vs Kerosene [54]



Figure 2-36: Safety comparison between a Hydrogen and Kerosene fuel leak [54]

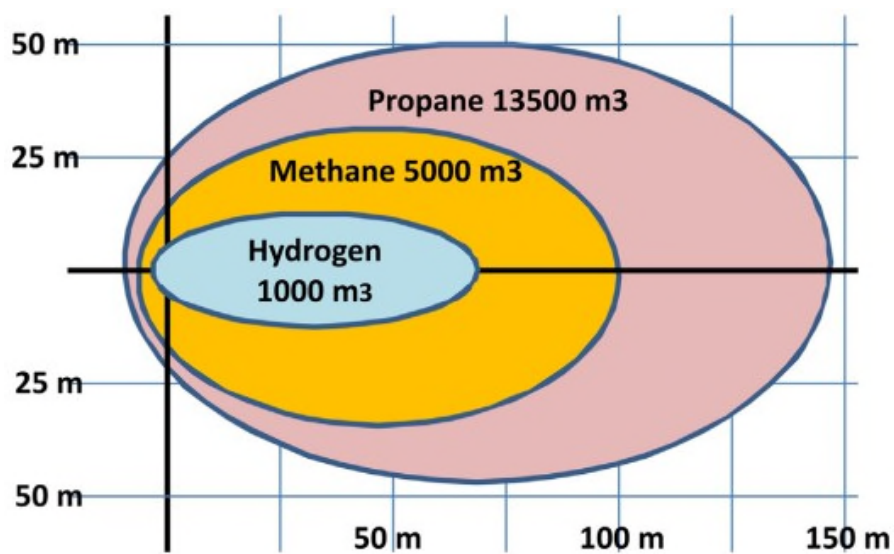


Figure 2-37: Danger zone of spilled liquid gas [54]

Wolters et al [55] assessed the impact of SAF at mission level for short haul and long haul aircraft. 50% blend with Jet A and 100% blend cases are investigated.

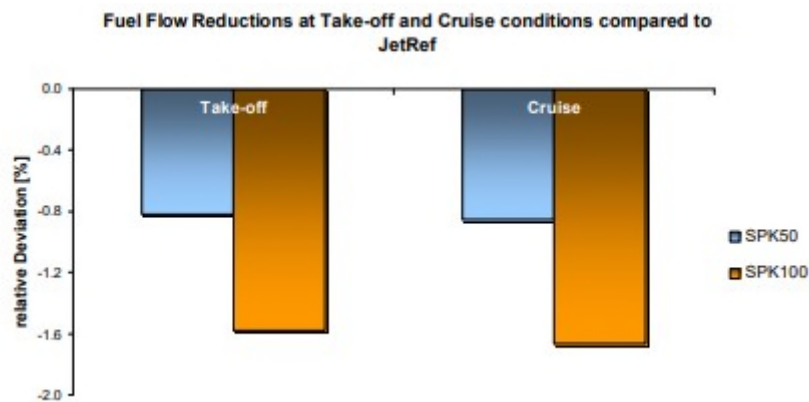


Figure 2-38: Fuel flow differences of SAF and its blends relative to Jet A [55]

Figure 2-38 highlights the impacts of blends of SAF with Jet A on engine fuel consumption. It showcases that the as the blend ratios are increased, the fuel consumption is reduced. This is because of different LHVs arising from the 50% blend and 100% blend of SAF.

Fuel	Fuel consumption	
	total [kg]	reductions to JetRef [%]
JetRef	3654	-
SPK50	3620	0.9
SPK100	3588	1.8

Fuel	Fuel consumption	
	total [kg]	reductions to JetRef [%]
JetRef	40978	-
SPK50	40547	1.1
SPK100	40139	2.0

Figure 2-39: Mission fuel comparison for short haul (above) and long haul (below) aircraft using blends and neat SAF [55]

Figure 2-39 demonstrates the effects of SAF at mission level for short haul and long haul aircraft. As one increases the blends, the fuel burn benefit increases. It is interesting to note the higher benefits of using SAF for long haul aircraft in

comparison to the short haul aircraft. This is mainly because the fuel load is more for long haul aircraft compared to short haul aircraft and hence, the impact in terms of mass difference is more pronounced for the long haul aircraft. However, the study did not investigate further implications of using SAF for the turbofan engines in terms of engine cycle design.

Chandrasekaran and Guha [56] investigated a three spool intercooled recuperated turbofan engine concept powered by liquid Hydrogen. Water injection is used for take-off and climb out to address the NO_x emissions with water injected ahead of the IPC. The liquid Hydrogen along with the bypass air is used in the intercooling process for the HPC. The exhaust heat after the LPT is recuperated and transferred just before entry into the combustor to increase the HPC T_{30} . The cycle is designed just for a single operating point cruise by selecting a specific thrust, BPR and OPR. The off design cases are simulated with water injection to investigate the performance. The Hydrogen powered concept provided increased overall efficiency mainly attributed to changes to propulsive and thermal efficiency compared to the baseline kerosene variant. For off design simulations, the water injection led to lower T_{40} and NO_x emissions. Although the results are interesting, pressure loss due to operation heat exchangers are not considered, the cycle at cruise is merely selected and not based on any multipoint design methodology and finally, the results are compared for the same thrust as of kerosene which is not the case for a Hydrogen aircraft. As a result, the implications on the Hydrogen operated engine appears to be approximated.

Blakey et al [57] investigates the effects of fuel properties on the range payload capability of a jet engine powered aircraft. The study use Breguet range equations to proceed with the assessments. The study investigated some alternative fuels for the assessments as shown in Figure 2-40. Although very preliminary in nature, it is useful to visualize the effects of alternative fuels on the payload range envelope of a typical medium range aircraft. It is seen that as the LHV of the alternative fuel increases, the range capability also increases. This is because, as the LHV increases, the energy stored in the tank increases and hence the

range obtained. It must be noted that no investigations for the engine are performed in the study.

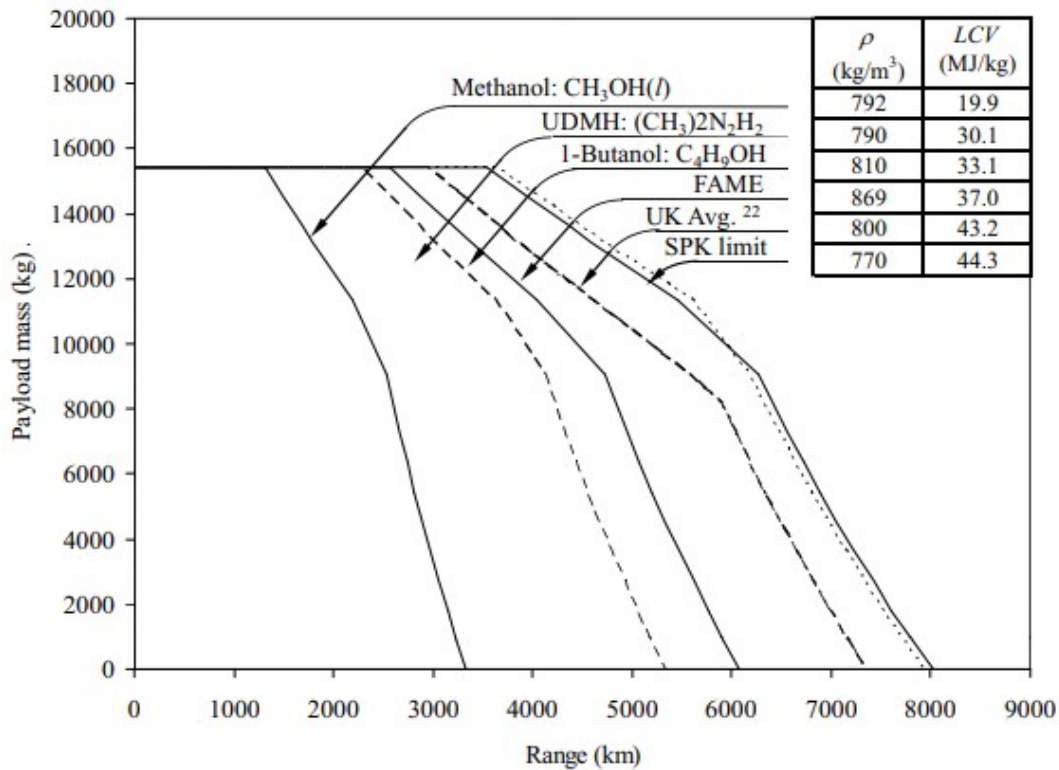


Figure 2-40: Changes to range performance of a Boeing 737-300 due to alternative fuels used for flight [57]

Dijk et al [58] assessed different ways to use liquid Hydrogen's heat sink potential to improve the turbofan cycle performance of a 2-spool engine. The assessments are made for a single operating point. Different methods such as cooling of stator vanes using liquid Hydrogen for reducing compressor power, intercooling, cooling turbine NGV directly using liquid Hydrogen and cooling the bleed air for turbine NGV using liquid Hydrogen. It is found that cooling of compressor stator vanes using liquid Hydrogen is not feasible mainly due to the limited heat transfer from the stator fins as they are too thin. Apart from this, ice formation, air liquification or even Hydrogen leaks causing stator embrittlement could also potentially rule out this method. Regarding the intercooling method, the pressure loss due to heat exchanger was 4% and onwards depending on the design of the heat exchanger which ultimately led to an increase in SFC. But its also stated that reducing the pressure loss can reduce the SFC. It also hints that perhaps intercooling is better

suited to engines that use higher pressure ratio IPC which can aid in the heat transfer process due higher temperature margins between compressor air and liquid Hydrogen. Cooling the bleed flows for HPT and LPT using liquid Hydrogen showed promise as they led to the best reduction in SFC and increased specific thrust mainly attributed to the reduction in cooling flows and as a result, increased thrust values. The direct cooling method of HPT and LPT NGV with liquid Hydrogen resulted in eliminating the cooling flows entirely for HPT and LPT which provided the maximum increment in specific thrust. Although the results are promising, the study is only based on a single operating point and not influenced by off design operating points. The fact that specific thrust is changed makes it difficult to pinpoint the reason behind the SFC improvement as it can be due to thermal efficiency and propulsive efficiency changes.

Seeckt and Scholz [59] assessed an ATR72 style freighter model aircraft with kerosene and Hydrogen as fuel using turboprop and turbofan propulsion systems. Hydrogen variants are reported to provide significant benefits in terms of CO₂ and NO_x emissions. Water vapor emissions increased 2.5 times upon using Hydrogen compared to kerosene, but this has a smaller climate impact compared to longer range aircraft due to lower cruise altitude of regional aircraft leading to no contrails. However, the propulsion system, that includes the turbofan engines using Hydrogen, were sized for the required thrust by simply scaling the engine cycles and hence does not assess the implications on engine cycle design and performance.

Lee et al [60] investigated the use of DME for gas turbines and found that it is a clean and efficient fuel. The experimental tests were performed with DME on a scaled down gas turbine combustor which is normally run with Natural Gas. The study concluded that only a small modification is need for the fuel nozzle to ensure clean and stable operation with DME fuel. Figure 2-41 demonstrates the DME and Natural gas flames from the experiment. The oxygen content of DME fuel is found to enable a smoke free (no soot) combustion as reported by Huang et al [61].

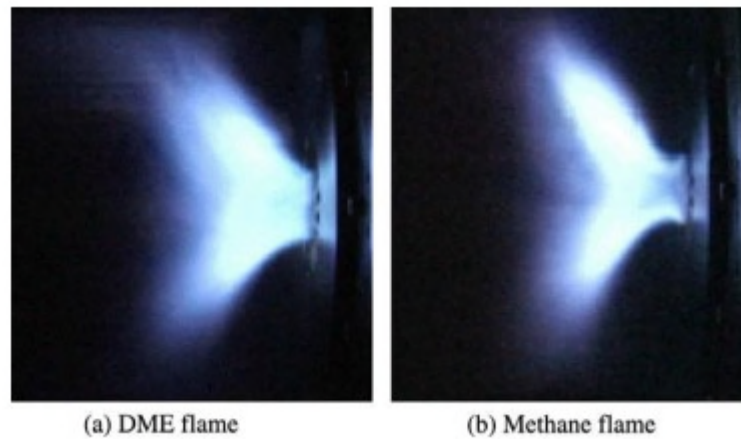


Figure 2-41: Comparison between Methane and DME flames obtained from the experiment [60]

Maniaci [62] compared long range liquid Hydrogen aircraft against the baseline kerosene for a Boeing 747-400 category mission. It is found that the compressibility drag affects the performance of the Hydrogen aircraft due to the larger cross sectional area of the fuselage compared to the baseline kerosene variant to store the cryogenic tank. As a remedy, it is suggested to reduce the cruise Mach number so that the block energy burn benefits of the Hydrogen aircraft can be increased. It is worth noting that the turbofan engines used in the assessments are the same as that of the baseline kerosene and the implications on the turbofan cycle design are not investigated.

Daggett et al [63] reviews alternative fuels for use in commercial aircraft. The study mainly looks at short term, medium term, and far future term options for commercial aviation. For short term, synthetic fuels are proposed. These are fuels derived from Fischer-Tropsch process based on feedstocks from fossil sources such as Coal or Natural Gas. The advantages of these fuels is that they are cleaner burning with no sulphur, they have higher thermal stability which can be important to high performance military engines, they have less particulate emissions, better low temperature properties and low viscosity at low temperatures. However, on the downside, due to their production energy requirements, the CO₂ emission from production is very high and as a result, for these fuels to be viable, CO₂ emissions have to be captured and sequestered

permanently. These fuels will be blended with conventional aviation fuels as demonstrated in Figure 2-42 for the near term.

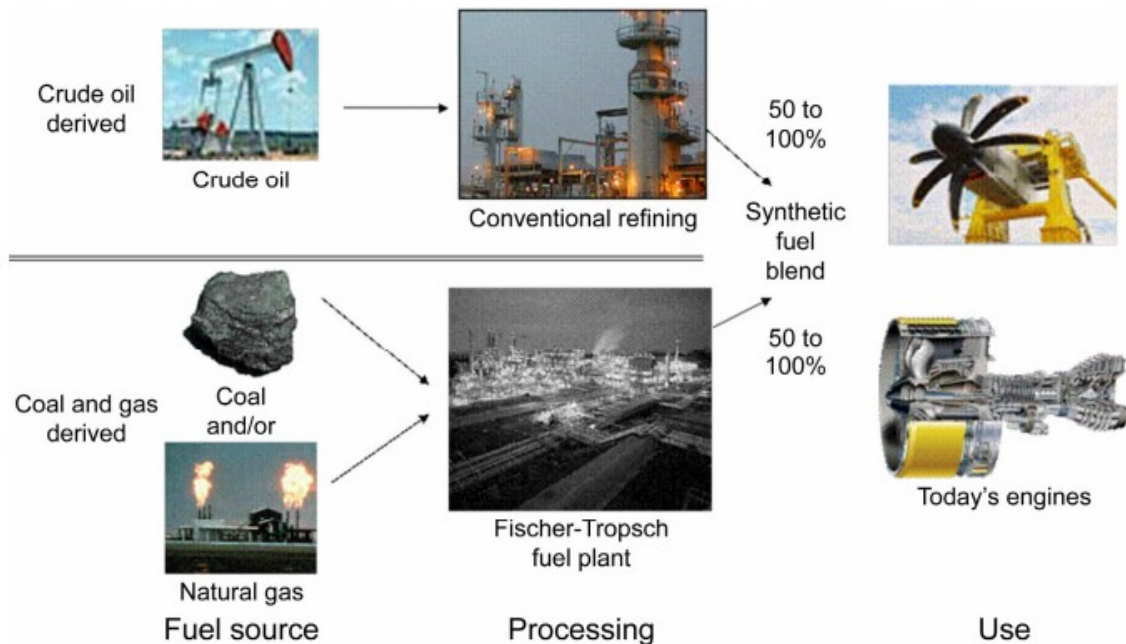


Figure 2-42: Near term aviation fuels derived from conventional and synthetic jet fuels [63]

For the medium term, biofuels are proposed. These are plant derived fuels that could include feedstocks such as soybean oils, palm oils, corn, switchgrass, and algae. These offer reduction in life cycle CO₂ emissions. The major drawback with these biofuels is the huge land requirements for farming to produce these fuels. These biofuels are then blended with the synthetic fuels as shown in Figure 2-43 coupled with new engine configurations.

For the far future term, low or zero carbon cryogenic fuels such as liquid Hydrogen and Methane with redesigned airframe and engine options are proposed as shown in Figure 2-44. It is stated that a heat exchanger will be required for vaporising and heating the fuel prior to combustion with modifications to the combustor and fuel system of the aircraft engine using these fuels.

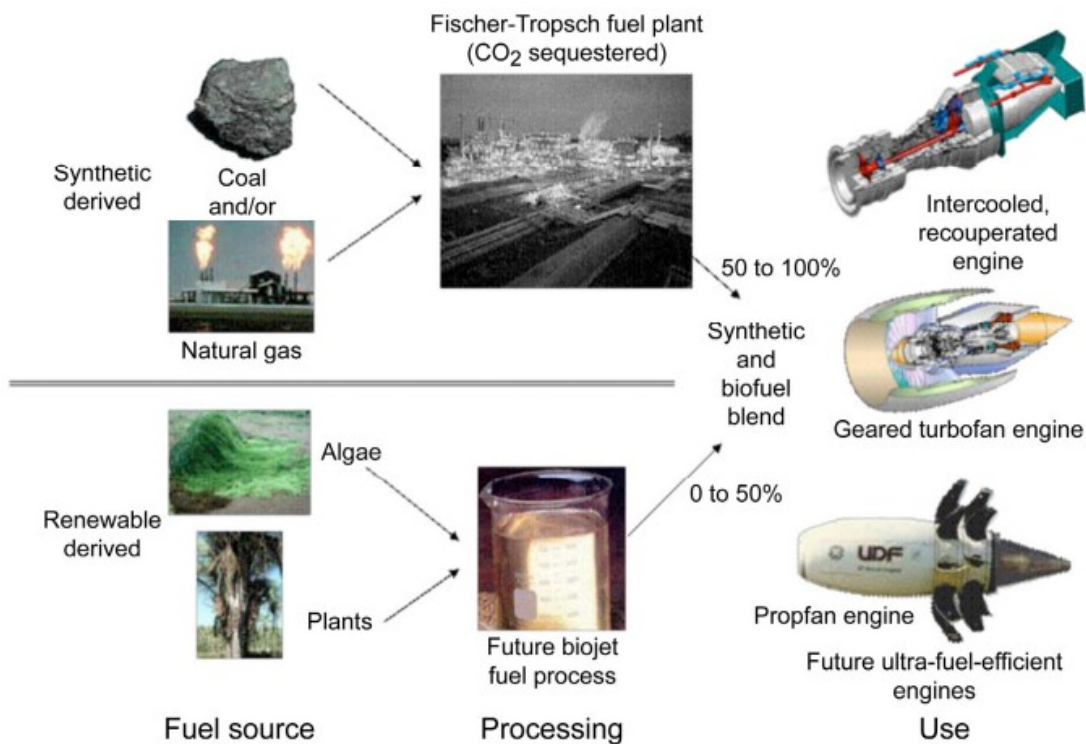


Figure 2-43: Midterm aviation fuels derived from blends of synthetic and biofuels [63]

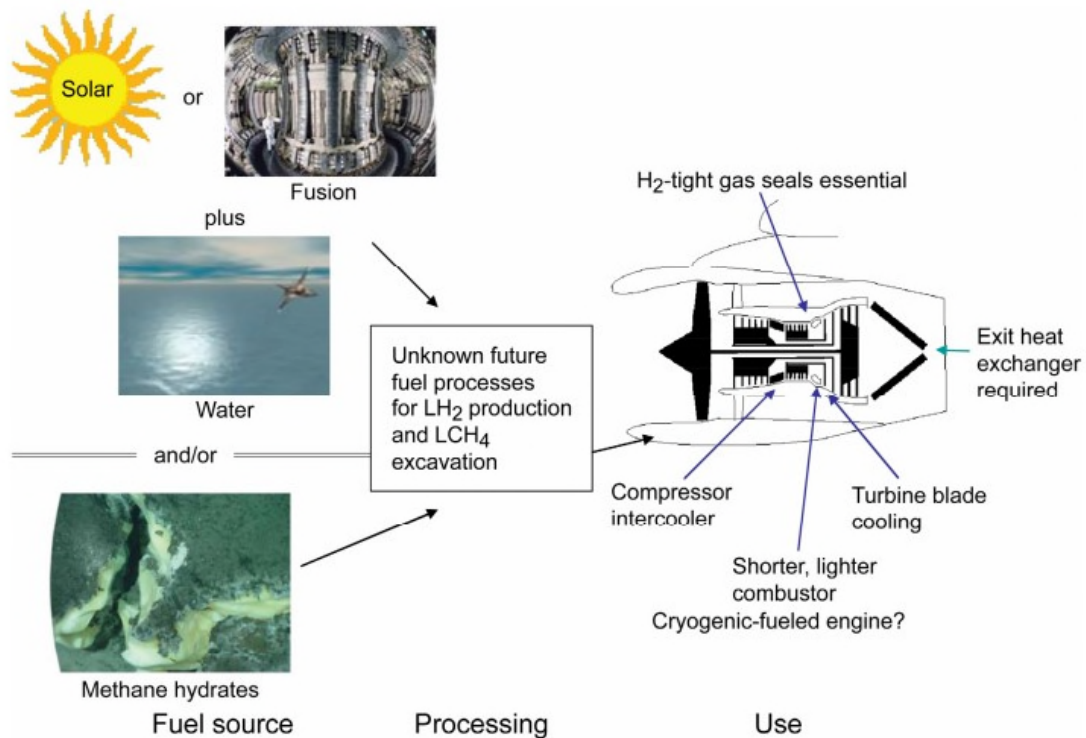


Figure 2-44: Far term aviation fuels Hydrogen and Methane [63]

Haglind and Singh [64] reports the effects of Hydrogen fuel on aero engine performance for a single design operating point at take-off. A heat exchanger at the exhaust is used to heat the Hydrogen to 250K before injecting into combustion chamber. The study highlights when switching to Hydrogen, TET reduces by more than 30K for a V2527-A5 turbofan engine for the same net thrust, or the net thrust increases when the TET is kept the same. This effect is due to the increased water content of the working fluid which has a higher C_p compared to CO_2 . However, the study assumes fixed thrust for both Hydrogen and kerosene engines which is not the case when aircraft thrust requirements are considered and only assesses for the same thermodynamic cycle without investigating potential implications for a cycle redesign. The pressure losses due to the operation of the heat exchanger are also not considered in the study.

Daggett et al [65] discusses the application of biofuels, methanol, ethanol, liquid Natural gas, liquid Hydrogen and synthetic fuels for aviation. It is reported that synthetic fuels synthesised by Fischer-Tropsch process can replace conventional kerosene. However, since their feedstocks are fossil based, their environmental credentials are not good. Biofuels on the other hand derived from plants can be carbon neutral but they need to go through additional fuel processing to match the aviation fuel standards which can be expensive. Also limited availability of arable lands are also a challenge for these fuels. Figure 2-45 shows the weight and volume requirements compared to conventional jet fuel.

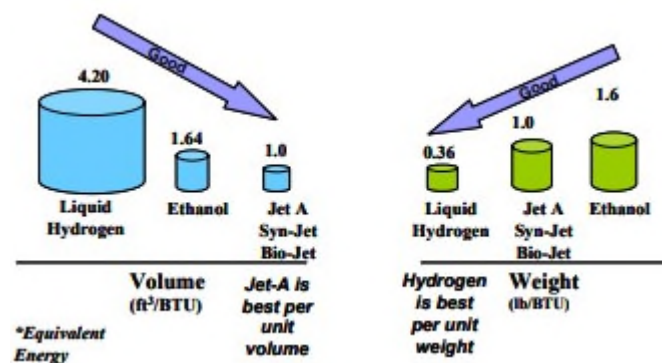


Figure 2-45: Aircraft fuels need to have high energy content per weight and volume [65]

Hydrogen production requires lots of energy such as clean electrical power and lots of clean water. Cryogenic fuels Hydrogen and Methane will require new and more complex ground transportation, storage, distribution, and vent capture system. Figure 2-46 demonstrates the impact of liquid Hydrogen on the design of a Boeing 737 style aircraft. The lighter Hydrogen fuel leads to using smaller engines.

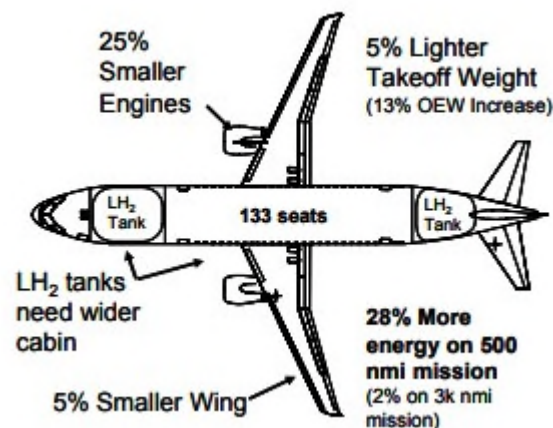


Figure 2-46: Effects of LH₂ on a Boeing 737 style aircraft [65]

When it comes to alcohol powered airplanes, the airplanes have also to be specifically designed if they want to achieve the same mission capability as kerosene variant. However, it is reported that the Ethanol fuel is much easier to store, and handle compared to cryogenic fuels. Since alcohol fuels have less energy in them, the airplane sized for a given mission tends to be larger in size. Figure 2-47 demonstrates the impact of Ethanol on the design of a Boeing 737 style aircraft. The heavier fuel leads to the usage of bigger engines. These problems are not faced with synthetic or biofuels as they are drop in fuels ready to be deployed in commercial aircraft.

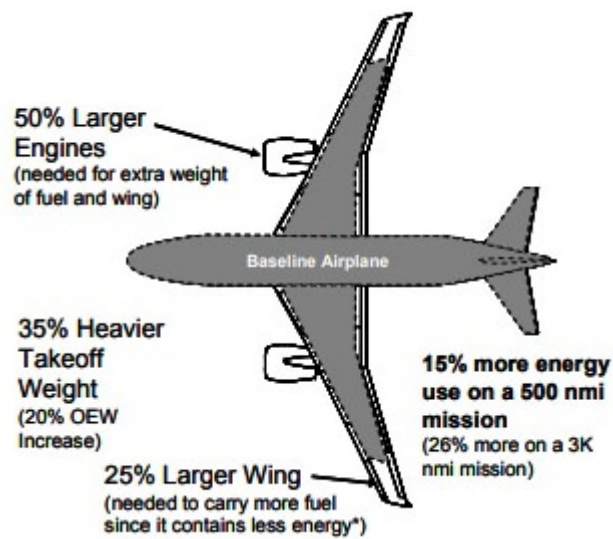


Figure 2-47: Effects of Ethanol on a Boeing 737 style aircraft [65]

Svensson et al [66] investigated the application of liquid Hydrogen for medium range aircraft and compared with kerosene variant from an environmental point of view. The effect of reduced cruise altitude is assessed in an attempt to observe the environmental impact. The aircraft is optimised every time for the new altitude. Although highly sensitive to GWP model assumptions, it is found that reducing the cruise altitude for Hydrogen aircraft is better from an environmental point of view as demonstrated in Figure 2-48.

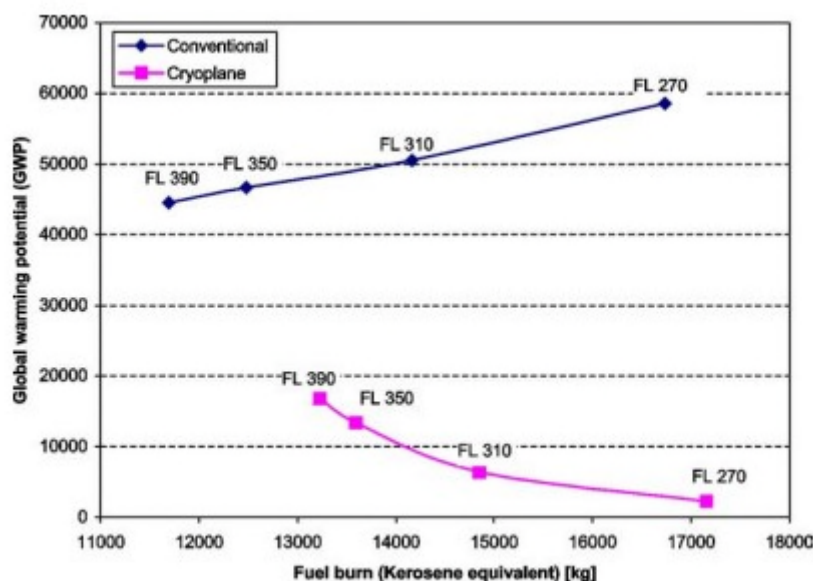


Figure 2-48: Effect of reducing cruise altitude for Hydrogen aircraft [66]

It must be noted that the effect of contrails is not considered in the assessment. When looking into the turbofan engines used for the assessment, the thermodynamic cycle is kept the same as the baseline kerosene and scaled according to the aircraft thrust requirements. As a result, the implications on the cycle design for Hydrogen fuelled turbofan are not discussed or investigated. A technology factor for SFC is simply applied to both kerosene and Hydrogen powered turbofan engines to consider future technology gains.

Corchero and Montanes [67] demonstrates the effects of Hydrogen fuel on engine performance of turbofan engines. As the fuel injection temperature is increased, the reduction in SFC and increase in TET for same thrust (or reduction in thrust for same TET) is demonstrated for Hydrogen turbofan engines. It is reported that a TET benefit of 37K is obtained when switching to Hydrogen fuel for the same net thrust. On comparing an engine with a heat exchanger installed at the LPT exit with an engine without the heat exchanger, the heat exchanger leads to performance penalty in terms of thrust loss and TET increase. However, the study assesses the performance of the Hydrogen turbofan engines for the same thermodynamic cycle without considering the Hydrogen aircraft thrust requirements and does not account for the heat exchanger pressure losses.

Airbus [68] conducted a systems analysis for aircraft powered by liquid Hydrogen. The investigations were conducted for a range of aircraft categories as demonstrated in Figure 2-49. It demonstrates the changes in OEW and MTOW.

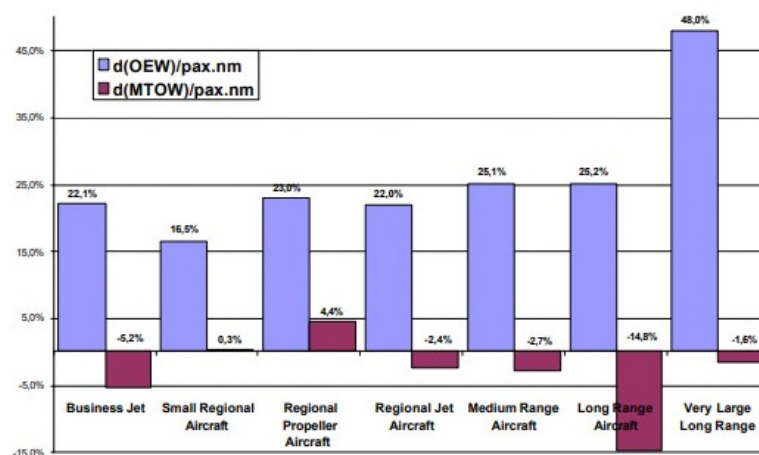


Figure 2-49: Change in OEW and MTOW when converted to liquid Hydrogen [68]

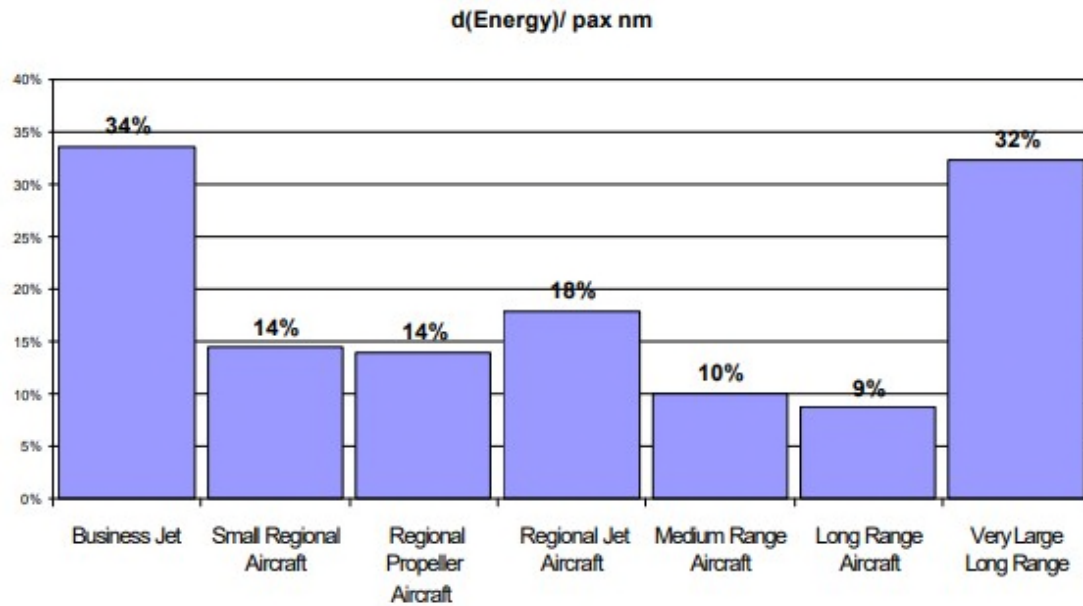


Figure 2-50: Change in energy consumption of Hydrogen powered aircraft [68]

Figure 2-50 demonstrates the increase in energy consumption compared to kerosene aircraft due to the bigger wetted surface of the aircraft due to the Hydrogen storage. The propulsion system assessment is the work done in the references ([67], [66], [64] [69]) and it is stated in the report that the engines can be scaled according to the requirements. As a result, the implication of these aircrafts on the cycle design of a Hydrogen turbofan engine are not investigated further.

Boggia and Jackson [69] investigated turbofan cycles using liquid Hydrogen heat sink capabilities. The assessments are made for a 2-spool turbofan engine. Three kind of engine concepts using liquid Hydrogen's heat sink capability are assessed namely, precooled engine, high TET engine and fuel preheating. The precooled engine cools the air using liquid Hydrogen before entry into the core of the engine. The OPR is increased to have the compressor exit temperature. The BPR is also increased. The high TET engine cools the turbine cooling air using gaseous Hydrogen once it is vaporized from the core exhaust heat. As a result, a higher TET is obtained for the same blade cooling effectiveness. The BPR is increased since the thrust is very high. In fuel preheating engine concept, the fuel temperature is increased to very high temperatures above 475K using the core

exhaust heat. It is reported that the fuel preheating concept with core exhaust heat is the simplest engine requiring minimum modifications whereas precooled and high TET concept looks attractive from an economic point of view. Although the results are interesting, the assessment does not take into account the pressure losses due to the operation of a heat exchanger and does not perform the assessments for a fixed thrust and specific thrust requirements to allow for proper efficiency quantification.

Sefain [70] investigated novel (unconventional) aircraft concepts for liquid Hydrogen powered aircraft in medium range category as illustrated in Figure 2-51.

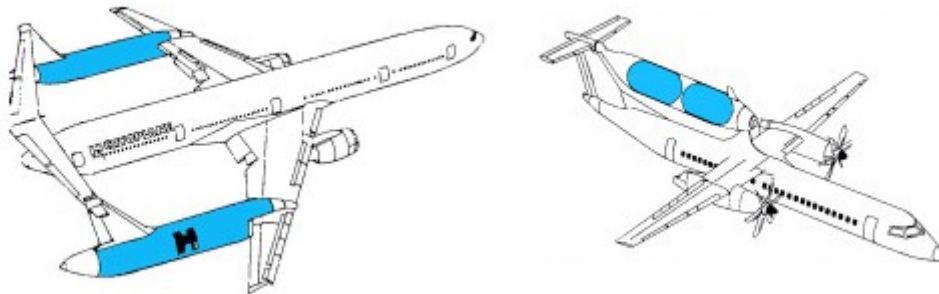


Figure 2-51: Twin tail-boom (left) and tail-tank (right) liquid Hydrogen aircraft concepts [70]

Although outside the scope of this thesis, it's interesting to see the different aircraft architectures possible when trying to address the Hydrogen storage into the aircraft. It is reported that Hydrogen fuelled aircraft will be at least as safe as kerosene aircraft. Since this is a conceptual study, the aircraft sizing was performed using values for Hydrogen engine SFC borrowed from the literature.

Studies by Pohl and Malychev [71] and Contreras et al [72] discusses the applicability of Hydrogen as an aviation fuel. The insulation of the cryogenic tanks has to allow for overnight stops of the aircraft without boil-off. For the turbofan engines, some component modifications are necessary. These are fuel pumps, heat exchangers to evaporate the LH_2 before injection into combustion chamber, the fuel control unit which has to consider both gaseous and liquid Hydrogen flow

metering and finally the combustion chamber. Although the Hydrogen aircraft can be draggier due to increased volume requirements of the tanks, using Hydrogen fuel's heat sink potential to cool down aircraft skin can enable laminar flow and thus enable significant reduction in aircraft drag. Liquid Hydrogen has a high liquid to gas volume expansion ratio which requires all the piping setup to have a pressure relief device. A more thorough understanding of ice crystal aerosols is required to study the effects of water vapour as a greenhouse gas.

Eiff et al [73] investigated the effects of Ethanol blended turbine fuels experimentally on a Allison T-63 combustor components. The tests were performed for Ethanol blends with Jet A by weight from 0% to 50% with incremental steps of 5%. The study observed significant reductions in CO₂, oxides of nitrogen and soot(smoke) emissions as the blend ratios of Ethanol were increased. Aldehyde emissions were increased as a negative effect when the blend ratios were increased. However, the study demonstrated the viability of ethanol blended turbine fuel for use in unmodified aircraft turbine engines and is an indicator for the performance of alcohol class of fuels for turbine engines.

Brewer [74]–[76] investigated liquid Hydrogen for aircraft applications particularly for low speed and high speed applications. When it comes to subsonic applications, engine and aircraft performance is assessed. Various candidate concepts are assessed for turbofan engines using LH₂'s heat sink capability. These include precooling, intercooling, cooling of turbine cooling air, regenerative fuel heating and fuel expander cycle. These cycles are designed based on only design point and compared with DOC as a figure of merit. It is reported that regenerative fuel heating, where Hydrogen is heated using exhaust heat from the heat exchanger after the LPT, was the least complicated concept and provided best DOC reduction on par with the expander cycle concept. The LH₂ aircraft was assessed covering short to long range aircrafts and found that the mission energy burn is lower for all ranges compared to kerosene based counterpart. However, it must be noted that the turbofan engines used for all these assessments are scaled to meet the desired thrust requirements, thereby keeping the same thermodynamic cycle and not investigating the implications on turbofan engine

designs due to the various aircraft thrust requirements. A comparison is also made with liquid Methane aircraft that's reported from the study by Carson et al [77]. Liquid Methane aircraft is observed to burn more mission energy compared to kerosene in some cases for the mission ranges assessed. The turbofan engines using liquid Methane are also scaled according to the aircraft thrust requirements keeping the same thermodynamic cycle. An engine cycle comparison is made between liquid Hydrogen, liquid Methane, and kerosene. However, the cycle design appears to be the same with just changes to the SFC values compared for the same thrust. As a result, the turbofan cycle design implications of aircraft carrying different fuel is not addressed properly since they could have different thrust requirements which could lead to a different cycle design.

Sosounov and Orlov [78] reported the details of the experimental NK-88 turbofan engine that was used for the demonstration flights powered by liquid Hydrogen and Methane on the TU-155 aircraft.

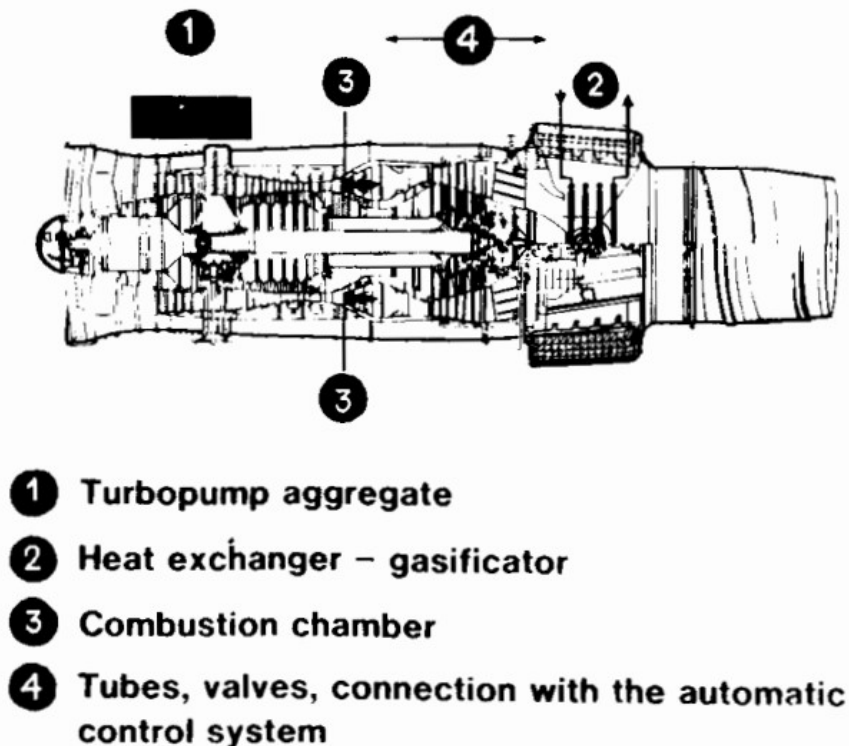


Figure 2-52: NK-88 basic Hydrogen systems [78]

The basic systems on the converted NK-88 turbofan engine are shown in Figure 2-52. It showcases the heat exchanger placed after the turbine to heat the Hydrogen before injection into the combustion chamber. The combustion chamber fuel nozzles were converted to operate on Hydrogen. Interestingly, the NK-88 Hydrogen engine on rig test demonstrated 40 – 50 K temperature drop in front of the turbines along with lower SFC for the same thrust as shown in Figure 2-53.

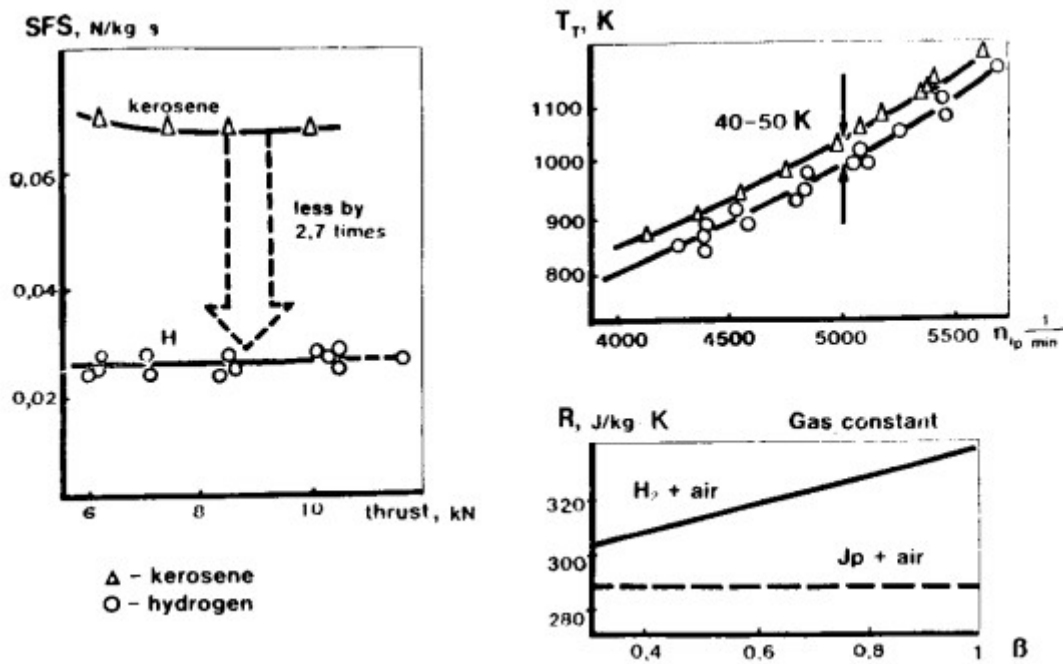


Figure 2-53: NK-88 Hydrogen engine rig performance [78]

Verkamp et al [79] investigated experimentally Ammonia combustion in gas turbine burners. The study highlighted certain challenges of burning Ammonia in gas turbine burners designed for hydrocarbon fuels which are high minimum ignition energy and low flame stability arising from low flame speeds. As a remedy, partial decomposition of Ammonia into Hydrogen for use in conventional burners to improve the performance was suggested. Pratt [80] also reports similar findings about the challenges of burning Ammonia in gas turbine combustors mainly attributable to the slow chemical reaction kinetics which leads to flame blowouts.

Kailos [81] reports details of the study that was done for the US army for Ammonia fuelled helicopter and propeller driven aircraft. The study highlights the significant limitations of Ammonia aircraft in the payload carrying capability especially since it was considered for a military application. Emissions were not an attribute that was investigated in this study and lacked an analysis of a turbofan engine.

Newhall and Starkman [82] investigated Ammonia as a gas turbine fuel and reported that Ammonia can provide superior thermal efficiencies up to 10% higher than hydrocarbons. However, the study is fundamental in nature and hence did not provide insights into turbofan engine performance and design using the fuel.

Siddiqui and Dincer [83] evaluates the life cycle emissions of alternative fuels for aviation. Alternative fuels such as Hydrogen, Ammonia, Ethanol, Methanol, Biodiesel and DME are assessed. The study considers airport, fuel and aircraft in its life cycle stages for the assessments. Its reported that the conventional steam methane reforming based route for Hydrogen and Ammonia fuels lead to highest global warming potential (0.098 kgCO₂eq /tonnekm for Hydrogen and 1.03 kgCO₂eq /tonnekm for Ammonia). The alternative production route from geothermal energy sources looked promising with less than 0.02 kgCO₂eq /tonnekm for Hydrogen and less than 0.2 kgCO₂eq /tonnekm for Ammonia. Among the hydrocarbon alternatives, DME appeared to produce the most global warming impact with 1.3 kgCO₂eq /tonnekm based on conventional route of production. However, it must be noted that production route using renewable energy is not considered and is proposed as further work.

2.3 Research questions

Based on the current state-of-the-art studies found in public domain regarding alternative fuels for civil aviation, the effects of alternative fuels on the design of turbofan engines are vague or poorly defined with much attention given to Hydrogen and Methane.

This is understood based on the following trends from the literature review:

1. Studies that discuss the effects of alternative fuels on turbofan engine performance and design, do so for the same thrust requirements as kerosene aircraft which can be misleading or inconclusive. Even for the same thrust requirements, there appears to be no study that tries to address the design space of turbofan engines operating with alternative fuels.
2. No studies were found to quantify the impact of alternative fuels on turbofan engine size and weight.
3. Studies that discuss the effects of alternative fuels at aircraft mission level, do so by simply scaling the turbofan engines according to the aircraft requirements, thereby not addressing the impacts on the turbofan engine cycle design under the influence of alternative fuelled aircraft mission.
4. Studies that investigate how fuel conditioning can be exploited to improve the engine performance, do so either only for design point calculations or do not assess for fixed thrust requirements. As a result, fuel conditioning impact of alternative fuels on turbofan cycle design appears to be incomplete.

Given the fact that alternative fuels could potentially power the next generation of turbofan engines, the following research questions are identified to provide knowledge contribution to both academia and industry:

- 1. How do alternative fuels impact the design space of turbofan engines?***
- 2. How do alternative fuels impact the size and weight of turbofan engines?***
- 3. How do alternative fuels impact the turbofan cycle design when aircraft mission is considered?***
- 4. How does fuel conditioning of alternative fuels impact the turbofan cycle design?***

3 METHODOLOGY

This chapter discusses the methodology and methods followed throughout this PhD project. First section presents an overall methodology which showcases the various activities involved throughout the project. The subsequent sections discuss the rationale and methods behind these activities.

3.1 General methodology

To tackle the aim of the PhD project, a suitable overall methodology is constructed. Figure 3-1 depicts the constructed methodology with the main blocks displayed. The detailed explanations of methods used under these blocks are provided in the subsequent sections.

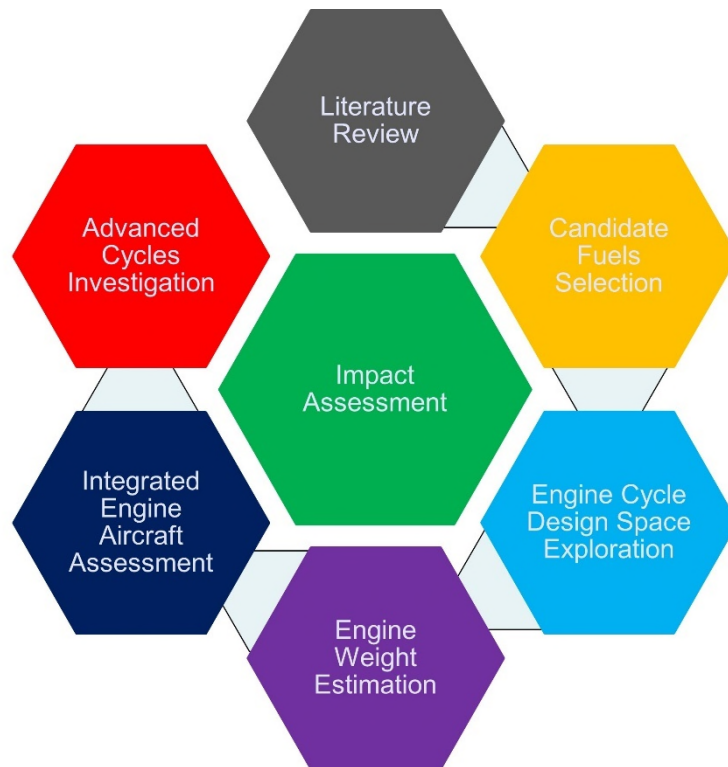


Figure 3-1: Overall methodology

The overall workflow (activities) in order is described as follows:

1. Literature review: This activity aimed to get familiarised with the topic of alternative fuels in aviation and in the process identify research gaps for the project.
2. Candidate fuels selection: The initial phase of the project required to shortlist potential candidate fuels for civil aviation. The shortlisted fuels are picked for further investigations in the project.
3. Engine cycle design space exploration: This activity aimed to support the main aim of the PhD project to assess the impact of alternative fuels on advanced turbofan engine designs.
4. Engine weight estimation: During the course of this PhD project, Cranfield University's engine weight estimation software ATLAS about which further details are provided later on, was equipped to handle only kerosene (Jet A/Jet A-1) fuel. Since turbomachinery parameters utilised quantities dependant on fuel properties, the software had to be adapted to handle alternative fuels before performing engine weight estimation assessments.
5. Integrated engine aircraft assessment: Every alternative fuel due to its fuel properties, impacts the aircraft in its range, payload, operating empty weight and fuel requirements. This ultimately affects the total weight of the aircraft using alternative fuels. Hence, this activity aims to investigate the impact of alternative fuels on turbofan engine design once the influence of alternative fuelled aircraft is considered.
6. Advanced cycles investigation: Alternative fuels are known to have varying heat capacities and as a result, different fuel conditioning requirements. This activity aimed to look at the impact of fuel conditioning on cycle design for turbofan engines using alternative fuels.

3.2 Candidate fuels selection

The objective of shortlisting potential candidate fuels for aviation is a very important aspect for this project as this probably can lead to uncovering aspects of different fuels never thought of before in context for aviation applications. Hence, this objective is tackled in a systematic manner. Figure 3-2 shows the tasks that are performed to accomplish this objective.

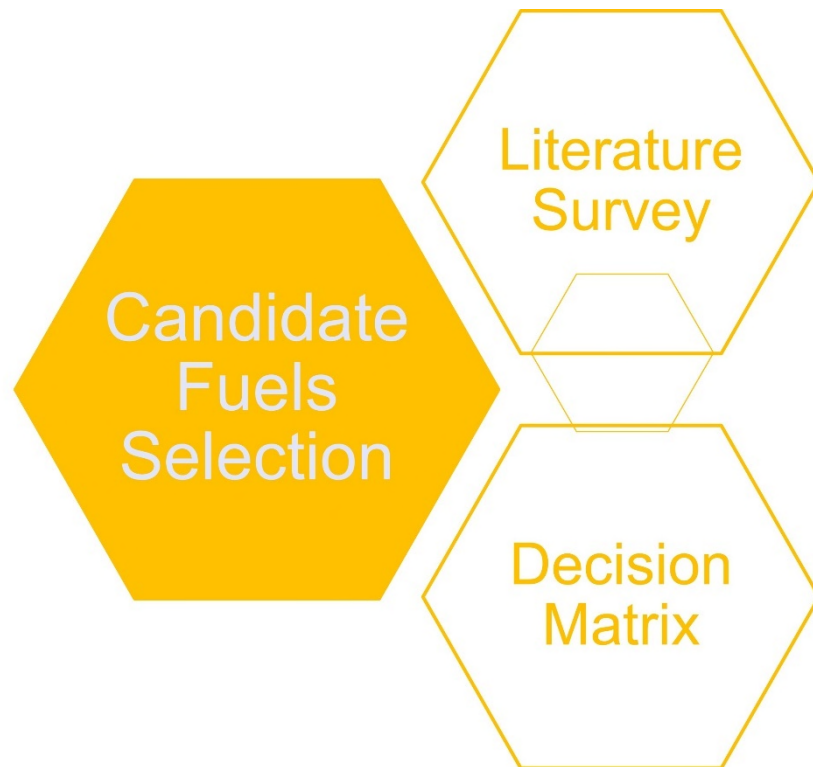


Figure 3-2: Tasks for candidate fuels objective

3.2.1 Literature survey

The approach to get started with accomplishing this task is to familiarise with the properties and terminologies associated with aviation fuel. The idea is to create a database of fuel properties populated with those of alternative fuels and later proceed with the comparison. A straightforward method is to assess the top level requirements set out in ASTM standards for Jet fuel D1655 [84] and compare them to alternative fuel properties obtained from literature. It is decided to consider different families of fuels to widen the search for alternative fuels for civil aviation. The fuels considered from different families are narrowed down based on certain top level requirements set out by ASTM D1655 and engineering judgement considering civil aviation.

3.2.2 Decision matrix (pugh matrix)

Once the alternative fuels were narrowed down, a decision matrix (Pugh Matrix) is developed to support the generation of candidate list of alternative fuels for further investigation in the PhD project. Fuel properties that are deemed important

for civil aviation are considered in the matrix. It is to be noted that these properties are by no means exhaustive as a thorough evaluation of fuels is outside the scope of this study. These properties are weighted to show their overall importance during the comparison between the fuels. The weights are employed considering the fuels application to aviation and gas turbine engines in general. The fuels are then ranked and scored based on their relative values of properties. This procedure helps one to obtain a clearer picture of the standings between the fuels. Table 3-1 shows the properties and weights considered in the decision matrix under 3 different criteria namely performance, sizing and handling and safety criteria. Each fuel property is ranked for different fuels with ranking varying from scale 0 to 20 where 0 corresponds to minimum rank and 20 corresponds to a maximum rank.

Table 3-1: Selection criteria

Performance criteria	Weighting
Specific energy (MJ/kg)	10
Energy density (MJ/L)	10
Cp of the fuel (kJ/kg.K)	8
Carbon number (Number of carbon atoms in the molecule)	6
Autoignition temperature (°C)	4
H/C atomic ratio	4
Sizing criteria	Weighting
Specific volume (L/kg)	10
Handling and safety criteria	Weighting
Flammability (RFL – LFL)	10
Molecular weight (g/mol)	10

RFL stands for Rich Flammability Limit and LFL stands for Lean Flammability Limit. These both properties quantify the amount of fuel in air by percentage volume defining the rich and lean mixtures.

The ranking and scoring calculations are performed according to the following guidelines:

1. For each fuel property, a best value is found among the fuels.
2. The fuel with the best value always gets the maximum rank i.e 20.
3. The remaining fuels' ranks are scaled according to their value compared to the best value.
4. The highest value is considered as best value for Specific energy, Energy density, Cp of the fuel, H/C atomic ratio. The lowest value is considered as best value for Carbon number, Autoignition temperature, Specific volume, Flammability and Molecular weight.
5. The rank is then multiplied by the weights of the properties to give a score.
6. The final score for each fuel is obtained by the summation of all the scores for all properties.

The significance of the different fuel properties under different criteria relevant to civil aviation and gas turbine engines is explained briefly as follows:

1. Specific energy: This parameter directly affects the fuel consumption in aircraft engines. Fuel consumption reduces as this parameter increases and can impact the aircraft weight. Hence, the range of the aircraft can be affected. A weighting of 10 is applied to highlight its importance for both engine and aircraft performance.
2. Energy density: It provides information pertaining to energy that will be stored in the tanks of the aircraft. This again will affect the range of the aircraft. In engines, the fuel flow rates can be metered on a volumetric basis, and hence this parameter can directly affect the fuel consumption of engines. A weighting of 10 is applied to highlight its importance for both engine and aircraft performance.
3. Cp of the fuel: It provides information about the ability of fuel to act as a heat sink. Heat sink capabilities are higher for higher values of this

parameter. This can be important since fuel is used for cooling the oil, before being injected into the combustion chamber and hence can recover waste energy. A weighting of 8 is applied to highlight its importance for engine performance and design.

4. Carbon number: This is seen as an indicator to the carbon distribution and carbon chain length in the fuel. It can directly impact the carbon dioxide, soot, and Unburned Hydrocarbon (UHC) emissions. Particulate emissions are a precursor for contrails. A weighting of 6 is applied to highlight its importance related to environmental impacts.
5. Autoignition temperature: This is utilised as a method to characterise the reactivity of fuels. A weighting of 4 is applied to highlight its importance in capturing the energetic nature of fuels.
6. H/C atomic ratio: This allows one to have an idea of the amount of water vapor relative to carbon dioxide produced upon stoichiometric combustion. Water vapor has higher C_p compared to carbon dioxide and can increase the enthalpy drop for the turbines as discussed by Burnes and Camou [26] and increase the performance of aircraft engines. The water vapor produced generally increases as this parameter increases. A weighting of 4 is applied to highlight its importance for engine performance.
7. Specific volume: Every fuel due to its physico-chemical characteristics has different volume requirements. This is particularly important for aviation since increasing space to accommodate fuels comes with consequences on aircraft such as increased drag, increased operating empty weight due to associated fuel tanks for it and finally increased take-off weight. A weighting of 10 is applied to highlight its direct impact on aircraft performance.
8. Flammability: This parameter points towards the safety aspect of adopting a fuel for aviation. Mainly the range of lean limit (LFL) and rich limit (RFL) of flammability is considered here. A weighting of 10 is applied to highlight its direct impact on risk for aviation.
9. Molecular weight: This parameter allows one to compare the safety hazard posed by a fuel in the event of a fuel leak. A fuel lighter than air tends to

rise up and is safer compared to ones that are heavier than air. A weighting of 10 is applied to highlight its direct impact on risk for aviation.

It must be noted that the weighting applied to the several properties are prioritised based on its aviation application as a whole and the performance impact it has on aircraft and turbofan engine. Further to it, as an additional investigation, a sensitivity analysis on the weighting is proposed as future work.

3.3 Engine cycle design space exploration

The idea behind this objective is to characterise and demonstrate the effects of the proposed alternative fuels on a typical turbofan engine of a selected architecture. Hence, this objective is divided into tasks as shown in Figure 3-3.

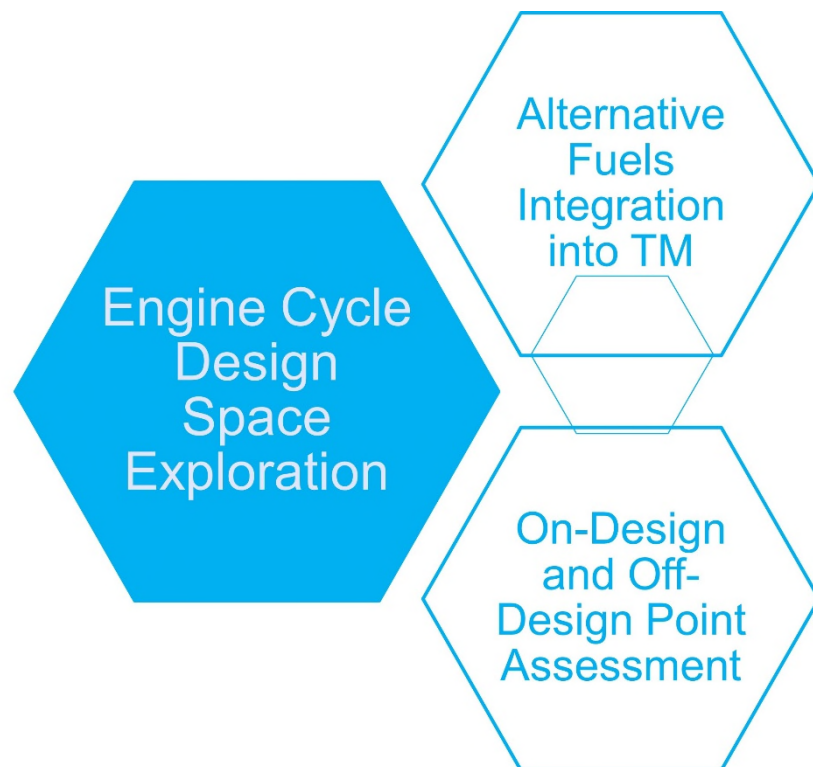


Figure 3-3: Tasks for engine cycle design space exploration objective

3.3.1 Alternative fuels integration into TM (TURBOMATCH)

One of the main tasks to assess alternative fuels for turbofan engines is to implement these fuels into TURBOMATCH. TURBOMATCH is Cranfield University's in house gas turbine performance software capable of simulating

both steady- state and transient performance of gas turbine engines. It's a Fortran based program with a modular structure enabling easy assessment of novel gas turbine configurations. At the time of this PhD, there existed some alternative fuels already implemented in TURBOMATCH. These included Hydrogen, Natural Gas from different sources and Biofuels sourced from Jatropha, Camelina and Microalgae. However, the fuels shortlisted had additional fuels other than already present in TURBOMATCH. There are several properties of the fuel required to be input to integrate it into TURBOMATCH. These are as follows:

1. Lower Heating Value (MJ/kg)
2. Stoichiometric moles of air
3. Stoichiometric FAR on a mass basis
4. Stoichiometric moles of components of the combustion products

The combustion products considered are water vapor, carbon dioxide and nitrogen. This is assuming complete combustion without any dissociation. Non dissociation model is adopted here as a first step to observe the effects on the turbofan cycle design. Dissociated model implementation to improve the fidelity of the assessment is a future step and will be discussed in future work section. The stoichiometric fuel properties with air are adopted from the works of Goodger [85]. The properties are cross verified by hand calculations before implementing it into TURBOMATCH.

3.3.2 On-design and off-design point assessment

To compare the performance of the turbofan engine cycles between alternative fuels, it is decided to assess them at an optimised design point for fixed thrust requirements, fixed design point component efficiencies and fixed flight conditions namely ISA, Mach number and altitude. The cycle design point considered for this task is cruise since this is the segment where the share of the fuel burn is highest and optimising the engines for this point can reduce the fuel consumption of the aircraft. For a given BPR, T40 & OPR, the FPR is selected as the design variable to achieve the correct bypass nozzle to core nozzle jet velocities ratio to minimise the SFC. This is a well-known method that is discussed by Guha [16] and Pilidis and Palmer [86]. For an unmixed exhaust

system which is the case for civil aircraft engines, as the FPR is varied, the bypass nozzle jet velocity and core exhaust jet velocity change. Once the jet velocities ratio reaches a certain value, maximum thrust is attained for a given fuel consumption rate i.e., in other words minimum SFC. According to Guha [16], minimum SFC occurs when this jet velocities ratio is equal to the so called engine transfer efficiency (approximately product of the fan and low pressure turbine isentropic efficiencies). However, one should note that jet velocities should be fully expanded for this to be true. The assessment is performed maintaining the pressure ratio split between the low pressure and high pressure compressor for a given OPR. Varying the pressure ratio split is beyond the scope of the present investigation and is seen as a potential future work for alternative fuels since it is expected to impact the off design operating points. Once the minimum SFC point is found, an off-design point namely max take-off (EOR) operating point is simulated for fixed thrust settings.

3.4 Engine weight estimation

ATLAS is Cranfield University's turbofan engine weight estimation software [13]. It allows the user to estimate the size and weight of the turbomachinery components. It uses the cycle performance outputs from TURBOMATCH for performing preliminary engine component design and sizing allowing the estimation of the engine component weights. As mentioned previously, ATLAS had the capability to assess engine weights only for kerosene (Jet A/Jet A-1) fuel. This was mainly limited by the fact that thermofluidic properties were only available for kerosene. Hence, this objective is divided into tasks as shown in Figure 3-4.

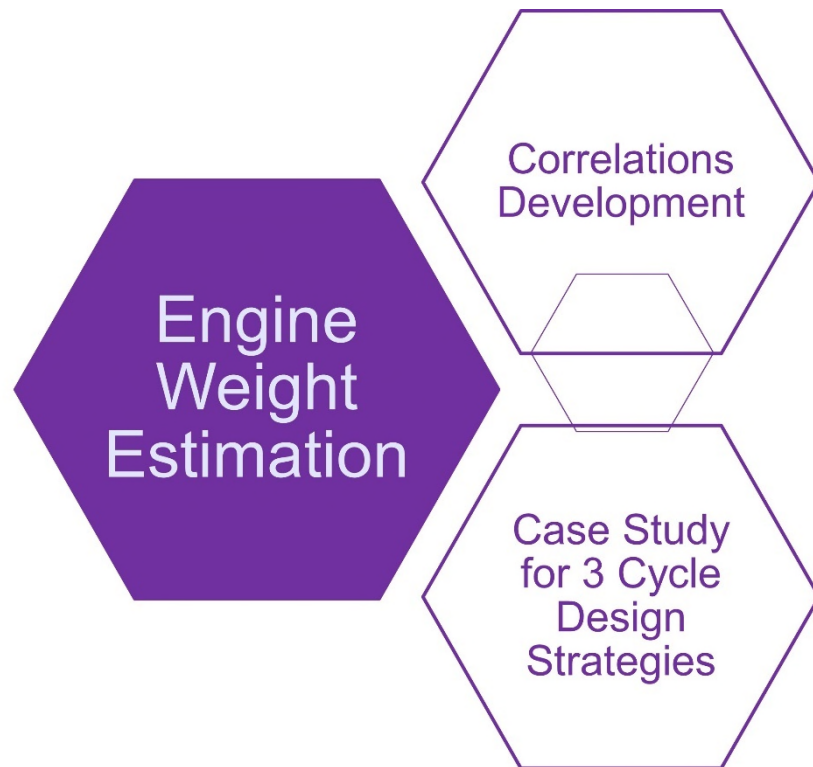


Figure 3-4: Tasks for engine weight estimation objective

As an extension to the contribution of the software, a case study is conducted to investigate the top level effects of the proposed alternative fuels on turbofan engine size and weights through various cycle design strategies.

3.4.1 Correlations development

The motivation behind this development activity is that the turbomachinery parameters utilise quantities dependant on fuel properties. This is mainly affected in the calculation process of the hot section components namely combustor, HPT, IPT and LPT. The parameters affected by the fuel properties are illustrated in Figure 3-5.

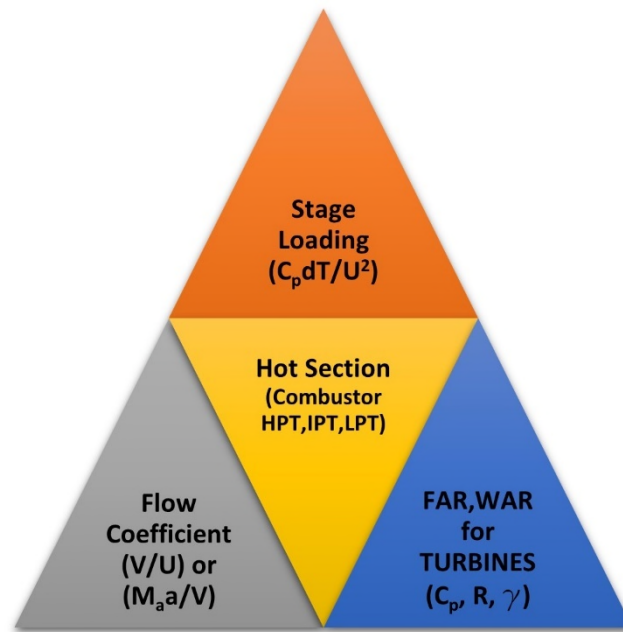


Figure 3-5: Fuel dependant parameters in ATLAS

NASA CEA software is used for developing correlations based on different operating fuels. CEA [87] is a software that can calculate the thermodynamic and transport properties of products in chemical equilibrium with each other. Figure 3-6 shows the steps in which the correlations are developed.

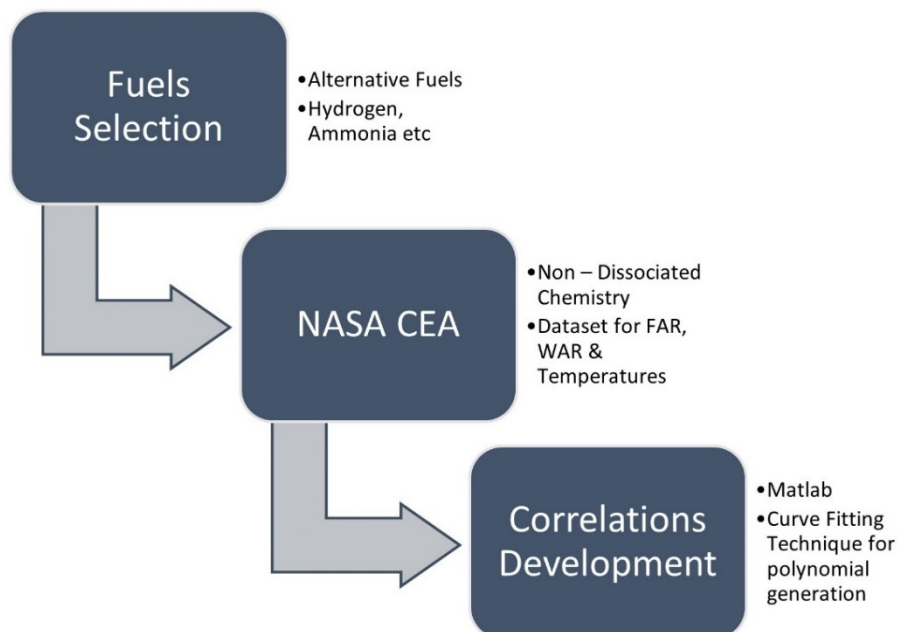


Figure 3-6: Steps taken to generate the correlations

The range of FAR's, WAR's and temperatures for the proposed alternative fuels are set up to be fed into CEA. The ranges are educated from the works of Sethi [25]. The ranges of FAR used for the dataset generation of alternative fuels thermodynamic properties are provided in Table 3-2.

Table 3-2: FAR bounds (equivalence ratio) used for the dataset generation

Fuel	FAR lower bound (equivalence ratio)	FAR upper bound (equivalence ratio)
Hydrogen	0 (0)	0.029158 (1)
Ammonia	0 (0)	0.1642 (1)
DME	0 (0)	0.111 (1)
Butanol	0 (0)	0.089 (1)
Methane	0 (0)	0.05801 (1)
Butane	0 (0)	0.0646 (1)
Octane	0 (0)	0.066 (1)
SAF (Jatropha)	0 (0)	0.0664 (1)

WAR ranged from 0.0 to 0.1. Temperatures ranged from 200K to 2750K with steps of 50K. The problem type is set to 'Assigned Temperature and Pressure' with pressure set to 50 atm. Only one pressure value is used as properties are mainly functions of temperature. This is checked by running another simulation with a different pressure and no change was observed. This is because a non-dissociation model is considered. The products of combustion were set to Ar, CO₂, N₂, H₂O & O₂. In reactants section, oxidiser is set to 'Air' at temperature 298.15K and fuel is set at temperature 298.15K. A dataset consisting of Cp & R for various values of FAR, WAR and temperatures for these fuels are generated. With the help of MATLAB curve fitting toolbox, polynomials for Cp and R are generated as a function of FAR, WAR and temperature with R² of approximately

0.99 for all fuels in the case of C_p and $R^2 = 1$ in the case of R . R^2 denotes the “closeness” of the polynomial to actual dataset.

3.4.2 Case study for 3 cycle design strategies

It is decided to explore the impact of alternative fuels on engine size and weights for turbofan engines since ATLAS has been adapted to handle different fuels. In order to do so, from the knowledge gained from completing the engine cycle design space exploration objective, 3 cycle design strategies are devised and assessed. The 3 cycle design strategies devised are:

1. Resized core
2. Fixed core size as baseline kerosene case
3. Fixed cycle as baseline kerosene case

The cycles are assessed for identical thrust requirements and flight conditions. This meant that power delivered by the engines are kept the same. Three point thrusts are considered for the assessments. These are mid cruise, top of climb and max take-off operating points. Mid cruise point is the design point whereas top of climb and max take-off are off design points. A 3-point cycle design exercise is performed to obtain the cycles for the Resized core strategy.

The methodology for the 3-point cycle design exercise is shown in Figure 3-7. This methodology is devised based on the approach used for multipoint cycle design in the works of Mourouzidis [20].

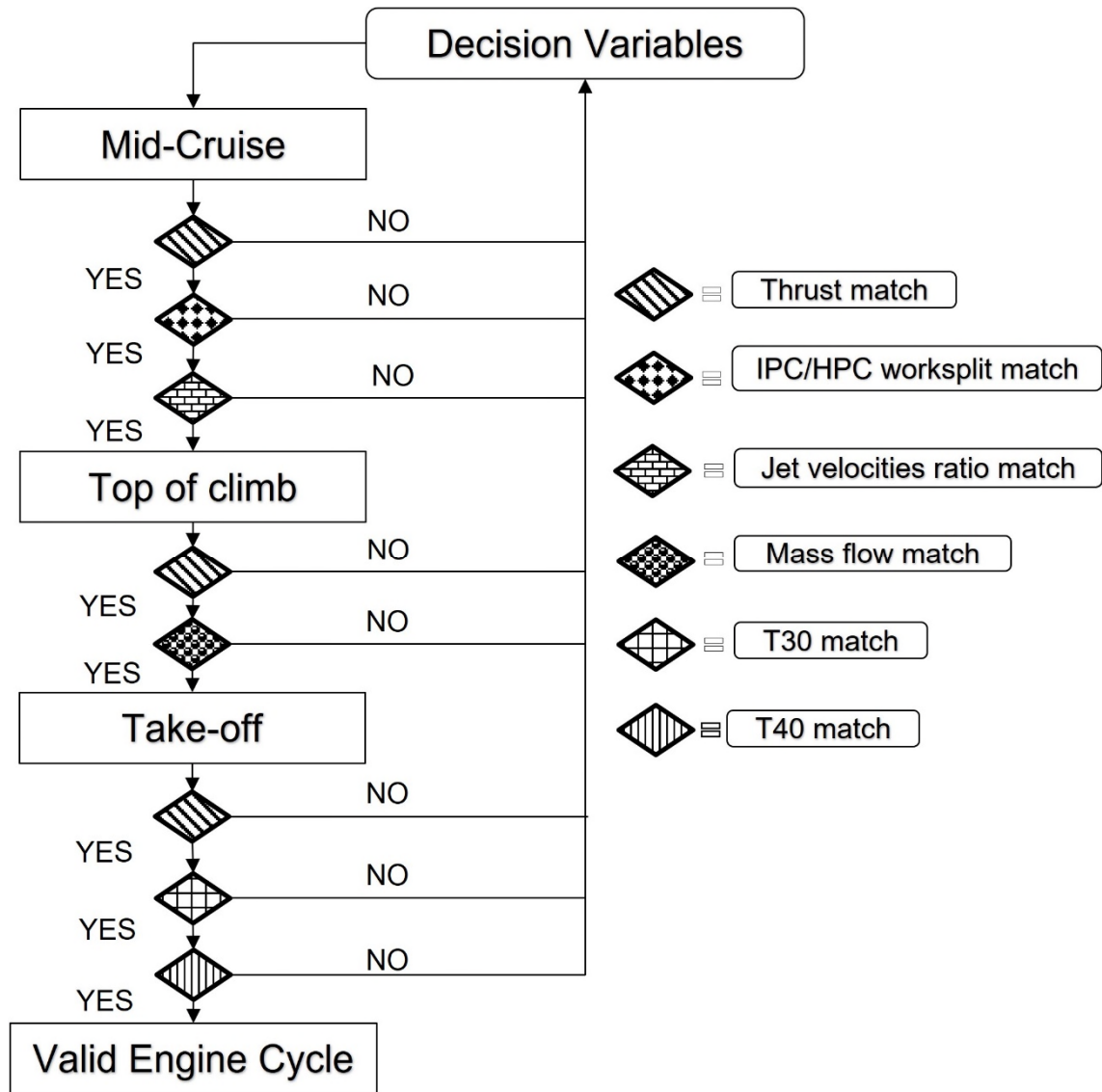


Figure 3-7: 3-point cycle design methodology

In the context of this PhD project, a solver based approach is adopted to perform the cycle design for alternative fuels. The applicability of solver based approach for cycle design has been demonstrated by the works of Kyprianidis [88], [89]. The solver is deployed as an MS-Excel plugin that is built to interact with TURBOMATCH. The decision variables are varied to solve for the matching constraints. The decision variables and the respective constraints for the solving the system of equations are presented in Table 3-3.

Table 3-3: Decision variables and constraints for 3-point cycle matching scheme

Decision variables	Constraints
Mid cruise T40	Take-off T40
IPC PR	Take-off T30
HPC PR	IPC/HPC pressure ratio split
Fan tip PR	TOC Mass flow
Mid cruise BPR	Jet velocities ratio
NGV cooling flow fraction	Take-off T41

The cycles are designed for the same take-off T40 as the baseline cycle with kerosene fuel to have identical peak cycle temperatures, same take-off T30 as the baseline cycle to have identical HPC blade exit temperatures, same core pressure ratio split as the baseline cycle, same TOC mass flow to have the same fan size (diameter) as the baseline cycle, a range of jet velocities ratios to minimize the SFC and same take-off T41 as the baseline cycle to have identical turbine rotor entry temperature. TOC mass flow is linked to fan size (diameter) through mass flow continuity relation in Equation (3-1).

$$\dot{m} = \rho * A * V \quad (3-1)$$

where $\dot{m}$ is the mass flow rate through the fan, ρ is the density of air at the fan inlet, A is the area of the flow at the fan inlet and V is the flow velocity at the fan inlet. Here A can be broken down into the relation in Equation (3-2).

$$A = \pi * (D^2/4) * (1 - (h/t)^2) \quad (3-2)$$

where D is the diameter for the fan and h/t is the hub to tip radius ratio. For fixed flight conditions and hub to tip ratio, fixing the mass flow rate fixes the fan diameter.

For Fixed Core size strategy, the decision variable is mid cruise T40, and constraint is specific thrust. The result of this procedure will result in turbofan

engine cycles for alternative fuels that have the same core inlet mass flows as that of the baseline kerosene cycle.

For Fixed Cycle strategy, the cycle parameters BPR, FPR, OPR and T40 are kept the same as the baseline kerosene cycle and off design cases simulated for fixed flight conditions and thrust requirements.

Once these cycles are obtained, the cycle performance parameters are fed into the ATLAS program to estimate and compare the bare turbofan engine size and weights.

3.5 Integrated engine aircraft assessment

The idea behind this objective is mainly to explore the opportunities for turbofan engines powered by alternative fuels once their respective mission level aircraft requirements are considered. This objective is divided into tasks as shown in Figure 3-8 .

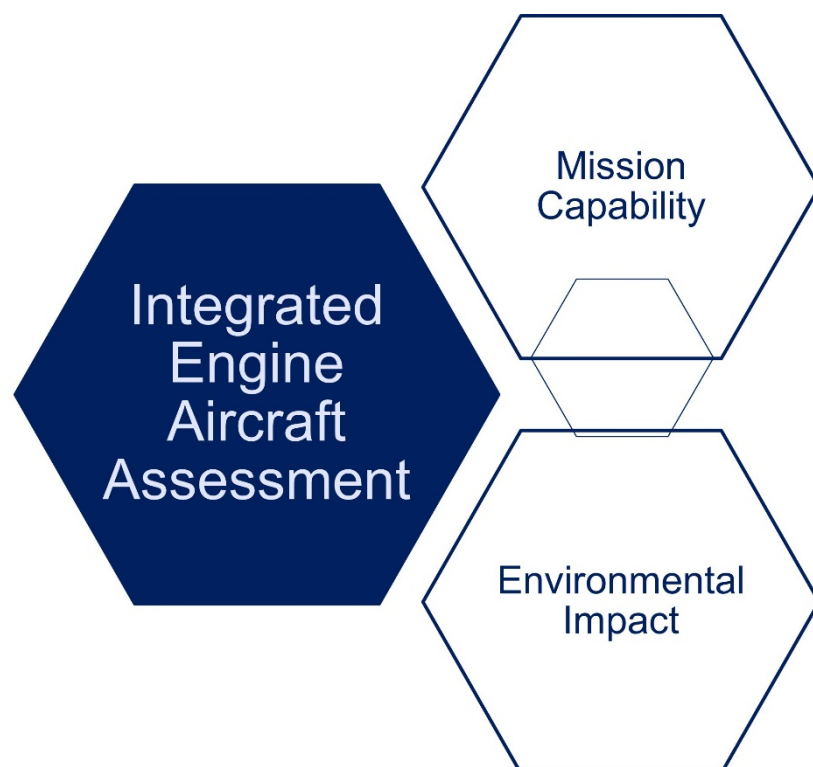
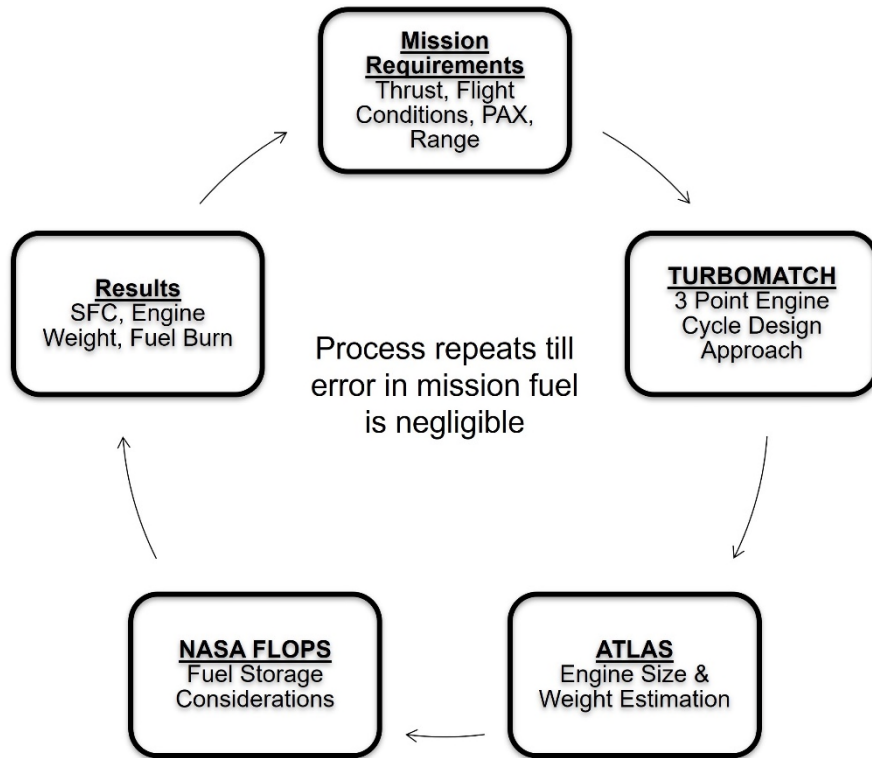


Figure 3-8: Tasks for integrated engine aircraft assessment objective

A suitable approach is devised and utilised to examine the opportunities for turbofan engines at mission level. Figure 3-9 shows flowchart of the applied approach with appropriate tools enabling the assessment.



The process starts with input flight conditions (Altitude and Mach number), aircraft requirements in terms of payload (passengers) & range and thrust requirements. Based on the thrust requirements, engine cycles are generated using a 3-point design approach as described in section 3.4.2. These cycle data are fed into ATLAS program to estimate engine weights. The compressors module requires the top of climb cycle information to be input whereas the combustor & turbine module require the take-off cycle information to be input. An engine performance deck is generated from the cycle and input into NASA FLOPS for assessment along with the engine weight. NASA FLOPS [90] is a multidisciplinary aircraft preliminary design and analysis package developed by NASA Langley Research Centre. Fuel storage impact of alternative fuels on aircraft performance is implemented through the tank gravimetric efficiency formulation where

applicable. The definition of tank gravimetric efficiency utilised for this project is provided in Equation (3-3):

$$\eta_{grav} = \frac{M_f}{M_f + M_T} \quad (3-3)$$

where η_{grav} is the tank gravimetric efficiency, M_f is the mass of the fuel & M_T is the mass of the tank. Assuming a certain tank technology level in the form of tank gravimetric efficiency provides tank weights that are used as inputs into NASA FLOPS, which depends on the mass of the fuel obtained from the mission performance. It should be noted that this parameter will not provide information on the type of tank technology used since for cryogenic tanks the materials for heat insulation can be foam based or vacuum based and for pressurised tanks for gaseous fuels, it can be stainless steel or any different anti-corrosive material. However, material properties directly affect the tank weights and hence, the tank gravimetric efficiency. For example, if light composite materials are used, then one can expect lighter tanks and as a result, a higher η_{grav} for the same mass of fuel. The mission fuel burn is also highly affected by this parameter due to direct impact of tank weights on OEW of the aircraft. The values for this parameter are based on engineering judgment educated from literature that's within the scope of the study. Liquid fuels are assumed to be stored inside the wings like kerosene. High boiling point gaseous fuels are assumed to be stored inside the wings with a certain degree of tank insulation imposed by the tank gravimetric efficiency. Cryogenic fuels are assumed to be stored inside the fuselage using cryogenic tanks. The tank geometry is chosen to be the one of a cylindrical shape with hemispherical cap end as this provides the least surface/volume ratio to minimise heat leakage [54]. Passenger capacity is reduced according to the required cryogenic tank length for retrofit aircraft case studies. For a given density of the fuel, volume is obtained from the mission fuel requirements. The relationship between the cryogenic tank length and volume used is provided in Equation (3-4):

$$Lt = \frac{4V}{\pi D^2} - \frac{2D}{3} + D \quad (3-4)$$

where Lt is the tank length, V is the tank volume and D is the diameter of the cylinder/hemisphere. Width of the fuselage is taken as the diameter. For a given seat pitch and number of seats abreast, the tank length gives an approximation of the passenger capacity to be reduced. Note that boil off/venting is not considered as this is outside the scope of the study.

Alternative fuels will have different fuel requirements due to difference in their LHV and density. LHV will affect the mission fuel requirements in terms of mass and density will affect the volume requirements. The mid cruise and top of climb thrust requirements are informed by FLOPS whereas take-off thrust is based on fixed Thrust/Weight ratio of the kerosene aircraft. The process is repeated with 3-point cycle design as in the flowchart Figure 3-9. The process is stopped when there is negligible change in mission fuel requirements. An automatic program is not set up here to execute these tasks since these programs are not working in a single programming environment. As a result, the sequence of steps in the flowchart Figure 3-9 is executed manually without any automation using external program.

3.5.2 Environmental impact

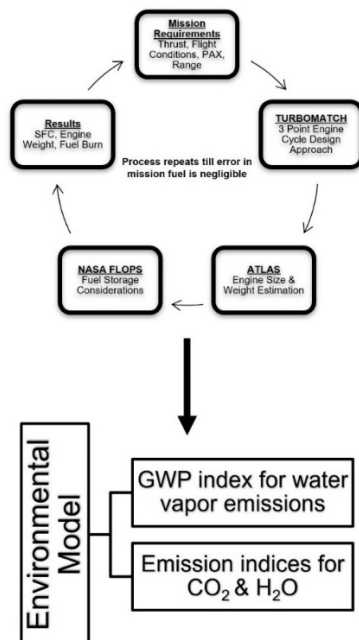


Figure 3-10: Environmental impact flowchart

Figure 3-10 shows the various aspects covered in this task. The information obtained from the previous task in section 3.5.1 is utilised to assess the environmental impact as shown in the above flowchart.

For environmental assessments, emission indices on an energy basis are used for CO₂ and H₂O emission calculations from alternative fuels. These indices are derived on stoichiometric combustion assumption. CO₂ and H₂O emissions are combined into total CO₂ emissions by adopting the usage of GWP index for H₂O emissions. Khandelwal et al [54] provides details of GWP index of H₂O emissions for different altitudes on a timescale of 100 years as shown in Figure 3-11.

Altitude (km)	GWP (CO ₂)	GWP (H ₂ O)
0	1	0.00
1	1	0.00
2	1	0.00
3	1	0.00
4	1	0.00
5	1	0.00
6	1	0.00
7	1	0.00
8	1	0.00
9	1	0.00
10	1	0.24
11	1	0.34
12	1	0.43
13	1	0.53
14	1	0.62
15	1	0.72

Figure 3-11 : GWP of H₂O emissions [54]

In this project, the aircraft missions are flown at a constant altitude of 35,000 ft which is between 10 and 11 km. Hence, the GWP index of H₂O emissions is selected to be 0.29. GWP of the greenhouse gas is related to CO₂ through the relation in Equation (3-5).

$$GWP = \frac{\text{Radiative forcing of 1 kg of Gas}}{\text{Radiative forcing of 1 kg of CO}_2} \quad (3-5)$$

It is worth noting at 9 km (29,527 ft) altitude and below, GWP of H₂O emissions is zero which provides opportunities to cruise at lower altitudes and enable flight trajectory optimisation with respect to climate impact. Alternative fuels, due to their molecular structure will have different soot emissions in combination with varying water vapor concentrations after combustion. This will lead to different contrail characteristics compared to kerosene fuel and hence different contrail GWP indices for alternative fuels. This has been described qualitatively in CleanSky [91] for Hydrogen fuel with regards to the optical thickness of contrail from Hydrogen combusted turbofan engines. This will lead to a different contrail GWP index for Hydrogen fuel.

NO_x emissions depend on many factors like flame temperature, fuel to air equivalence ratios throughout the combustor, residence times, combustor parameters like T40, T30 & P30 and finally, the type of combustor itself. Alternative fuels have varying adiabatic flame temperatures as stated by Goodger [85], which will affect thermal NO_x production. Fuels that have fuel bound nitrogen in them causes increased fuel NO_x production. Hence, the total amount of NO_x production depends on detailed combustor modelling. Detailed combustor modelling with appropriate chemical kinetics model for alternative fuels is required to predict soot generation for contrails estimations along with NO_x calculations. In view of the broader scope of the project, this aspect of the work has been proposed in future work section. Hence NO_x and contrails impact has not been considered for the environmental assessments.

3.6 Advanced cycles investigation

Alternative fuels have different heat capacities C_p which often dictate the amount of energy required to heat up the fuel to satisfactory conditions for proper combustor performance. The main idea behind this objective is to identify the fuel conditioning requirements in terms of heat loads for alternative fuels and investigate the impact of fuel conditioning on cycle design for the most demanding fuels in terms of heat loads. Hence, this objective is divided into tasks as shown in the Figure 3-12.

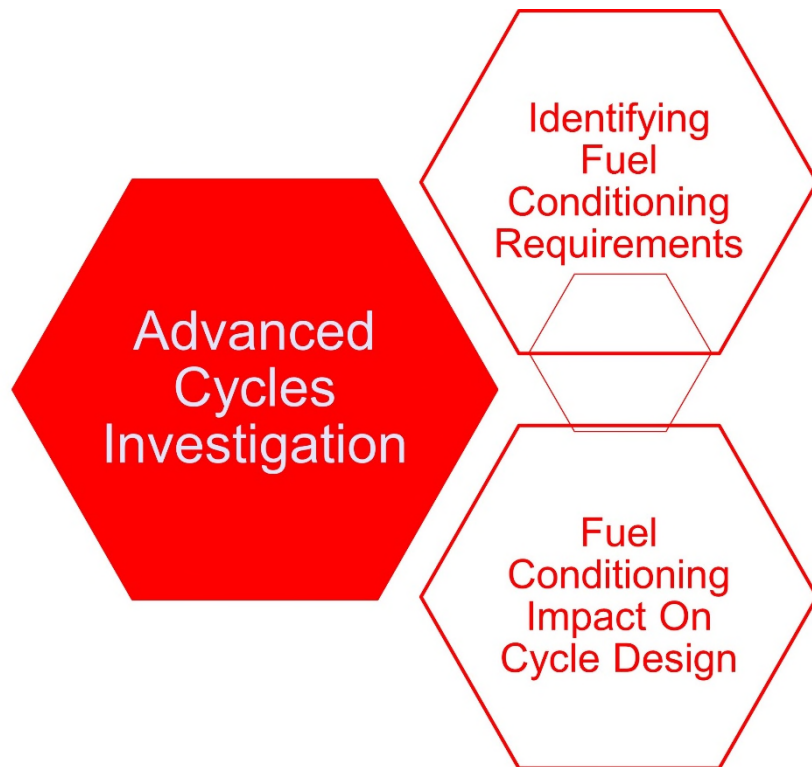


Figure 3-12: Tasks for advanced cycles assessment objective

3.6.1 Identifying fuel conditioning requirements

Fuel conditioning requirements for alternative fuels are identified with the help of engine cycle data obtained from section 3.5.1. The fuel flow rate is the parameter utilised to accomplish this task. REFPROP is used to calculate the heating requirements for the fuels based on the cycle data (fuel flow rates). REFPROP [92] is an industry standard software that has thermophysical properties of many fluids over a wide range of conditions. Based on certain tank storage conditions in aircraft (pressure and temperature) and combustor injection conditions, REFPROP is coupled with the fuel flow rate to quantify the heating/fuel conditioning requirements in terms of thermal power. Specific enthalpy parameter is used for tank conditions and combustor injection conditions. Their difference provides the energy requirements to bring the fuel from tank to combustor conditions. This is multiplied by fuel flow rate to get heat loads in terms of thermal power.

3.6.2 Fuel conditioning impact on cycle design

Once the fuel conditioning requirements are obtained from section 3.6.1, the most demanding fuel in terms of heating requirements (fuel conditioning) is identified to assess the impact of heating the fuel to the required conditions on the cycle design. To accomplish this task, a similar methodology to that discussed for 3-point cycle design in section 3.4.2 is utilised. Figure 3-13 shows the methodology used to assess the impact of fuel conditioning on cycle design for alternative fuels. The decision variables to match the fuel conditioning requirement constraints depend on the strategy of fuel conditioning chosen. Various strategies to condition the fuel are devised and assessed based on the engine architecture, available technology, and the nature of the problem. The decision variables to match the remaining constraints are same as those mentioned in Table 3-3.

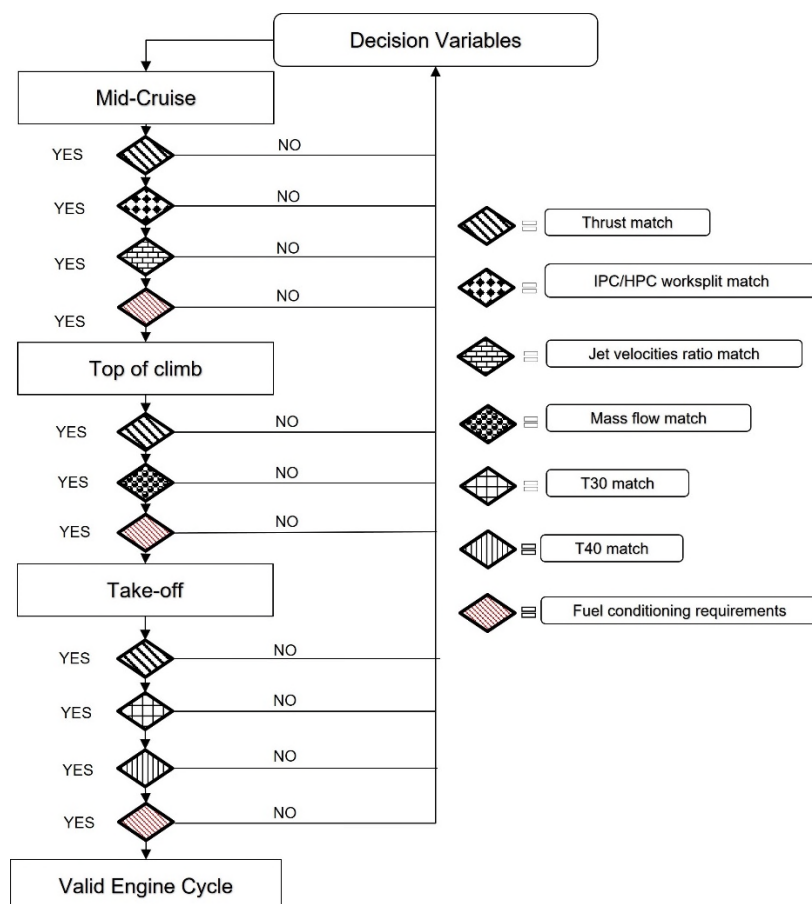


Figure 3-13: 3-point cycle design methodology incorporating fuel conditioning requirements

The following subsections describe the various strategies considered for fuel conditioning along with their working assumptions. Note that the fuel is assessed for fixed heating requirements that is from tank conditions to combustor conditions in terms of temperature and pressure for satisfactory performance of the combustor. Hence, for assessments involving a heat exchanger (HEX), the heat exchanger effectiveness is calculated once a valid cycle design is obtained. HEX effectiveness is calculated using the NTU method described by A.F. Mills and C.F.M. Coimbra [93]. The HEX effectiveness is defined as the ratio of actual heat transfer rate to the maximum possible heat transfer rate.

The effectiveness values assessed are at the cold side of the heat exchanger where the fuel is conditioned before combustor entry.

3.6.2.1 Electric heating

In this strategy, an electric heater is considered to be drawing power from the HPT. The HPT is considered in the assessment as a power source since power off-takes usually are from the high pressure spool. The power transfer line for such a system is envisaged with a gearbox connected to an electric heater via a generator. The pump is assumed to draw fuel from the tanks and pressurise it to the required pressures where the electric heater will heat it to the required injection temperature before the combustor. The envisaged schematic of such a system for a 3-spool architecture is showcased in Figure 3-14. The fuel conditioning requirement (heating power) is extracted from the HPT and in this way, the impact on the cycle can be assessed. Efficiencies of the electric heater or the associated systems necessary for this kind of a setup are not considered for this assessment due to the preliminary nature of this assessment. Alternatively, electric power could be drawn from the IP or LP spool and their application is discussed in the future work section.

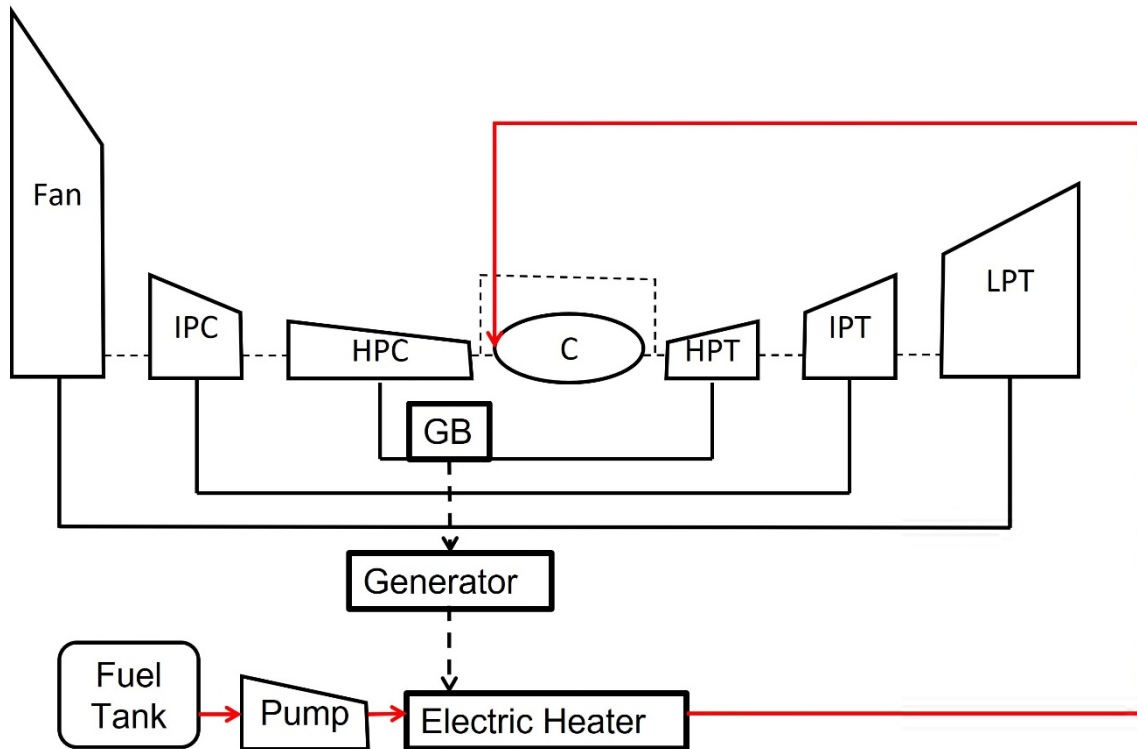


Figure 3-14: Schematic of an electric heating fuel conditioning setup on a 3-spool architecture

3.6.2.2 Preheater

An external preheater system is assumed to be installed on the aircraft at an appropriate location. The preheater will provide the necessary energy to condition the fuel. An additional combustor will burn the assessed fuel with the air that is bled between IPC and HPC. The combustion is assumed to be stoichiometric for this assessment. The type of this additional combustor could be operating in a high pressure environment, or it could be an atmospheric burner where the pressurised air could be used to do some auxiliary work. A heat exchanger will transfer the energy released from combustion to preheat the assessed fuel. The bleed port/location could be changed depending on the design of the whole engine. For this particular assessment, the location between IPC and HPC is selected as an initial guess which seemed to satisfy the currently assessed operating conditions. Further operating points will need to be carefully assessed before selecting this strategy which is discussed in future works. The bleeding of air will impact the cycle performance. The schematic of such a system for a 3-

spool architecture is showcased in Figure 3-15. Since this is a preliminary assessment, the efficiencies of the preheater system are not considered and the integrated engine cycle – preheater optimisation is not performed.

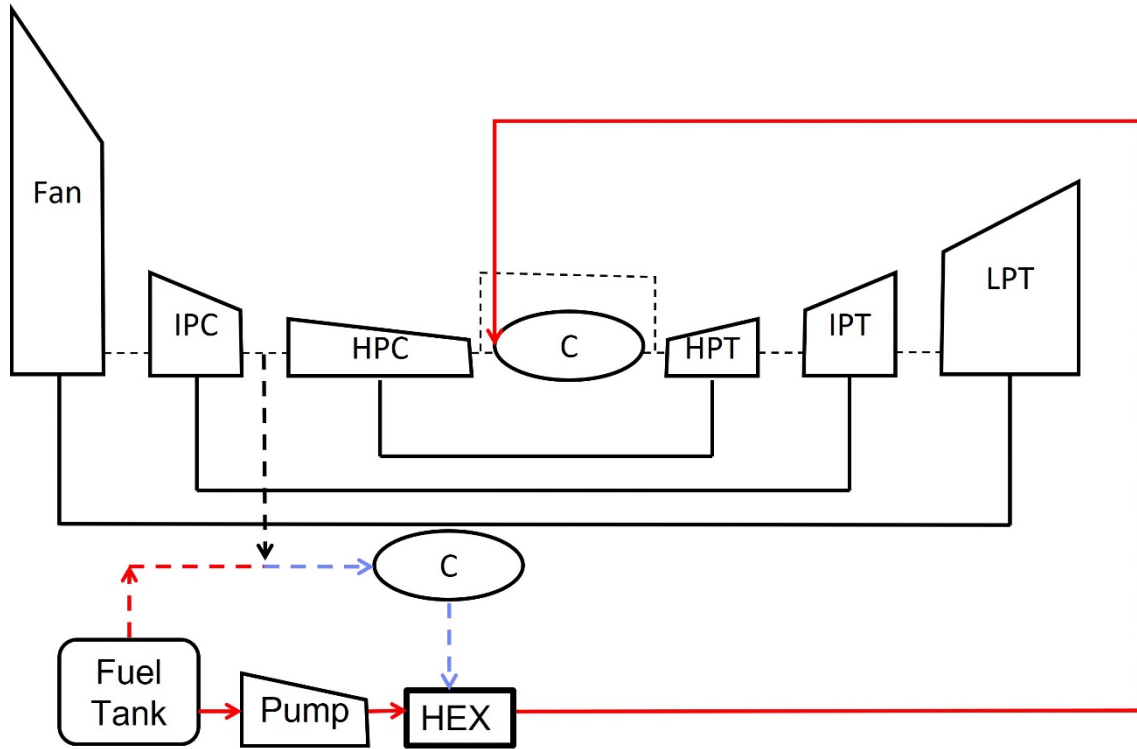


Figure 3-15: Schematic of a preheater fuel conditioning setup on a 3-spool architecture

3.6.2.3 Exhaust heating (Ex)

In this strategy, the exhaust gases exiting the LPT are utilized to provide energy to condition the fuel. A total pressure loss in the flow path is assumed due to the operation of the heat exchanger as a HEX technology factor. Extracting energy from the core stream after the LPT will impact the cycle performance due to the total pressure and temperature loss. Various total pressure loss values are considered to assess the impact of HEX technology on cycle design. A 4% total pressure loss is assumed as baseline for the assessment. The fuel is drawn from the tank and pressurised using the pump after which the HEX increases the temperature of the assessed fuel to the required temperature. The schematic of such a system for a 3-spool architecture is showcased in Figure 3-16.

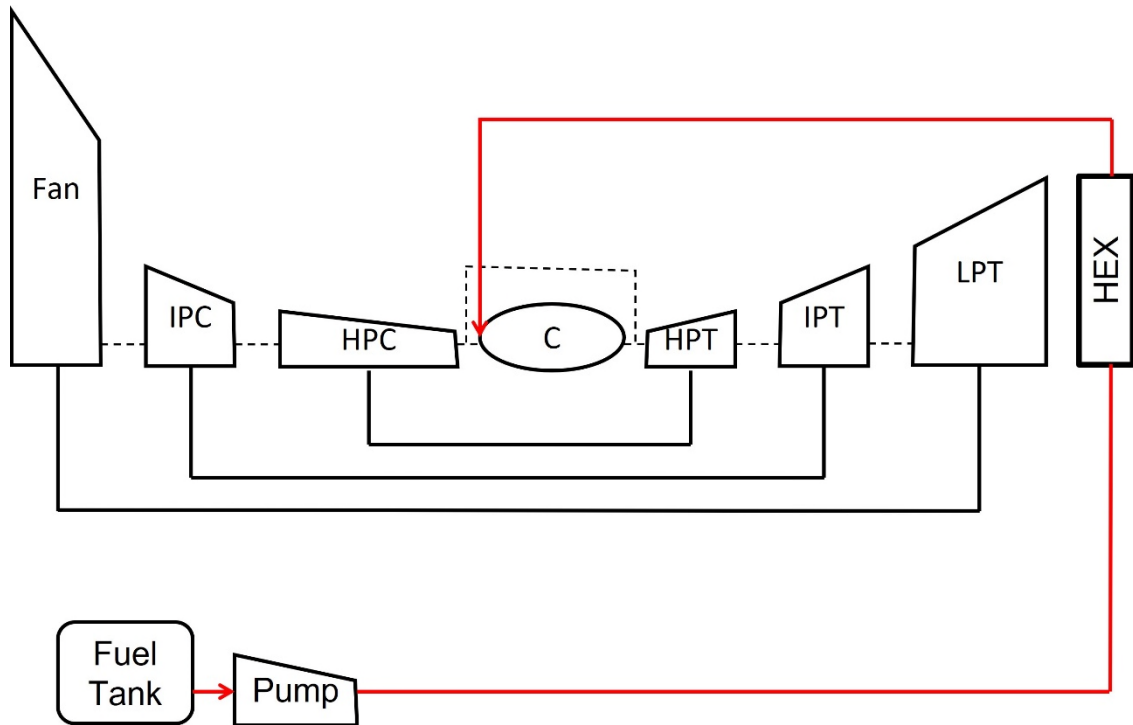


Figure 3-16: Schematic of an exhaust fuel conditioning setup on a 3-spool architecture

3.6.2.4 Intercooling (IC)

A heat exchanger is assumed to be installed between IPC and HPC. Fuel conditioning works similarly to exhaust heating with a 4% baseline total pressure loss assumed in the flow path as a technology factor due to the operation of a heat exchanger. Conditioning the fuel from the cold end of the engine has its advantages since reducing temperatures after heat exchange allows to reduce the compressor work and hence increase performance of the engine. Similar to Exhaust heating strategy, the impact of HEX technology is assessed through application of various total pressure loss values. The pressurised fuel is passed through a heat exchanger that is situated between the IPC and the HPC to heat the assessed fuel. The schematic of such a system for a 3-spool engine architecture is showcased in Figure 3-17. It must be noted that although not in the scope of analysis, intercooling strategy may bring up potential icing issues due to condensation of air or water vapor present in the atmosphere.

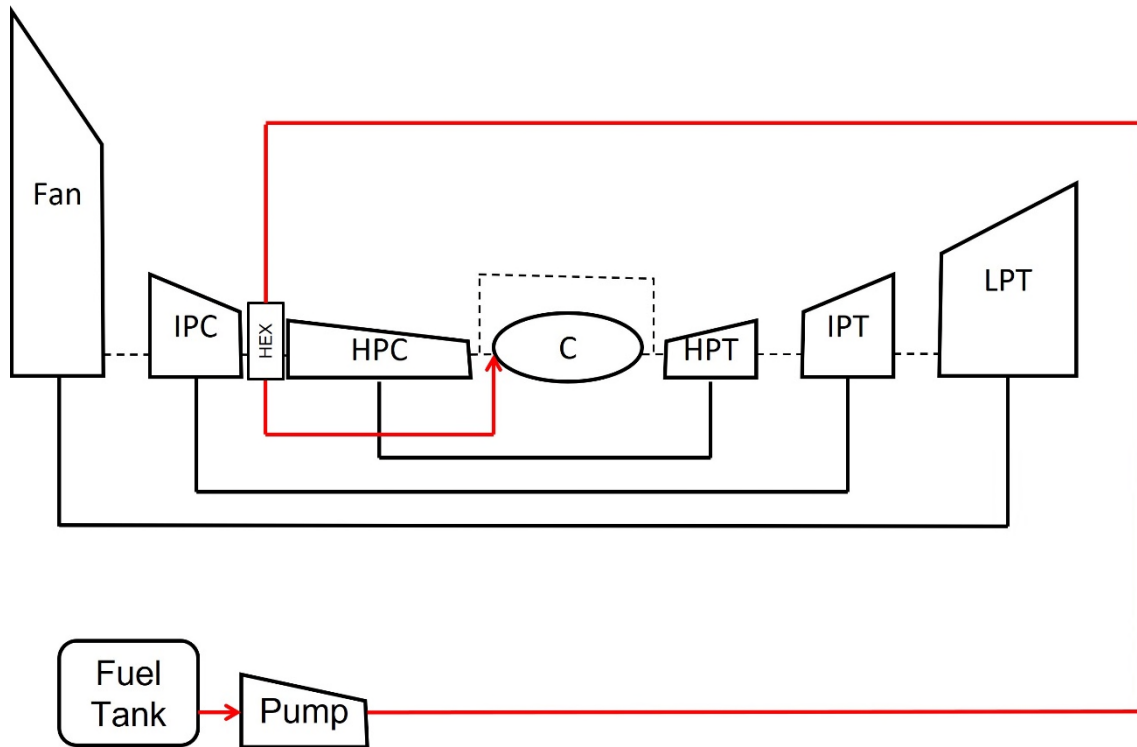


Figure 3-17: Schematic of an intercooling fuel conditioning setup on a 3-spool architecture

3.6.2.5 Bleed air heating

Hot air that is bled after the HPC to cool the HPT NGV blades is also used to provide energy to condition the fuel with a heat exchanger. This allows reduction of cooling flows since the air entering the NGV stream is now colder and more effective in cooling the blades. This is expected to impact the cycle design. The fuel is drawn from the tanks, pressurised using the pumps and heated up to the required temperature using a heat exchanger. The schematic of such a system for a 3-spool engine architecture is showcased in Figure 3-18.

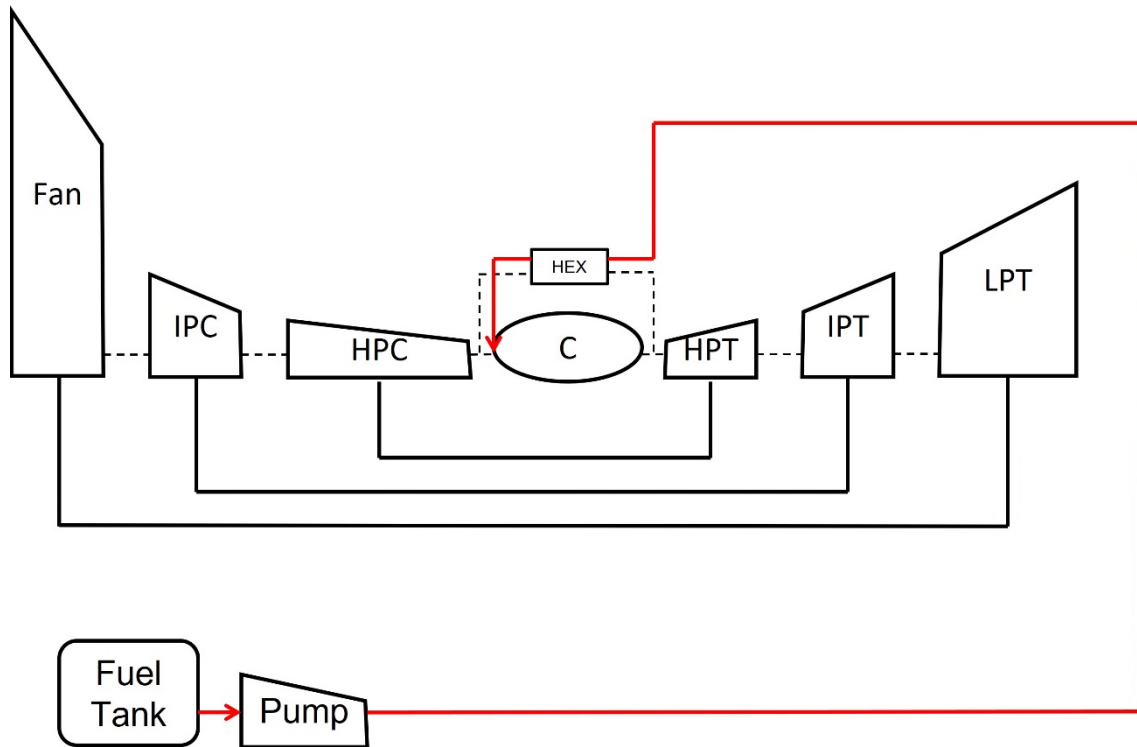


Figure 3-18: Schematic of a bleed air fuel conditioning setup on a 3-spool architecture

3.6.2.6 Precooling

The process is like intercooling strategy. The fuel conditioning is carried out with the support of heat exchanger situated behind the fan (low pressure system) just in front of the IPC module. This allows cooler temperatures across the IPC and HPC module which will reduce both the compressors work while conditioning the assessed fuel. A baseline 4% total pressure loss is assumed in the flow path as a HEX technology factor. Similar to the intercooling fuel flow path, the pressurised fuel is driven through a heat exchanger behind the fan to heat the assessed fuel before injecting it into the combustor. The schematic of such a system for a 3-spool engine architecture is showcased in Figure 3-19. It must be noted that although not in the scope of analysis, precooling strategy may bring up potential icing issues due to condensation of air or water vapor present in the atmosphere.

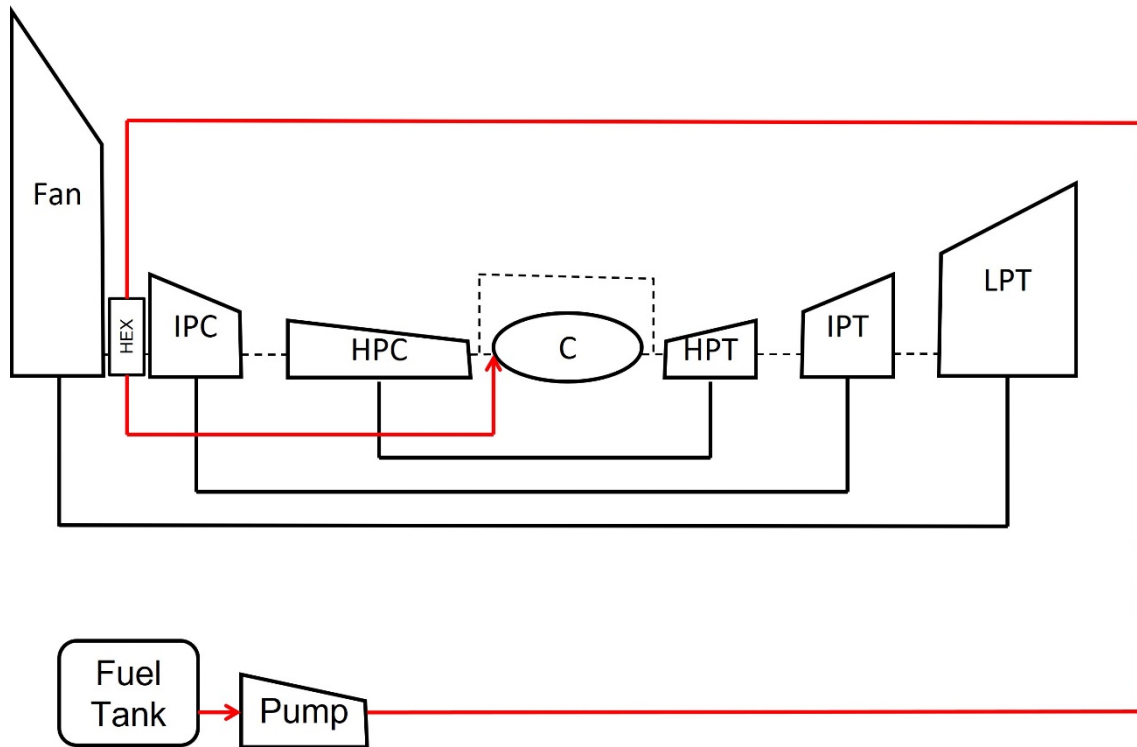


Figure 3-19: Schematic of a precooling fuel conditioning setup on a 3-spool architecture

3.6.2.7 Intercooling & exhaust heating

In this strategy, the effect of fuel conditioning from both the hot end and cold end of the engine is investigated. A baseline total pressure loss of 4% as a HEX technology factor is assumed for each of the two HEX involved on the either end of the engine. The pressurised fuel drawn from the tanks is assumed to be passed through the cold end first, where intercooling happens, and then it is passed through a second heat exchanger to condition the fuel from the exhaust before injecting it into the combustor. The schematic of such a system for a 3-spool system is showcased in Figure 3-20.

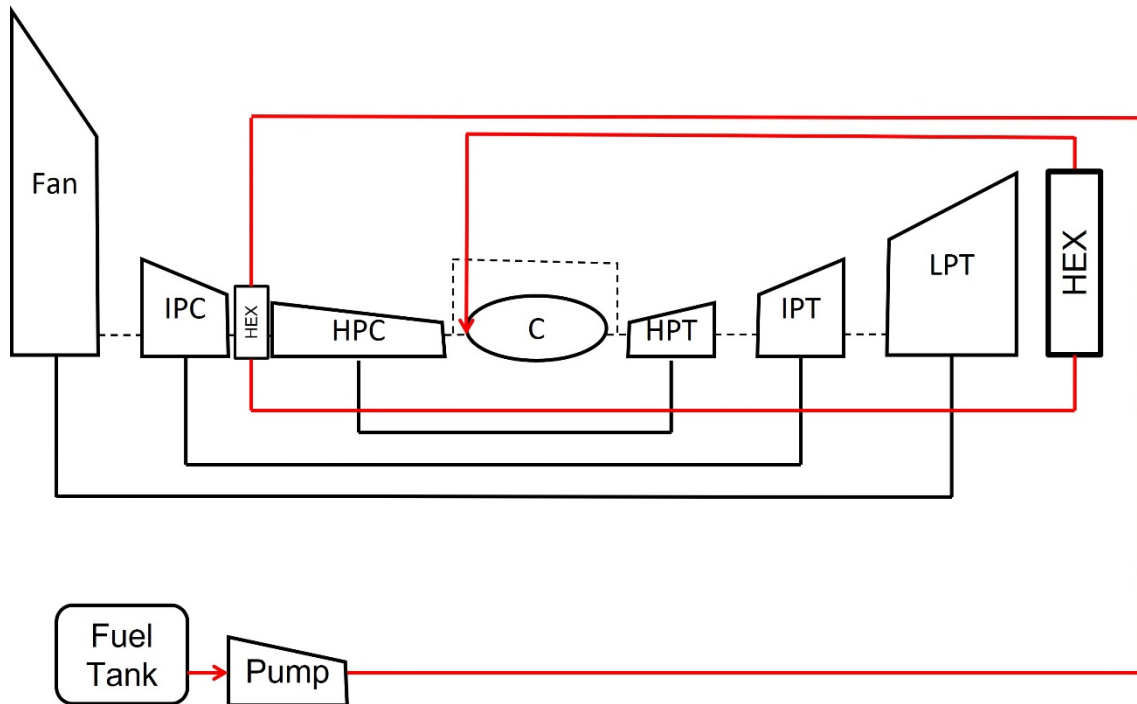


Figure 3-20: Schematic of an intercooling + exhaust fuel conditioning setup on a 3-spool architecture

The decision variables to match the fuel conditioning requirement constraints for the various strategies described are provided in Table 3-4.

Table 3-4: Decision variables for fuel conditioning requirements

Strategy	Decision variables	Constraints
Electric heating	HPT offtakes	Fuel thermal power
Preheater	Core flow fraction after IPC	Fuel thermal power
Exhaust heating	Core exhaust temperature	Fuel thermal power
Intercooling	Core HPC inlet temperature	Fuel thermal power
Bleed air heating	HPC bleed air exit temperature	Fuel thermal power
Precooling	Core IPC inlet temperature	Fuel thermal power
IC + Ex	Core HPC inlet temperature; Core exhaust temperature	Fuel thermal power

4 RESULTS & DISCUSSION

This chapter presents the main findings of this research. It is separated into 6 sections based on the activities described in the previous chapter.

Section 1 presents the discussion and results of the alternative fuels identification phase of the project. The final shortlisted fuels are presented. Section 2 presents the potential impacts of these identified alternative fuels on a turbofan engine from a thermodynamic perspective. Section 3 presents the potential impacts on size and weight for turbofan engines operating with the alternative fuels. Section 4 presents the potential impacts of alternative fuels on turbofan engines when their respective aircraft mission capability is considered, enabled by an integrated engine aircraft assessment reflecting the realistic application of fuels in civil aviation. Section 5 presents the discussion and results of potential strategies to condition the alternative fuels and its impact on turbofan cycle design. Finally, section 6 presents discussion and results of the activity to investigate the feasibility of Ammonia as a Hydrogen carrier for civil aviation.

4.1 Candidate fuels

One of the important phases of the PhD project is to identify potential candidate alternative fuels for the future of civil aviation. This section presents the potential candidate fuels for civil aviation that are shortlisted with which further investigations proceeded. How these fuels came into the final list of consideration is presented in this section. The final outcomes and their significance are discussed.

4.1.1 Literature survey

During this process, fuel properties and terminologies are familiarised regarding aviation fuel. Inspired by the works of Goodger [85], fuels from different classes (family) are categorised in search of alternative fuels for future civil aviation. Certain top level requirements set out in ASTM D1655 standards are used to gain an understanding of the implications if the considered alternative fuels were to be used for civil aviation. It also acts as a method to filter out certain fuels. The top

level requirements and their significance are described before the performance of the considered alternative fuels against the current civil aviation fuel Jet – A1 is showcased. Some of them have already been described in section 3.2.2. These include Specific Energy, Energy Density, Specific Heat Capacity, Carbon Number, Autoignition Temperature, H/C atomic ratio, Specific Volume, Flammability and Molecular Weight. The other ones which have not been described earlier are discussed here as follows:

1. Freezing Point: This parameter characterises the low temperature fluidity of the fuel. The temperature at which a fuel first shows the presence of solid particles or wax crystals (as its temperature is decreased) is called its freezing point [94].
2. Kinematic Viscosity: It highlights atomisation and pumping power required for liquid fuels. Liquid fuels are not ‘pumpable’ with a kinematic viscosity of less than 1 cSt, and atomisation will be unsatisfactory above 10 cSt [15].
3. Flash Point: It emphasizes the volatility of the fuel. The flash point is defined as the lowest temperature at which a fuel gives off sufficient vapor to form a flammable mixture with air [94].

The different classes of fuels investigated initially include Hydrogen, Boron Hydrides, Carbon Hydrides, Nitrogen Hydrides, Nitro hydrocarbons, Hydrocarbon Oxygenates and Metal powders. The fuels considered under these classes are as follows:

1. Boron Hydrides: Diborane, Pentaborane
2. Carbon Hydrides: Methane, Propane and Butane (LPG), Octane, Sustainable Aviation Fuel
3. Nitrogen Hydrides: Ammonia, Hydrazine
4. Nitro hydrocarbons: Nitromethane
5. Hydrocarbon Oxygenates: Alcohols (Methanol, Ethanol, Propanol, Butanol) and Ethers (DME, DEE)
6. Metal Powders: Aluminium, Magnesium, and Boron

Figure 4-1 compares the Specific Energy and Energy Density of the considered fuels.

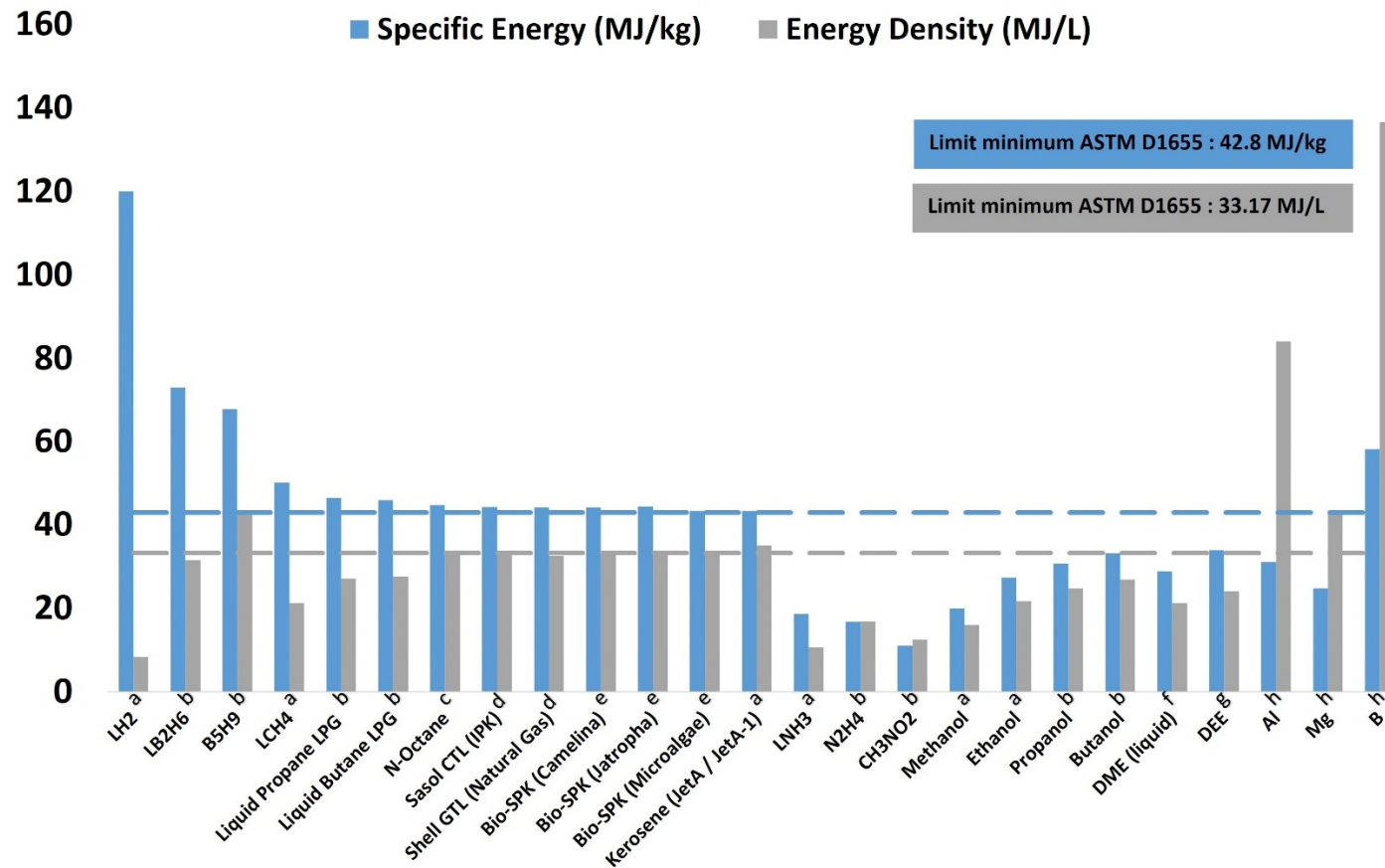


Figure 4-1: Specific energy and energy density of considered fuels

a - Bicer and Dincer [95], b - Goodger [85], c - Goldmann et al [46], d – Corporan et al [96], e – Lokesh et al [50], f – Gupta et al [97], g – Bailey et al [98], h – Gany [99]

Hydrogen, Boron Hydrides, Carbon Hydrides, and Boron from the metal powder group provide higher specific energy than the ASTM minimum limit of 42.8 MJ/kg. However, all the Nitrogen Hydrides, Nitro Hydrocarbons, Hydrocarbon Oxygenates, Aluminium and Magnesium provide lower specific energy than the limit. When looking at the required energy density, fuels such as Pentaborane, N-Octane, Aluminium, Magnesium and Boron qualify the requirement. Hydrogen, Diborane, Methane, Propane, Butane, Nitrogen Hydrides, Nitro Hydrocarbons and Hydrocarbon Oxygenate do not qualify the requirement. Note that Sasol CTL and Shell GTL are fossil based fuels utilising feedstocks such as Coal and Natural Gas respectively. Hence, they are not sustainable but showcased only for comparison purposes.

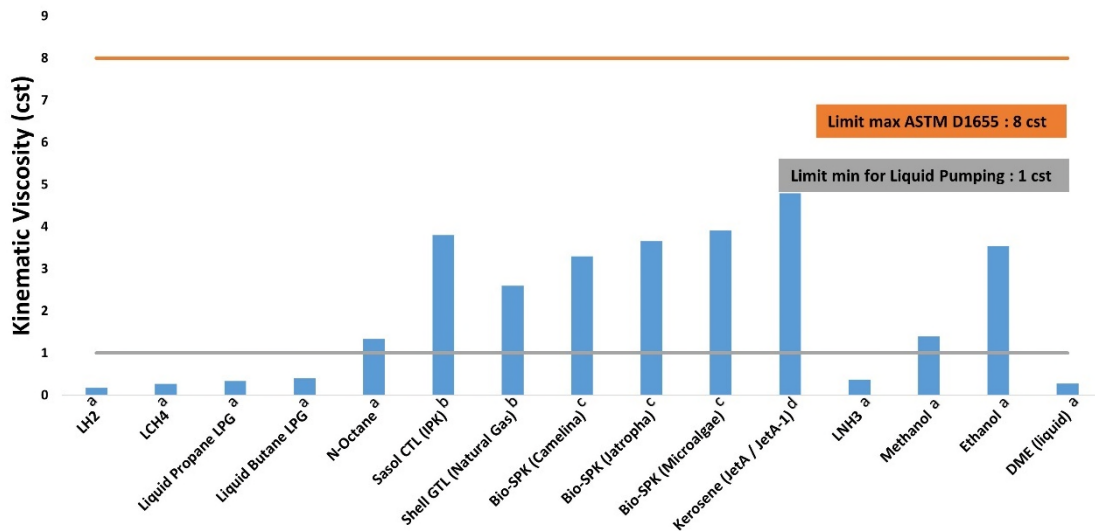


Figure 4-2: Kinematic viscosity of the considered fuels

a - REFPROP [92], b - Corporan et al [96], c – Lokesh et al [50], d – Scheuermann et al [100]

Figure 4-2 showcases the kinematic viscosity of the considered fuels at -20°C as per the ASTM standards. Kinematic viscosity at this temperature is also a measure of low temperature fluidity. Note that all the fuels showcased earlier in Figure 4-1 are not displayed here due to lack of public data available. Gaseous fuels such as Hydrogen, Methane, Propane, Butane, Ammonia and Dimethylether (DME) are assessed at their boiling points since at -20°C, they

exist in a gaseous state. All the liquid fuels such as N-Octane, Sasol CTL, Shell GTL, Bio-SPKs, Methanol and Ethanol are within the limits which indicate a better suitability for fuel pumps and fuel injection system. All the gaseous fuels, even at their liquid state, fall outside the limits which indicates that the fuel pumps and fuel injection systems will have to be adapted accordingly.

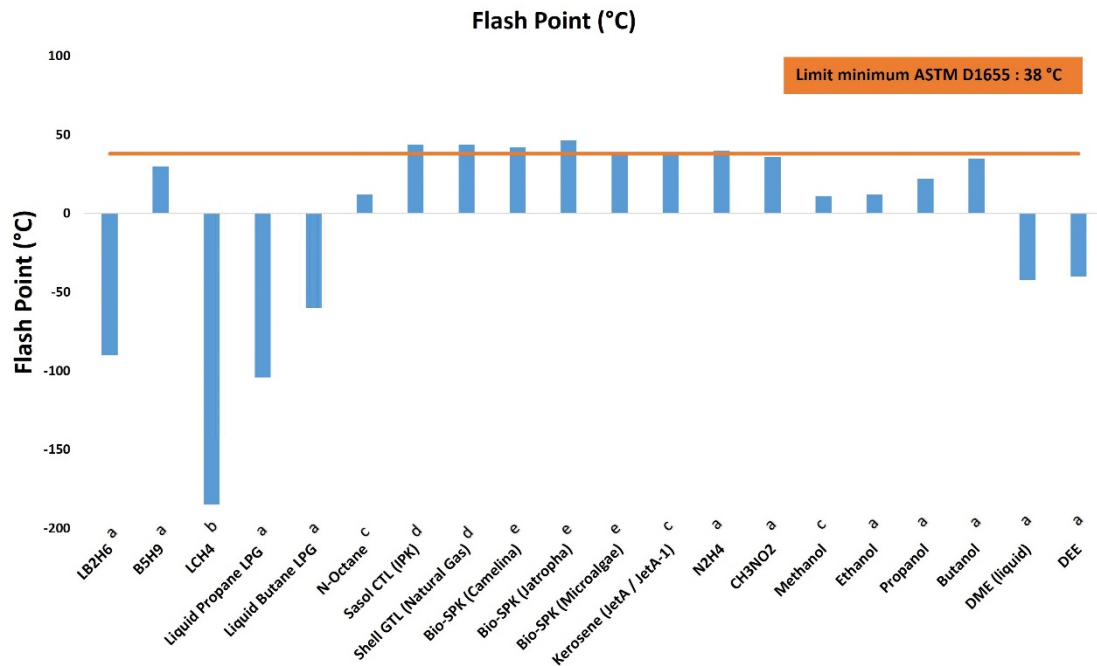


Figure 4-3: Flash point of the considered fuels

a - GESTIS Substance Database [101], b – Goodger [102], c - Goldmann et al [46], d – Corporan et al [96], e – Lokesh et al [50]

Figure 4-3 depicts the flash points of the considered fuels. Note that Hydrogen and Ammonia data is not provided due to lack of public data. The requirement for flash point is a minimum of 38 °C. It is expected that all the gaseous fuels will have flash points in negative apart from liquid fuel DEE (diethylether) indicating high volatility. Hence, safety practices will have to be reconsidered when operating with these fuels. Liquid fuels Pentaborane, N-Octane, Alcohols and Nitromethane have flash points lower than the minimum requirement, which means handling of these fuels will need done with care. All the synthetic and bio variants of the kerosene satisfy the minimum requirement which is expected as they are manufactured to be used as a replacement for Jet A/Jet A-1. Metal

powders since they are solids do not exhibit this characteristic. Keeping evaporation and combustion in mind, lower values of flash point are preferable.

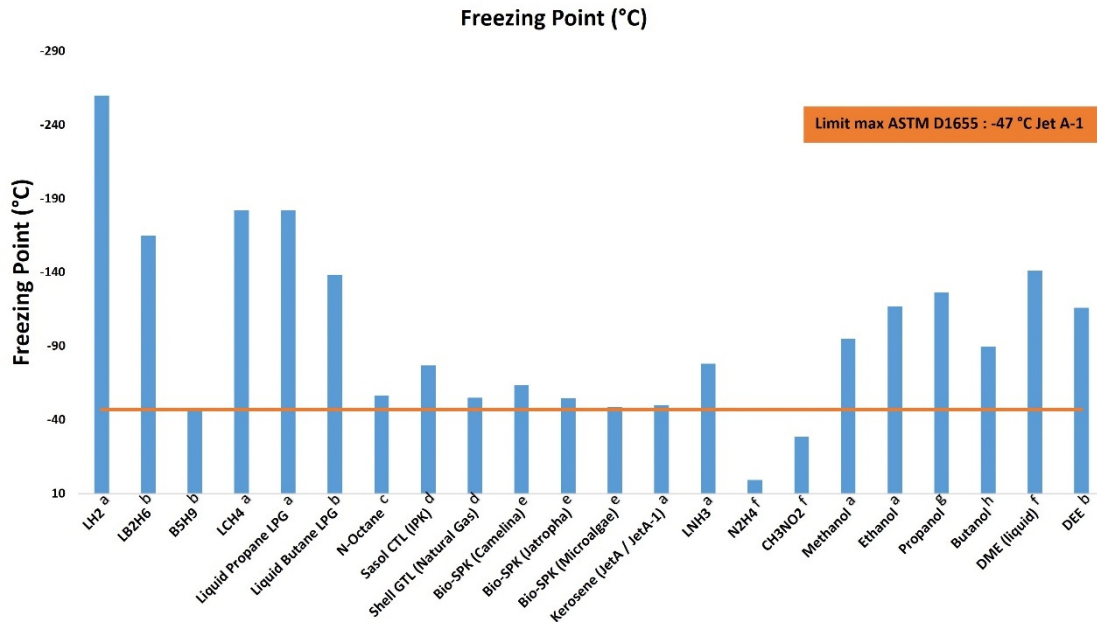


Figure 4-4: Freezing point of the considered fuels

a – Gas Turbine Combustion [94], b – GESTIS Substance Database [101], c - PUBCHEM [103], d - Corporan et al [96], e – Lokesh et al [50], f – Goodger [102], g - Goodger [85], h - CRC Handbook of Chemistry and Physics [104]

Figure 4-4 showcases the freezing point of the considered fuels. Note that metal powders are not included since they are solids and do not exhibit this characteristic. Public data for freezing point where not available, melting point has been considered since they are more likely to coincide. Freezing point is an important requirement for aviation since the low temperatures of cruising altitudes can degrade the fluidity of the fuels. The maximum limit for the freezing point in ASTM standards is -47°C . All the fuels considered satisfy this requirement except for Hydrazine and Nitromethane.

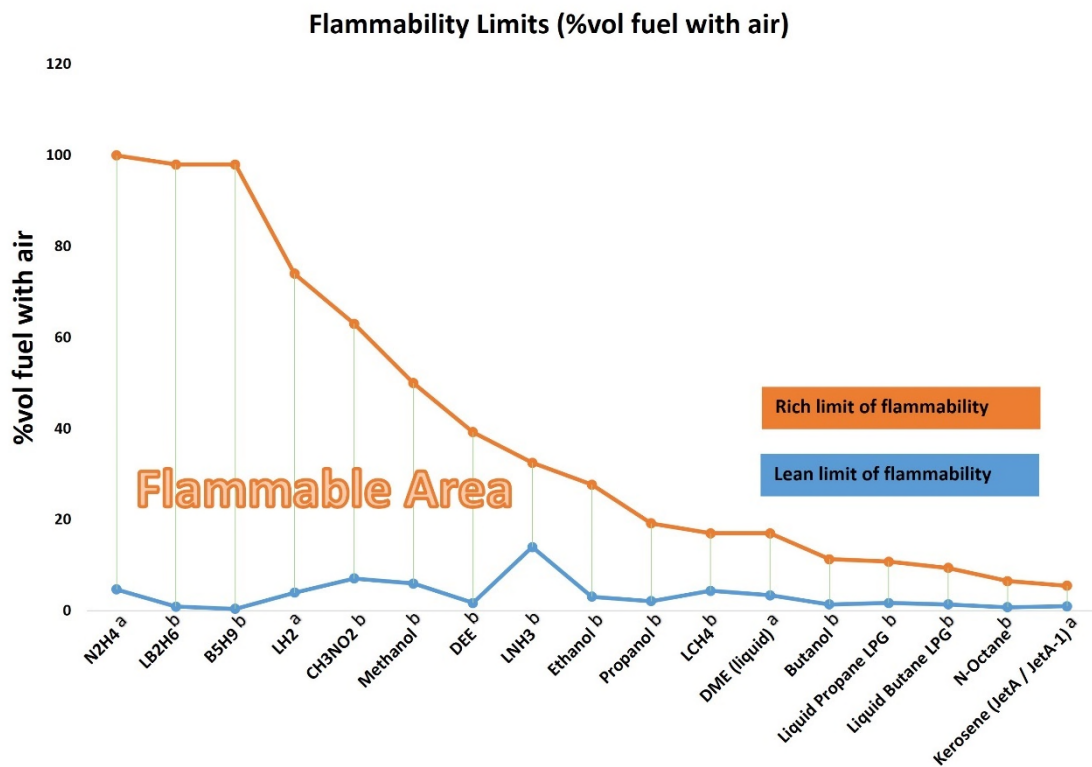


Figure 4-5: Flammability tendency of the considered fuels

a - Goodger [102], b – GESTIS Substance Database [101]

Figure 4-5 highlights the flammability characteristics of the considered fuels. Note that metal powders are not showcased due to lack of public data. Compared to Jet A-1, all considered fuels have wider flammability limits with regards to lean and rich limit of flammability. Flammability limits can be viewed with a positive and negative mindset. Positive mindset represents better operational capability for the combustor whereas negative mindset represents aspects related to fire & safety. It is worth noting that for Hydrazine fuel, the RFL is a 100% meaning that it is flammable without any air present primarily due to self-decomposition upon heating and will pose a significant risk if adopted for aviation.

Looking closely at the various aspects of these considered fuels, some showstoppers are identified before proceeding to the next step of the assessments. The Boron Hydrides and Metal Powders considered here on combustion generate their respective oxides. In the case of Diborane and Pentaborane, Boric Oxide (B₂O₃) is created while Aluminium, Magnesium and

Boron powder generates Aluminium Oxide (Al_2O_3), Magnesium Oxide (MgO) and Boric Oxide (B_2O_3) respectively. These oxides are solids in nature and tend to become liquids under jet engine operating temperatures as reported by Olson and Setze [105]. This can penalise the jet engine performance causing problems in nozzle expansion. Further to that, a report by NACA [106] has highlighted deposit formation of Diboranes at the injector due to high temperatures and problems associated to the state of Boric Oxide being solid and liquid at different temperatures. Due to these reasons, it is decided to eliminate Boron Hydrides and Metal Powders from further procedures. From Figure 4-4, it is seen that Hydrazine and Nitromethane do not satisfy the freezing point requirement set out by ASTM standards which has the potential to affect the operability of the aircraft at higher altitudes. Hence, it is decided to eliminate Hydrazine and Nitromethane from further procedures.

Hence, the fuels narrowed down are Hydrogen, Ammonia, Methane, Propane, Butane, Octane, SAF, Methanol, Ethanol, Propanol, Butanol, DME and DEE. These are grouped under their respective fuel classes (families) to proceed with the decision matrix assessment. Note that the decision matrix assessment is just to support the generation of a candidate list of fuels for civil aviation.

4.1.2 Decision matrix

For this part of the assessment, the fuels are grouped under the following classes (families):

1. Alkanes: Methane, Propane, Butane, Octane
2. Alcohols: Methanol, Ethanol, Propanol, Butanol
3. Ethers: DME, DEE
4. Non Hydrocarbons: Hydrogen, Ammonia
5. SAF: Bio SPKs (Microalgae), Bio SPKs (Jatropha), Bio SPKs (Camelina)

The populated decision matrix with their corresponding property values and scores after ranking is presented in Table 4-1 to Table 4-10.

Table 4-1: Decision matrix for alkane class of fuels with their corresponding property values

Fuel Property Values		Alkanes			
Performance Criteria	Weighting	LCH4	L Propane	L Butane	N-Octane
<i>Specific Energy (MJ/kg)</i>	10	50	46.39	45.77	44.64
<i>Energy Density (MJ/L)</i>	10	21.2	27	27.55	33.2
<i>CP of fuel (kJ/kg.K)</i>	8	*3.87 ^a	*2.48 ^a	*2.36 ^a	2.23 ^b
<i>Carbon Number</i>	6	1	3	4	8
<i>Autoignition Temperature (°C)</i>	4	595 ^c	470 ^d	365 ^d	205 ^c
<i>H/C atomic ratio</i>	4	4	2.67	2.5	2.25
Sizing Criteria					
<i>Specific Volume (L/kg)</i>	10	2.35 ^e	1.720578 ^d	1.66113 ^a	1.416431 ^f
Handling and Safety Criteria					
<i>Flammability (%vol fuel in air)</i>	10	4.4 - 17	1.7 – 10.8	1.4 – 9.4	0.8 – 6.5
<i>Molecular Weight (g/mol)</i>	10	16	44	58	114

a – Goodger [85], b – CRC Handbook of Chemistry and Physics [104], c - Goldmann et al [46], d – GESTIS Substance Database [101], e - Bicer and Dincer [95], f - REFPROP [92], * - Boiling Point; Note: Specific Volume is taken as inverse of Density from the public data.

Table 4-2: Decision matrix for alkane class of fuels with their corresponding scores

<i>Rankings and Scores</i>		Alkanes			
<i>Performance Criteria</i>	<i>Weighting</i>	LCH4	L Propane	L Butane	N-Octane
<i>Specific Energy (MJ/Kg)</i>	10	20.0	18.6	18.3	17.9
<i>Energy Density (MJ/L)</i>	10	12.8	16.3	16.6	20.0
<i>CP of fuel (kJ/kg.K)</i>	8	20.0	12.8	12.2	11.5
<i>Carbon Number</i>	6	20.0	6.7	5.0	2.5
<i>Autoignition Temperature (°C)</i>	4	6.9	8.7	11.2	20.0
<i>H/C atomic ratio</i>	4	20.0	13.4	12.5	11.3
<i>Sizing Criteria</i>					
<i>Specific Volume (L/Kg)</i>	10	12.1	16.5	17.1	20.0
<i>Handling and Safety Criteria</i>					
<i>Flammability (%vol fuel in air)</i>	10	9.0	12.5	14.3	20.0
<i>Molecular Weight (g/mol)</i>	10	20.0	7.3	5.5	2.8
Total		1126.30	941.68	939.76	1038.83

Table 4-3: Decision matrix for alcohol class of fuels with their corresponding property values

Fuel Property Values		Alcohols			
Performance Criteria	Weighting	Butanol	Propanol	Ethanol	Methanol
<i>Specific Energy (MJ/kg)</i>	10	33.1	30.7	27.2	19.9
<i>Energy Density (MJ/L)</i>	10	26.84	24.67	21.6	15.9
<i>CP of fuel (kJ/kg.K)</i>	8	2.59 ^a	2.47 ^a	2.4 ^a	2.3 ^a
<i>Carbon Number</i>	6	4	3	2	1
<i>Autoignition Temperature (°C)</i>	4	325 ^b	385 ^b	400 ^b	455 ^c
<i>H/C atomic ratio</i>	4	2.5	2.67	3	4
Sizing Criteria					
<i>Specific Volume (L/kg)</i>	10	1.234568 ^b	1.25 ^b	1.259446 ^d	1.256281 ^d
Handling and Safety Criteria					
<i>Flammability (%vol fuel in air)</i>	10	1.4 - 11.3	2.1 – 19.2	3.1 – 27.7	6 - 36
<i>Molecular Weight (g/mol)</i>	10	74.124	60.094	46	32

a - Goodger [85], b - GESTIS Substance Database [101], c – Goldmann et al [46], d – Bicer and Dincer [95]; *Note:* Specific Volume is taken as inverse of Density from the public data.

Table 4-4: Decision matrix for alcohol class of fuels with their corresponding scores

Ranking and Scores		Alcohols			
Performance Criteria	Weighting	Butanol	Propanol	Ethanol	Methanol
<i>Specific Energy (MJ/kg)</i>	10	20.0	18.5	16.4	12.0
<i>Energy Density (MJ/L)</i>	10	20.0	18.4	16.1	11.8
<i>CP of fuel (kJ/kg.K)</i>	8	20.0	19.1	18.5	17.8
<i>Carbon Number</i>	6	5.0	6.7	10.0	20.0
<i>Autoignition Temperature (°C)</i>	4	20.0	16.9	16.3	14.3
<i>H/C atomic ratio</i>	4	12.5	13.4	15.0	20.0
Sizing Criteria					
<i>Specific Volume (L/kg)</i>	10	20.0	19.8	19.6	19.7
Handling and Safety Criteria					
<i>Flammability (%vol fuel in air)</i>	10	20.0	11.6	8.0	6.6
<i>Molecular Weight (g/mol)</i>	10	8.6	10.6	13.9	20.0
Total		1206.34	1102.67	1074.23	1100.49

Table 4-5: Decision matrix for ether class of fuels with their corresponding property values

Fuel Property Values		Ethers	
Performance Criteria	Weighting	DEE	L DME
<i>Specific Energy (MJ/kg)</i>	10	33.89	28.8
<i>Energy Density (MJ/L)</i>	10	24.1	21.168
<i>CP of fuel (kJ/kg.K)</i>	8	2.32 ^a	2.22 ^a
<i>Carbon Number</i>	6	4	2
<i>Autoignition Temperature (°C)</i>	4	175 ^b	235 ^c
<i>H/C atomic ratio</i>	4	2.5	3
Sizing Criteria			
<i>Specific Volume (L/kg)</i>	10	1.4 ^b	1.36 ^b
Handling and Safety Criteria			
<i>Flammability (%vol fuel in air)</i>	10	1.7 – 39.2	3.4 - 17
<i>Molecular Weight (g/mol)</i>	10	74.12	46.07

a - NIST Webbook Condensed Phase Thermochemistry Data [107], b - GESTIS Substance Data [101], c – Gupta et al [97];

Note: Specific Volume is taken as inverse of Density from the public data.

Table 4-6: Decision matrix for ether class of fuels with their corresponding scores

Ranking and Scores		Ethers	
Performance Criteria	Weighting	DEE	L DME
<i>Specific Energy (MJ/kg)</i>	10	20.0	17.0
<i>Energy Density (MJ/L)</i>	10	20.0	17.6
<i>CP of fuel (kJ/kg.K)</i>	8	20.0	19.1
<i>Carbon Number</i>	6	10.0	20.0
<i>Autoignition Temperature (°C)</i>	4	20.0	14.9
<i>H/C atomic ratio</i>	4	16.7	20.0
Sizing Criteria			
<i>Specific Volume (L/kg)</i>	10	19.4	20.0
Handling and Safety Criteria			
<i>Flammability (%vol fuel in air)</i>	10	7.3	20.0
<i>Molecular Weight (g/mol)</i>	10	12.4	20.0
Total		1157.80	1358.31

Table 4-7: Decision matrix for non-hydrocarbon class of fuels with their corresponding property values

Fuel Property Values		Non-Hydrocarbons	
Performance Criteria	Weighting	LH2	LNH3
<i>Specific Energy (MJ/kg)</i>	10	120	18.6
<i>Energy Density (MJ/L)</i>	10	8.4	10.52
<i>CP of fuel (kJ/kg.K)</i>	8	*8.68 ^a	*4.6 ^a
<i>Carbon Number</i>	6	0	0
<i>Autoignition Temperature (°C)</i>	4	560 ^b	630 ^b
<i>H/C atomic ratio</i>	4	-	-
Sizing Criteria			
<i>Specific Volume (L/kg)</i>	10	14 ^c	1.46 ^d
Handling and Safety Criteria			
<i>Flammability (%vol fuel in air)</i>	10	4 – 74	14 – 32.5
<i>Molecular Weight (g/mol)</i>	10	2	17

a – Goodger [85], b – Goldmann et al [46], c – Bicer and Dincer [95], d – Gas Turbine Combustion [94], * - Boiling Point; *Note:* Specific Volume is taken as inverse of Density from the public data.

Table 4-8: Decision matrix for non-hydrocarbon class of fuels with their corresponding scores

Ranking and Scores		Non-Hydrocarbons	
Performance Criteria	Weighting	LH2	LNH3
<i>Specific Energy (MJ/kg)</i>	10	20.0	3.1
<i>Energy Density (MJ/L)</i>	10	16.0	20.0
<i>CP of fuel (kJ/kg.K)</i>	8	20.0	10.6
<i>Carbon Number</i>	6	20.0	20.0
<i>Autoignition Temperature (°C)</i>	4	20.0	17.8
<i>H/C atomic ratio</i>	4	20.0	20.0
Sizing Criteria			
<i>Specific Volume (L/kg)</i>	10	2.1	20.0
Handling and Safety Criteria			
<i>Flammability (%vol fuel in air)</i>	10	5.3	20.0
<i>Molecular Weight (g/mol)</i>	10	20.0	2.4
Total		1073.41	1010.43

Table 4-9: Decision matrix for SAF class with their corresponding property values

Fuel Property Values		SAF		
Performance Criteria	Weighting	Bio-SPK (Camelina)	Bio-SPK (Jatropha)	Bio-SPK (Microalgae)
<i>Specific Energy (MJ/Kg)</i>	10	44.1	44.3	43.2
<i>Energy Density (MJ/L)</i>	10	33.207	33.18	32.616
<i>Carbon Number</i>	6	11.2 ^a	11.2 ^a	11.5 ^a
<i>H/C atomic ratio</i>	4	2.176 ^a	2.178 ^a	2.174 ^a

a – Lokesh et al [50]; Note: Other properties are not compared due to lack of public data and also due to the similar physico-chemical characteristics to Jet – A1

Table 4-10: Decision matrix for SAF class with their corresponding scores

Ranking and Scores		SAF		
Performance Criteria	Weighting	Bio-SPK (Camelina)	Bio-SPK (Jatropha)	Bio-SPK (Microalgae)
<i>Specific Energy (MJ/Kg)</i>	10	19.9	20.0	19.5
<i>Energy Density (MJ/L)</i>	10	20.0	20.0	19.6
<i>Carbon Number</i>	6	20.0	20.0	19.5
<i>H/C atomic ratio</i>	4	20.0	20.0	20.0
Total		599.0236	599.8374	588.197

From Table 4-2, the scores in the decision matrix for the alkane class of fuels indicates that cryogenic fuel Methane stands better in comparison to other fuels in the class. However, all the scores are close to one another. During the course of this project, it was decided later to also assess the other members in the class due to the exploratory nature of this project. In civil aviation, storage requirements for the fuels inside the aircraft is very important and on observing the other members in the class, those fuels are promising in terms of storage requirements. Octane is a liquid fuel representative of the gasoline family used in the automotive industry and hence is expected to provide an advantage in storage requirements for aviation compared to the other fuels. Propane and Butane are gaseous fuels whose boiling points are higher compared the cryogenic fuel Methane. Hence, it is expected to have lower degree of insulation requirements compared to Methane and hence be competitive when considering storage requirements. Hence, Methane, Butane, and Octane are selected from this class for further assessment.

Regarding alcohol fuels, the scores can be observed from Table 4-4 which indicates that Butanol fuel stands better in comparison to other fuels in the class. In the automotive industry, alcohol fuel is already blended with gasoline going by the names E10 (10% Ethanol by volume) and E85 (85% Ethanol by volume) to reduce emissions. For aviation applications, based on the scores obtained from the decision matrix, Butanol is selected from this class for further assessment.

In Ether class of fuels, the scores from Table 4-6 indicates that DME fuel stands better in comparison to DEE fuel. DME also exhibits a similar handling characteristic to Propane and Butane as in its boiling point is high making a gaseous fuel be stored as a liquid without increasing the insulation requirements. Hence, DME is selected from this class for further assessment.

Hydrogen and Ammonia are selected since they are zero carbon fuels, which is very important considering the ongoing decarbonisation efforts of the aviation industry. Ammonia exhibits similar handling characteristic to Propane and Butane due to its high boiling point and hence requiring less insulation to keep the fuel

cool. Their scores can be observed from Table 4-8 with both the fuel score standings close to each other.

When it comes to SAF, since these are synthetically made to be a replacement for the current conventional jet fuel, all the properties need not be considered. Table 4-10 showcases the scores for fuels considered in this class and suggests biofuel sourced from Jatropha feedstock to be taken ahead for further assessment. However, one must note that the scores are very close to each other and considering the scope of this project, only one is selected.

Hence, the shortlisted potential candidate fuels for future civil aviation are as follows:

1. Liquid Fuels: Butanol, Octane, SAF (Jatropha)
2. Gaseous Fuels: Hydrogen, Ammonia, Methane, Butane, DME

These fuels are further assessed for the project.

4.2 Engine cycle design space exploration

The aim of this activity is to identify the top level effects of the shortlisted candidate fuels on turbofan engine design. This section presents the reasons behind why this exploration study is needed, after which the impacts of the shortlisted fuels on turbofan cycle design space of a selected engine architecture is presented. The final outcomes and their significance are discussed.

4.2.1 Why is the exploration study required?

It is known that alternative fuels have different LHVs. This will lead to different FAR inside the combustor of the turbofan engine. This can affect the working fluid's thermodynamic properties. Typically, for turbofan engines utilizing kerosene as fuel, FAR is approximately 0.0213, which is lean combustion since FAR for stoichiometric combustion is 0.068. To get the FAR for alternative fuels, Equation (4-1) is used. This equation is found to be an adequate first order approximation for cycle performance assessment studies.

$$FAR_{fuel} = \frac{FAR_{KE} * LHV_{KE}}{LHV_{fuel}} \quad (4-1)$$

where FAR_{fuel} is the Fuel Air Ratio of the alternative fuel; FAR_{KE} is the Fuel Air Ratio of kerosene; LHV_{KE} is the Lower Heating Value of kerosene; LHV_{fuel} is the Lower Heating Value of the alternative fuel.

The FAR_{fuel} and mole % of combustion product composition for the candidate alternative fuels is showcased in Table 4-11.

Table 4-11: FAR for alternative fuels

Fuel	LHV (MJ/kg)	FAR_{fuel}	X_{H_2O} (%)	X_{CO_2} (%)
HY	120	0.0076	10.462	0.03
CH ₄	50.05	0.0184	6.438	3.25
Butane	45.77	0.0201	4.896	3.948
Octane	44.78	0.0205	4.591	4.112
SAF	44.3	0.0208	4.533	4.176
KE	43.124	0.0213	4.168	4.38
Butanol	33.1	0.0278	5.27	4.247
DME	28.8	0.0320	5.805	3.901
NH ₃	18.61	0.0495	11.435	0.029

For the FAR shown in Table 4-11, Cp is evaluated using NASA CEA as this term appears in the fundamental definitions of enthalpy and entropy used for gas turbine performance simulations. The effects are showcased in Figure 4-6.

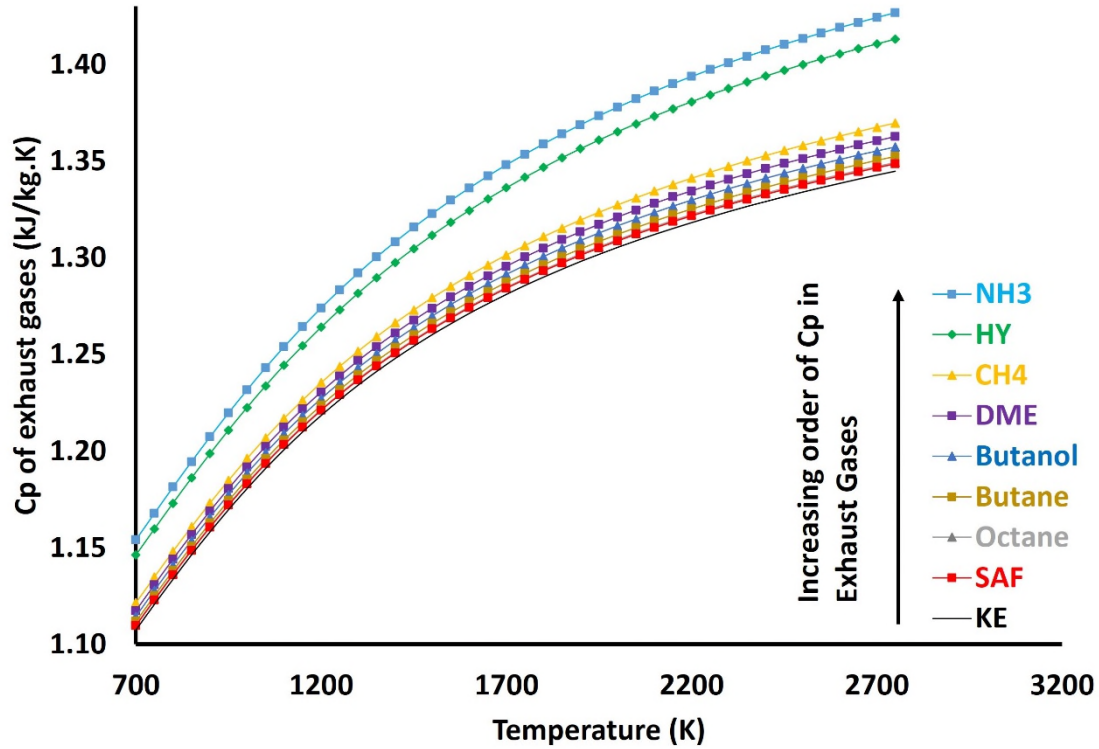


Figure 4-6: Exhaust gases Cp for a range of temperatures

From Figure 4-6, it is found that exhaust gases contain different heat capacities. This can be attributed to the amount of water content in the exhaust gases as shown in Table 4-11. Water is known to have higher Cp than CO₂. The turbine power equation can be defined as follows:

$$W_t = \dot{m} C_p dT \quad (4-2)$$

where W_t is the turbine power; $\dot{m}$ is the mass flow rate of exhaust gases; C_p is the heat capacity of exhaust gases at constant pressure; dT is the temperature drop across the turbine.

Therefore, higher Cp values can lead to increased turbine power output. As shown previously, in Table 4-11, FAR is different for alternative fuels due to different LHVs. Goodger [108] reports that a fuel that has components such as

nitrogen and oxygen, reduces its LHV as is seen for Ammonia, DME and Butanol. Hence, the exhaust gas mass flow rate $\dot{m}$ will also be different in Equation (4-2). Hence, the total turbine output power is different and how this can affect the turbofan cycle design needs to be addressed.

Due to the above reasons, a preliminary thermodynamic engine cycle design space exploration is seen as the best way to capture the cumulative effects on a turbofan engine design.

4.2.2 3-spool turbofan engine

A 3-spool turbofan engine is modelled in TURBOMATCH representative of Rolls-Royce Trent-1000 series. The exploration study is conducted for fixed flight conditions, thrust requirements, IPC/HPC pressure ratio split and component efficiencies. The flight conditions and thrust requirements are showcased in Table 4-12.

Table 4-12: On-design and off-design conditions

MCR Altitude	35,000 ft
MCR Mach	0.85
MCR ISA dev	0
MCR Thrust	42,033 N
MCR BPR	8, 10, 12
MCR T40 (K)	1450, 1500, 1550, 1600
MCR OPR	36.214
MTO Altitude	0 ft
MTO Mach	0.25
MTO ISA dev	15
MTO Thrust	178,710 N

The IPC/HPC pressure ratio split and component efficiencies are showcased in Table 4-13.

Table 4-13: Pressure ratio split and component efficiencies

<u>Technology</u>	<u>Value</u>
IPC/HPC pressure ratio split	1.44
$\eta_{poly,Fan}$	0.91
$\eta_{poly,IPC}$	0.92
$\eta_{poly,HPC}$	0.90
$\eta_{poly,HPT}$	0.89
$\eta_{poly,IPT}$	0.895
$\eta_{poly,LPT}$	0.90

Figure 4-7 showcases the impacts of using alternative fuels on turbofan cycle design space for a fixed OPR. The relationship between overall efficiency and energy consumption is provided in Equation (4-3).

$$\eta_o = \frac{V_o}{ESFC} \quad (4-3)$$

where η_o is the overall efficiency, V_o is the flight speed & ESFC is the energy specific fuel consumption which is the product of S.F.C and LHV.

For a given specific thrust (constant propulsive efficiency), as one moves from long chain hydrocarbons to zero carbon fuels, the carpet plot shifts down i.e., ESFC reduces.

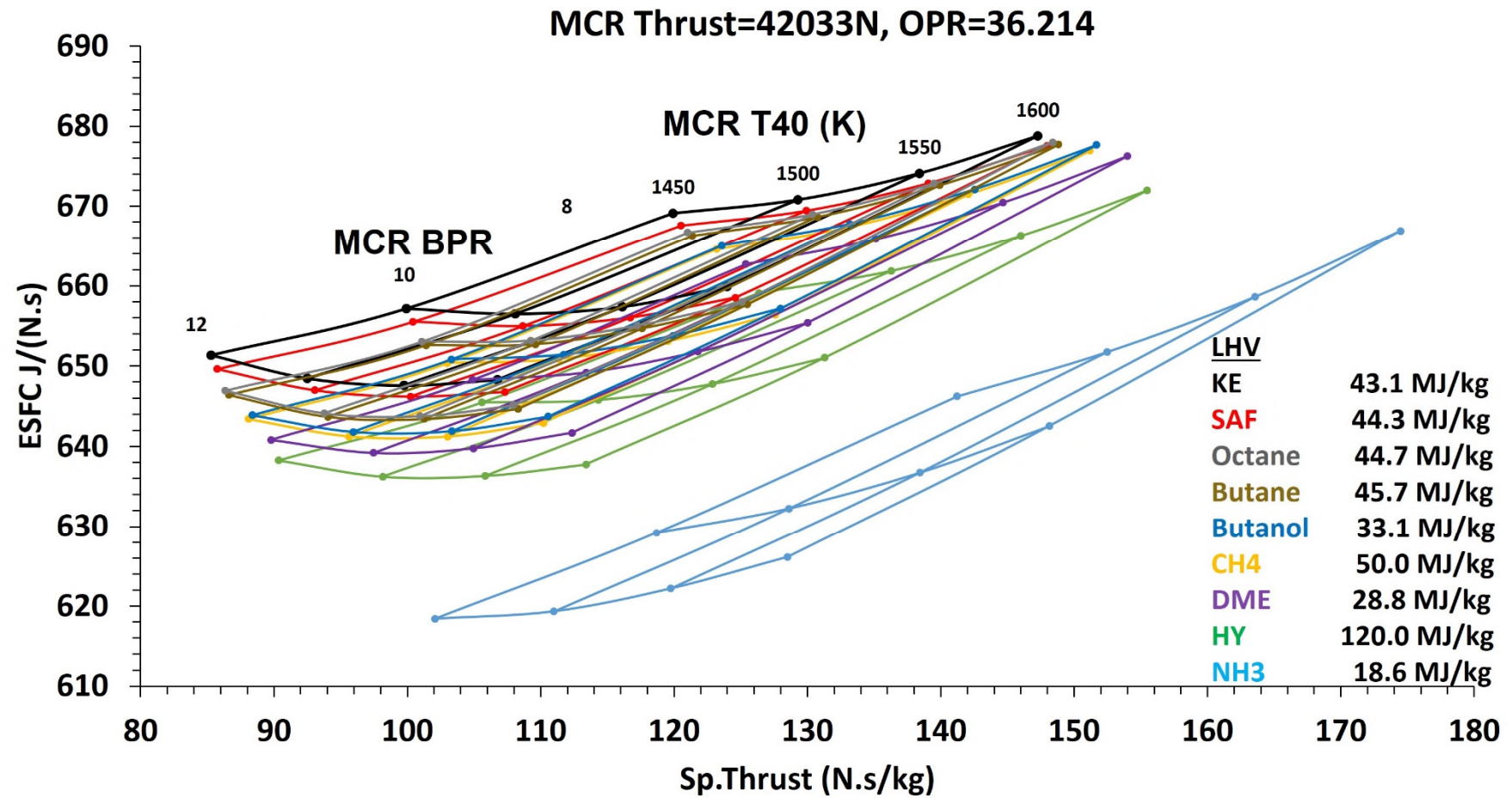


Figure 4-7: Impact of alternative fuels on turbofan cycle design space

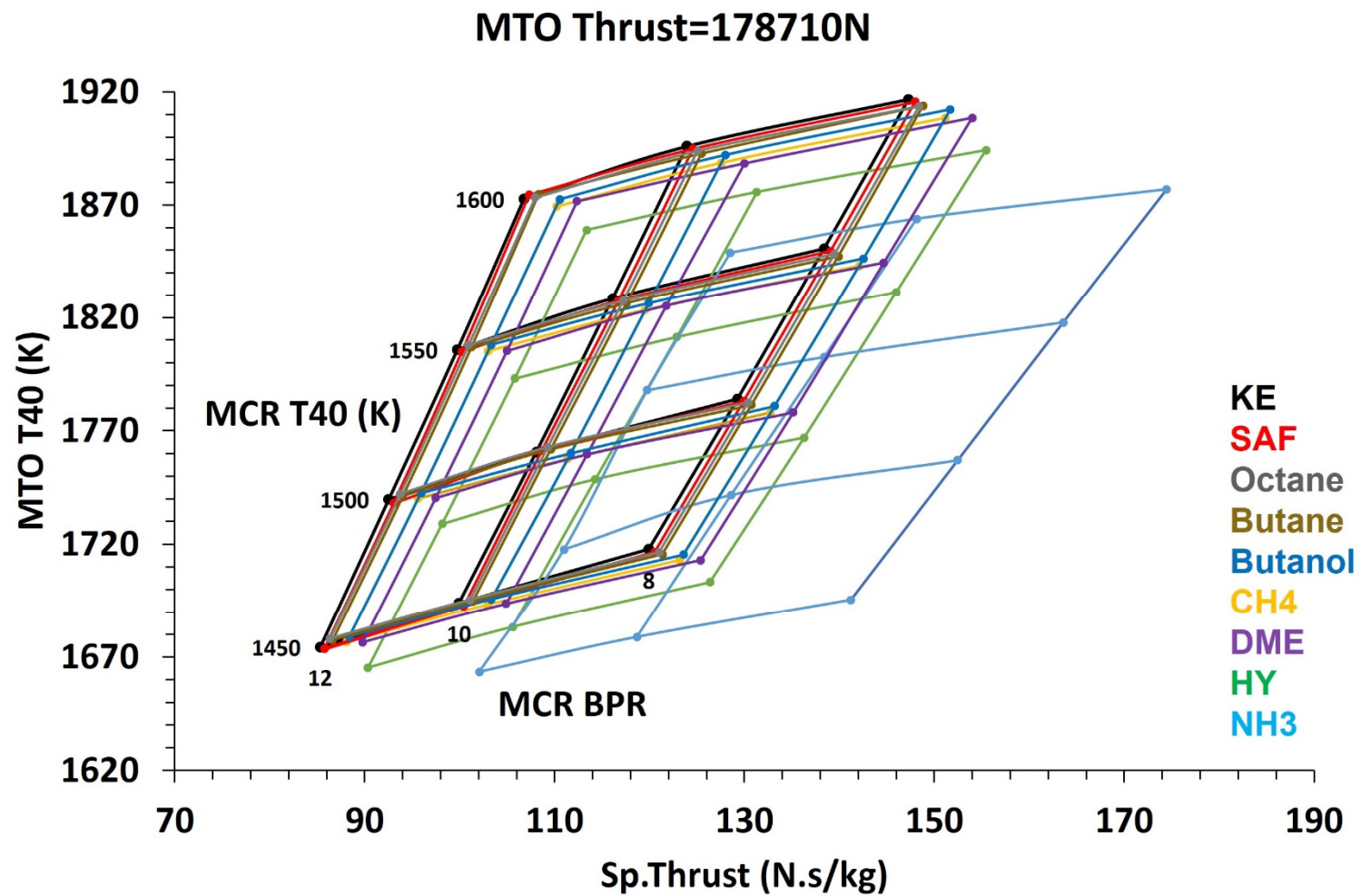


Figure 4-8: Impact of alternative fuels on take-off T40

One should note that every design point in the carpet plot has been optimized for minimum SFC by optimizing the FPR. Overall efficiency is a product of thermal, propulsive, and transfer efficiency. For a given specific thrust, propulsive efficiency is approximately fixed, while transfer efficiency is fixed for fixed isentropic efficiency of LP spool components. Thus, since flight speed is kept constant, any changes in ESFC are directly linked to changes in thermal efficiency. Hence, it is found that alternative fuels increase thermal efficiency leading to lower energy specific fuel consumption for a given thrust condition. It is also observed that the carpet plot tends to shift towards the right, indicating higher optimum specific thrust values and ultimately, smaller engine sizes for a given set of thrust requirements and technology constraints. Hence, novel alternative fuels for turbofan engines provides the capability to either go towards smaller core operating with same temperature as kerosene or lower core temperature engine design, all for the same specific thrust (fan size) as that of kerosene. It is observed that zero carbon fuels Hydrogen and Ammonia provide an ESFC benefit of approximately 3% and 6% respectively when compared to kerosene.

The off-design effects of utilizing alternative fuels at max take-off conditions are showcased in Figure 4-8. It is observed that there are take-off T40 benefits for alternative fuels compared to the baseline kerosene. Due to the increased heat capacities in the exhaust gases for alternative fuels, they generate more power. Hence, for the same take-off thrust condition, lower T40s are observed. The maximum reduction in T40 observed is approximately 40K and 20K for Ammonia and Hydrogen respectively compared to baseline kerosene. Therefore, utilizing alternative fuels for turbofan engines can result in engine life benefits due to reduced peak cycle temperatures.

The results showcase that among the alternative fuels investigated, zero carbon fuels Hydrogen and Ammonia present the maximum degree of impact on the turbofan cycle design space and performance at off design point for take-off. As a result, the impact of OPR on the cycle design space of zero carbon fuels is investigated. The flight conditions, component efficiencies, IPC/HPC pressure

ratio split and thrust requirements at cruise and take-off are kept the same. However, the range of BPRs and T40s are expanded as shown in Table 4-14 to capture the effect of OPR.

Table 4-14: Expanded range of BPRs and T40s for OPR impact assessment

MCR BPR	8, 10, 12,14,16
MCR T40 (K)	1450, 1500, 1550, 1600,1650,1700
MCR OPR	30,35,40,45,50,55,60

Figure 4-9, Figure 4-10, Figure 4-11 presents the outcomes of the investigation.

For any given specific thrust, 100 (Ns/kg) in this case, since the thrust requirements and flight conditions are the same, the fan diameter can be assumed to be same for a fixed hub to tip radius ratio. In Figure 4-9, when one moves to zero carbon fuels such as Hydrogen and Ammonia, for a given OPR (e.g. 30), the core size can be reduced when the core temperatures are kept the same (e.g. 1450 K). The maximum effect is observed for Ammonia followed by Hydrogen. In Figure 4-10, for a given OPR (e.g. 30), the core temperatures can be reduced when the core size is kept the same (e.g. BPR = 14). The maximum effect is observed for Ammonia followed by Hydrogen. In Figure 4-11, for a given core size and temperature (BPR = 12, 1500K<T40<1550K approx.), the OPR can be higher for Hydrogen (OPR = 40) and Ammonia (OPR = 60). On observing a kerosene based system from the figure, increasing OPR improves the ESFC i.e thermal efficiency. Hence, apart from the thermal efficiency benefits of zero carbon fuels for fixed OPR, using zero carbon fuels, allows higher OPR for a given core size and temperature provided the compressor technology is not a barrier, which further pushes the thermal efficiencies to higher levels. Figure 4-12 presents the impact of OPR on off-design performance for take-off. It is found that there is a positive impact of OPR on take-off T40s. Figure 4-13 and Figure 4-14 showcases all the cases of OPR from 30 to 60.

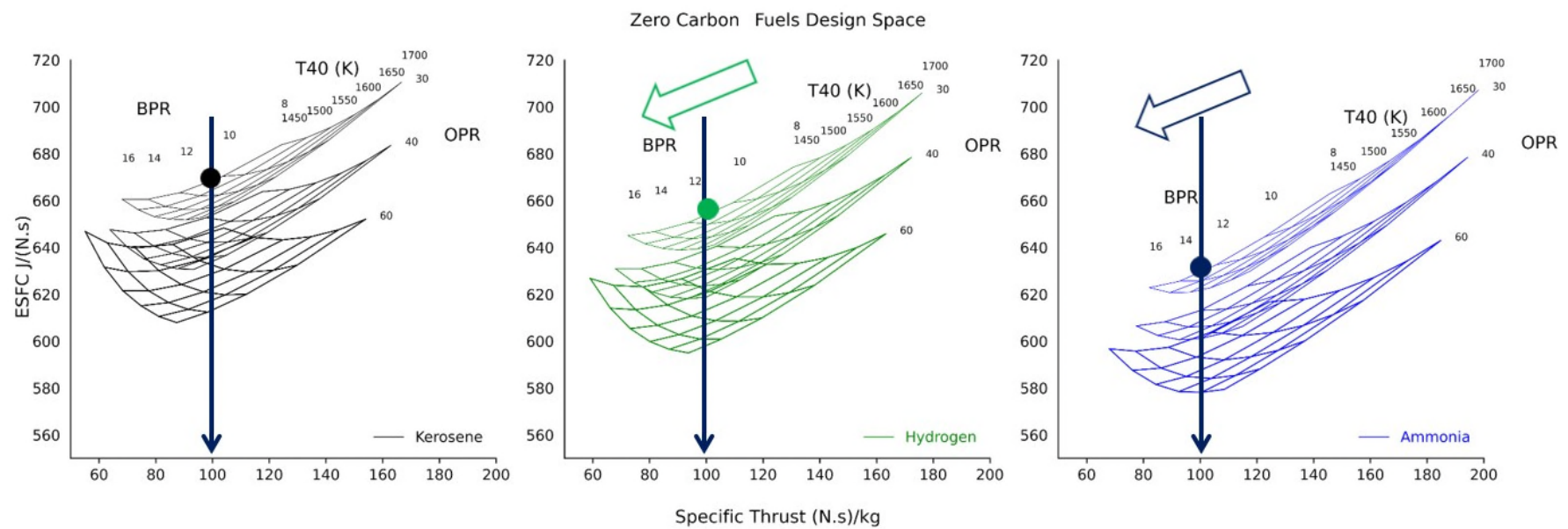


Figure 4-9: Smaller cores for same core temperature and OPR

Energetic (Zero carbon) fuels provide leverage to:

- A. Reduce core size $\rightarrow$ (fixed : fan diameter, core temperature, OPR)

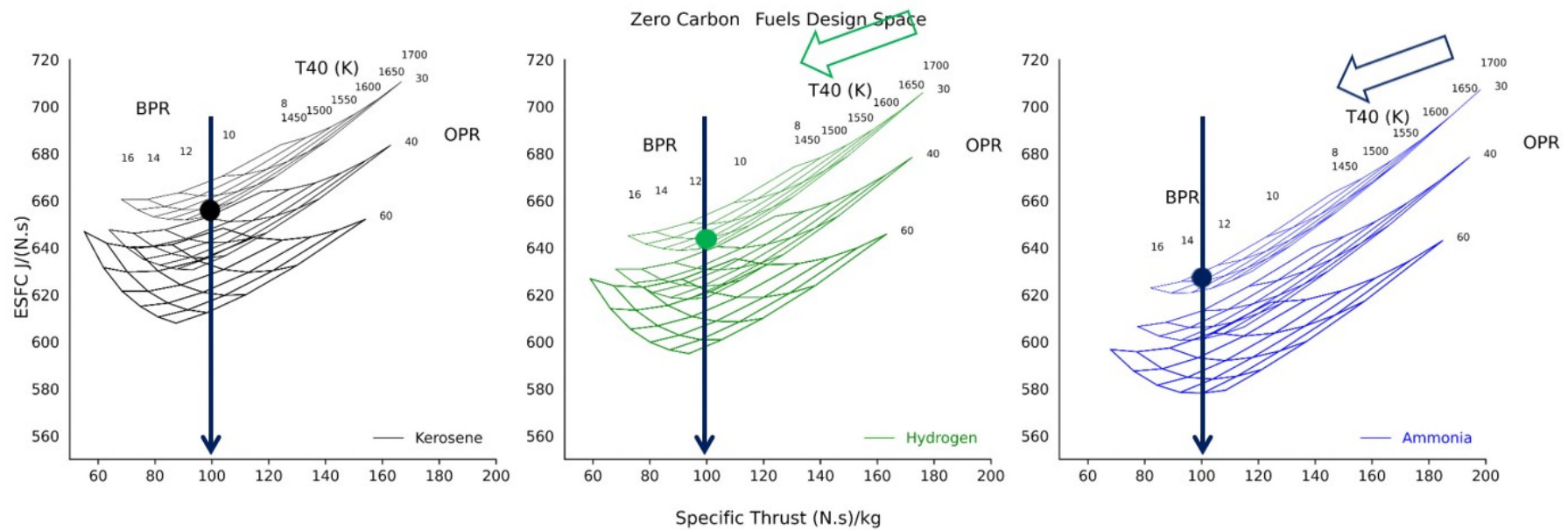


Figure 4-10: Lower core temperatures for same core size and OPR

Energetic (Zero carbon) fuels provide leverage to:

B. Reduce core temperature $\rightarrow$ (fixed : fan diameter, core size, OPR)

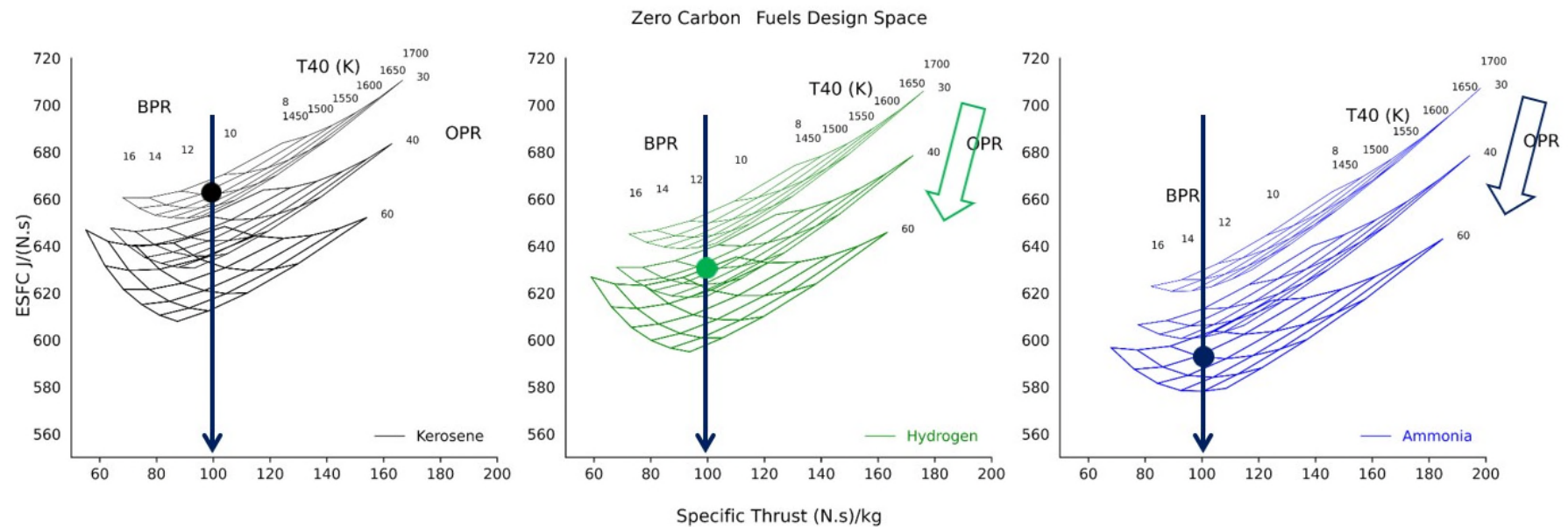


Figure 4-11: Higher OPR for same core size and temperature

Energetic (Zero carbon) fuels provide leverage to:

C. Allow higher OPR → (fixed : fan diameter, core temperature and size)

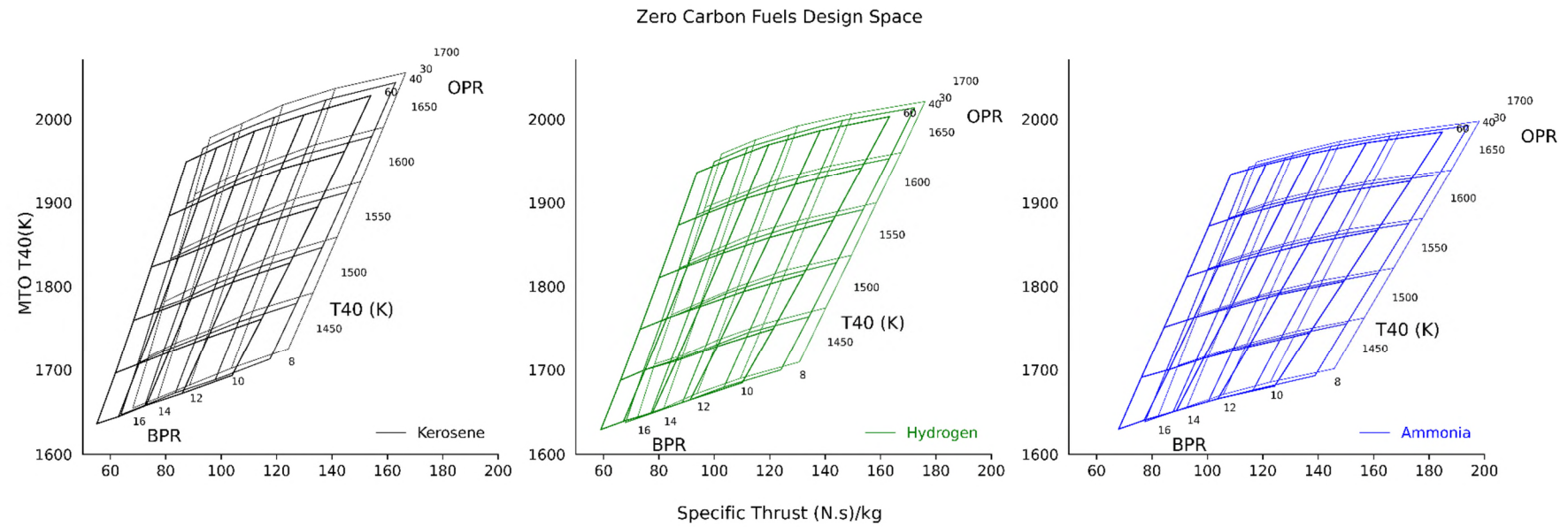


Figure 4-12: Impact of OPR on take-off T40

Figure 4-12 presents the trends of reducing take-off T40s as the design space shifts to higher OPRs.

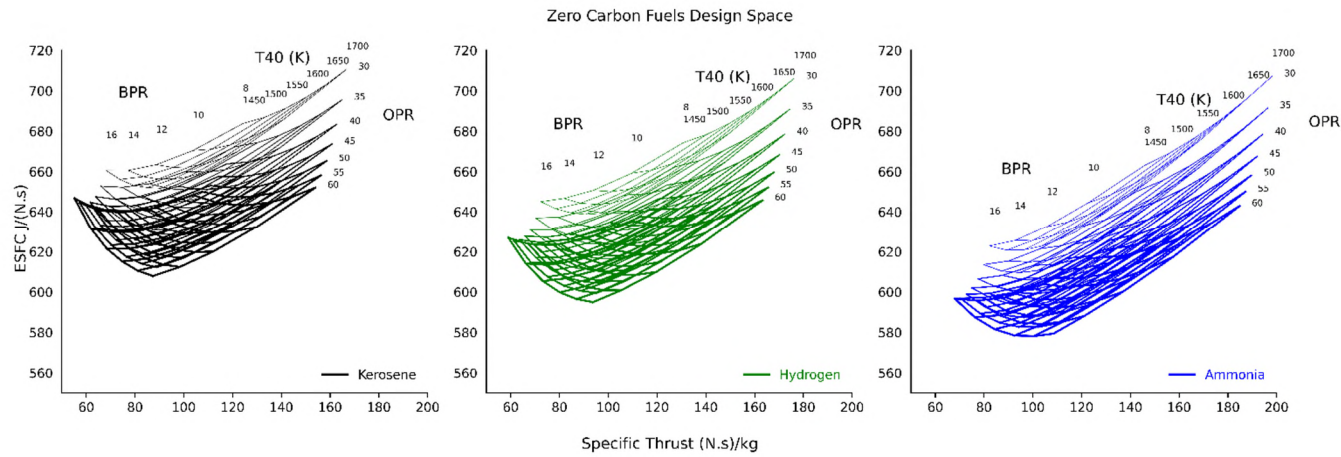


Figure 4-13: Impact of OPR on turbofan cycle design space (all OPRs)

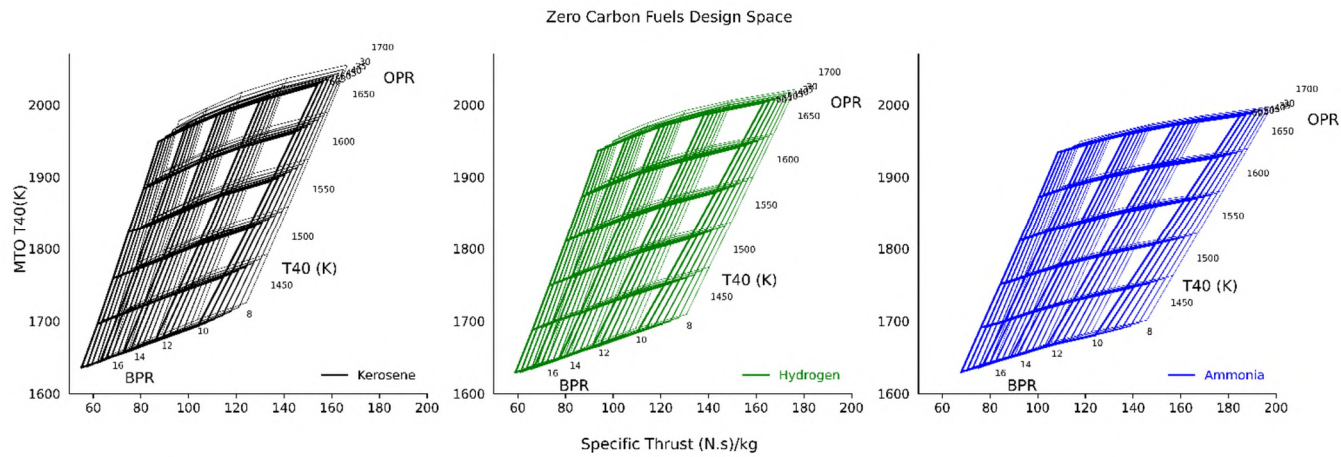


Figure 4-14: Impact of OPR on take-off T40 (all OPRs)

4.3 Impact of alternative fuels on turbofan engine weights

This activity aimed to identify the opportunities offered by alternative fuels when considering turbofan engine weights. The results presented in this section have potential implications for the OEMs (e.g. Rolls-Royce), especially since alternative fuels will need additional fuel systems on board the aircraft and weights will be of paramount importance. Hence, this section presents the results of the activity followed by a discussion on the significance of the outcomes. Note that discussions made in this section regarding turbofan cycle design, performance, size and weights correspond to a 2-spool engine architecture. In the upcoming section 4.4, results and discussions pertaining to 3-spool engine architecture as part of integrated engine-aircraft study is presented. Since this assessment aimed to identify major top-level trends in terms of turbofan engine size and weight, the outcomes and trends from the study of this section is believed to be largely applicable to any turbofan engine architecture.

4.3.1 Turbofan cycle design strategies and performance

As mentioned previously in section 3.4.2, three cycle design strategies are devised. These are resized core maintaining peak cycle temperatures at take-off as baseline kerosene, fixed core size as baseline kerosene and fixed cycle at design point as baseline kerosene. A 2-spool variant of baseline kerosene is considered in this activity for the assessment. The flight conditions and thrust requirements considered for the assessment are provided in Table 4-15. The pressure ratio split and component efficiencies are provided in Table 4-16. The flight conditions and thrust requirements are modelled after a SMR category aircraft namely Airbus A321neo variant that uses a CFM LEAP 1-A turbofan engine.

Table 4-15: Flight conditions and thrust requirements

MCR Altitude	35,000 ft
MCR Mach	0.78

MCR ISA dev	0
MCR Thrust	22,417 N
MCL Altitude	35,000 ft
MCL Mach	0.78
MCL ISA dev	10
MCL Thrust	29,142 N
MTO Altitude	0 ft
MTO Mach	0.25
MTO ISA dev	15
MTO Thrust	109,760 N

Table 4-16: Assumed pressure ratio split and component efficiencies

<u>Technology</u>	<u>Value</u>
IPC/HPC pressure ratio split	0.3
$\eta_{is,Fan}$	0.89
$\eta_{is,booster}$	0.891
$\eta_{is,HPC}$	0.874
$\eta_{is,HPT}$	0.914
$\eta_{is,LPT}$	0.926

The turbofan cycle performance at the design MCR operating point for the three strategies regarding the candidate alternative fuels is presented in Table 4-17, Table 4-18 and Table 4-19.

From Table 4-17, for the fixed cycle strategy at design point as baseline kerosene (same FPR, BPR, T40, OPR), the top of climb (TOC) mass flow rates which sizes the fan is seen to progressively decrease as one move towards zero carbon fuels. This indicates that the fan diameter reduces as one move towards zero carbon fuels with this strategy. Also, the specific thrust compared to kerosene is seen to increase as one moves to zero carbon fuels. This aligns with the findings of higher specific thrust capability of alternative fuels as discussed in section 4.2.2. Since the assessment is run for fixed thrust requirements, this essentially results in a smaller engine footprint.

From Table 4-18, for the resized core strategy that uses the 3-point cycle design method as discussed in section 3.4.2, differences are observed in core size, temperature and OPR compared to the baseline kerosene cycle. The core size (core inlet mass flow rates) progressively decreases as one moves towards zero carbon fuels. Since the fan size is maintained as the top of climb mass flow rates are unchanged, this translates into increase in BPR as one moves towards zero carbon fuels. There are minor deviations in OPR that can be seen. The core operating temperatures increases as one move towards zero carbon fuels. But it must be noted that the peak cycle temperatures at take-off is maintained as baseline kerosene cycle. The take-off temperature benefit of alternative fuels as discussed section 4.2.2 allows reducing the core size to reach the peak cycle temperatures as kerosene. Smaller cores then cause the cruise temperatures to increase to maintain the thrust requirements.

From Table 4-19, for fixed core size strategy, a reduction in core operating temperatures is observed. The core temperatures progressively decrease as one move towards zero carbon fuels. In pursuit of maintaining the core size, the core temperatures are reduced, which ultimately brings the specific thrust levels back to the same as baseline kerosene. This then causes the fan diameter to be same

as that of the kerosene cycle. Note that FPR, BPR, OPR are maintained as the kerosene cycle to make this possible.

The cycle efficiencies in terms of ESFC benefits are observed to be best for the resized core strategy as showcased in Figure 4-15 since these are optimised cycles for optimum jet velocities ratio. The best ESFC benefit is observed for zero carbon fuel Ammonia followed by Hydrogen. The other two strategies have different jet velocities ratios primarily due to higher core exhaust velocities by fixing T40s of fixed cycle strategy and lower core exhaust velocities by reduced T40s of fixed core strategy. The jet velocities ratios and their comparisons are provided in Table 4-20.

Table 4-17: Differences compared to baseline kerosene for fixed cycle strategy

<i>MCR</i>	<i>KE</i>	<i>SAF</i>	<i>Octane</i>	<i>Butane</i>	<i>Butanol</i>	<i>Methane</i>	<i>DME</i>	<i>Hydrogen</i>	<i>Ammonia</i>
<i>W (kg/s)</i>	214.4	-0.5	-1.1	-1.4	-3.3	-3.0	-4.7	-5.3	-14.4
<i>W_{TOC} (kg/s)</i>	223	-0.6	-1.1	-1.4	-3.3	-3.0	-4.7	-5.2	-14.1
<i>W_{core} (kg/s)</i>	17.9	-0.5	-1.1	-1.4	-3.3	-3.0	-4.7	-5.3	-14.4
<i>BPR</i>	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>OPR</i>	42.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>T40 (K)</i>	1508.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Sp.Thrust (N.s/kg)</i>	104.5	0.5	1.1	1.4	3.4	3.1	4.9	5.6	16.8
<i>FPR</i>	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>SFC (g/kN.s)</i>	14.4	-2.9	-4.2	-6.3	29.3	-14.6	48.1	-64.6	127.6
<i>ESFC (J/N.s)</i>	618.9	-0.2	-0.5	-0.6	-0.8	-0.9	-1.1	-1.5	-1.8

Note: Differences are in % against kerosene where negative indicates reduction and positive indicates increment. T40 differences are in degree K and not in % compared to kerosene.

Table 4-18: Differences compared to baseline kerosene for resized core strategy

<i>MCR</i>	<i>KE</i>	<i>SAF</i>	<i>Octane</i>	<i>Butane</i>	<i>Butanol</i>	<i>Methane</i>	<i>DME</i>	<i>Hydrogen</i>	<i>Ammonia</i>
<i>W (kg/s)</i>	214.4	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0
<i>W_{TOC} (kg/s)</i>	223	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>W_{core} (kg/s)</i>	17.9	-0.8	-1.3	-1.7	-4.4	-4.1	-6.5	-8.5	-23.1
<i>BPR</i>	11.0	1.0	1.5	1.9	5.2	4.8	7.7	10.0	32.8
<i>OPR</i>	42.0	0.0	-0.1	-0.1	-0.2	0.2	-0.1	1.1	0.5
<i>T40 (K)</i>	1508.4	1.5	0.8	1.4	6.0	6.4	9.3	18.3	43.4
<i>Sp.Thrust (N.s/kg)</i>	104.5	-0.1	-0.1	0.0	-0.1	-0.1	-0.1	0.0	0.0
<i>FPR</i>	1.5	-0.4	-0.6	-0.4	-0.8	-0.5	-0.6	0.0	-0.1
<i>SFC (g/kN.s)</i>	14.4	-3.0	-4.3	-6.5	28.7	-15.0	47.0	-65.0	116.3
<i>ESFC (J/N.s)</i>	618.9	-0.3	-0.6	-0.7	-1.2	-1.3	-1.8	-2.7	-6.6

Note: Differences are in % against kerosene where negative indicates reduction and positive indicates increment. T40 differences are in degree K and not in % compared to kerosene

Table 4-19: Differences compared to baseline kerosene for fixed core strategy

<i>MCR</i>	<i>KE</i>	<i>SAF</i>	<i>Octane</i>	<i>Butane</i>	<i>Butanol</i>	<i>Methane</i>	<i>DME</i>	<i>Hydrogen</i>	<i>Ammonia</i>
<i>W (kg/s)</i>	214.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>W_{TOC} (kg/s)</i>	223	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>W_{core} (kg/s)</i>	17.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>BPR</i>	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>OPR</i>	42.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>T40 (K)</i>	1508.4	-3.4	-6.9	-8.9	-21.0	-19.2	-30.5	-35.2	-100.8
<i>Sp.Thrust (N.s/kg)</i>	104.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>FPR</i>	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>SFC (g/kN.s)</i>	14.4	-2.9	-4.2	-6.3	29.3	-14.6	48.0	-64.7	122.0
<i>ESFC (J/N.s)</i>	618.9	-0.2	-0.5	-0.6	-0.8	-0.9	-1.2	-1.7	-4.2

Note: Differences are in % against kerosene where negative indicates reduction and positive indicates increment. T40 differences are in degree K and not in % compared to kerosene

Table 4-20: Jet velocities ratio and their differences compared to optimised resized core strategy

Jet Velocity Ratio	KE	SAF	Octane	Butane	Butanol	Methane	DME	Hydrogen	Ammonia
Fixed Cycle	0.76	0.75	0.74	0.74	0.70	0.70	0.67	0.64	0.61
Resized Core	0.76	0.74	0.74	0.75	0.73	0.74	0.74	0.74	0.75
Fixed Core	0.76	0.76	0.77	0.77	0.77	0.77	0.78	0.75	0.79
Delta % compared to resized core of each fuel									
Fixed Cycle	0.0	0.9	0.5	-1.7	-4.2	-5.4	-9.1	-13.6	-18.2
Resized Core	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fixed Core	0.0	2.6	4.0	2.7	6.1	3.8	5.0	1.4	4.9

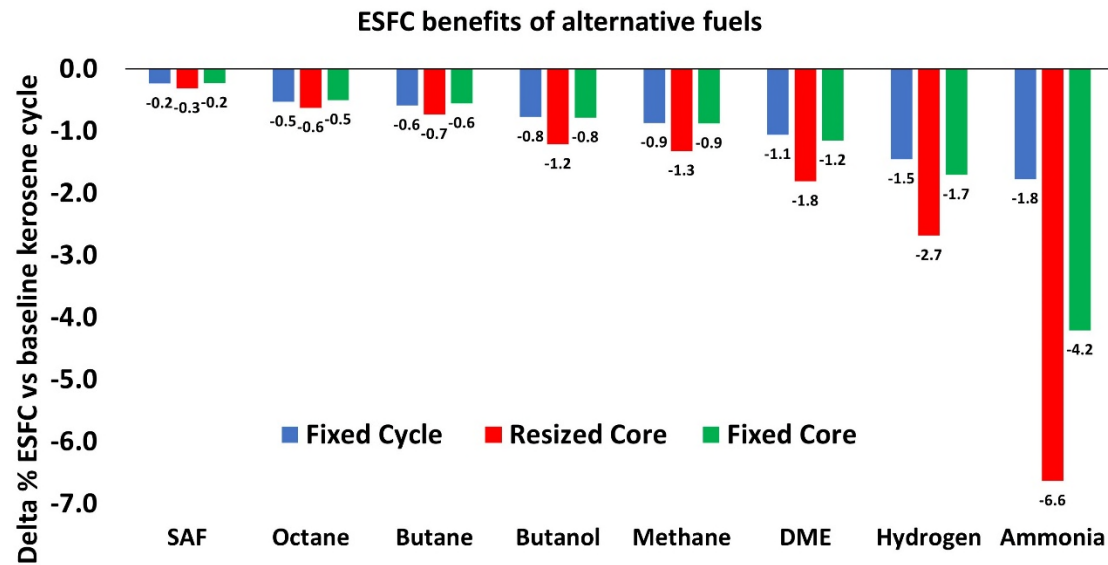


Figure 4-15: ESFC benefits comparison of strategies for alternative fuels

4.3.2 Turbofan engine weights and ATLAS annulus diagrams

In this subsection, the bare engine weights of the 3 strategies namely Fixed Cycle, Resized Core and Fixed Core are presented which is then followed by the bare engine annulus diagrams, all generated by ATLAS for candidate alternative fuels. Figure 4-16 showcase the differences in bare engine weights for the 3 strategies compared to the baseline kerosene turbofan cycle.

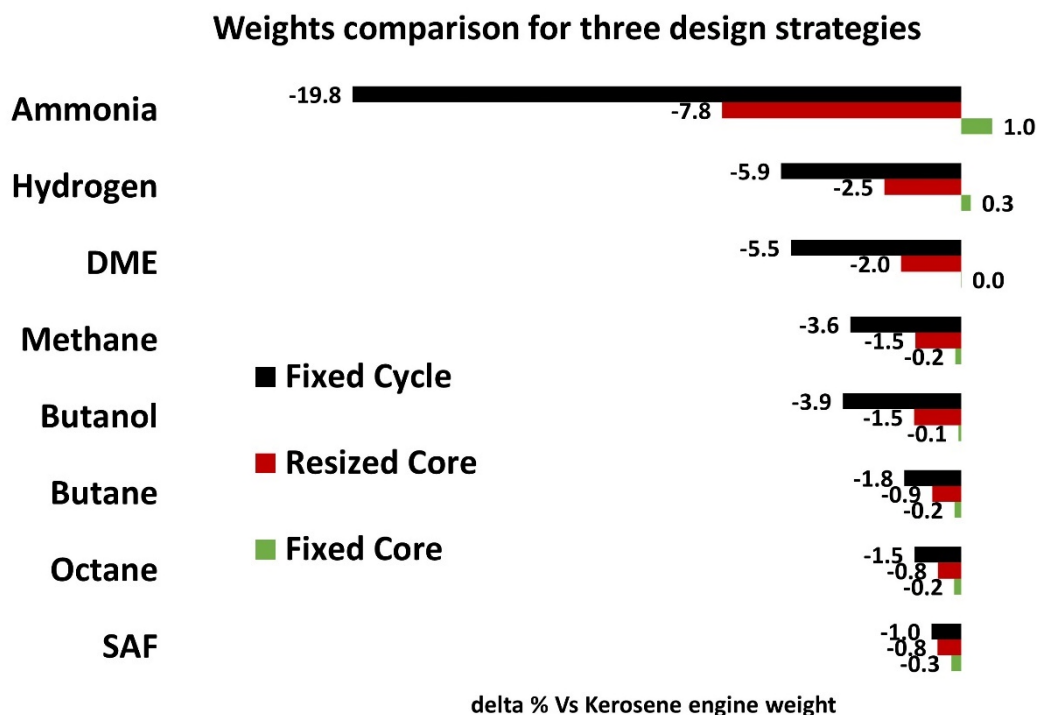


Figure 4-16: Engine weights comparison with kerosene for alternative fuels

It is found that the fixed cycle strategy provides the best benefit when it comes to engine weight reduction possibilities for alternative fuels since the entire engine has a smaller footprint. This is then followed by the resized core strategy for the same fan size. Finally, for the fixed core strategy, the engine footprint essentially remains same as that of kerosene and hence does not show any major differences when it comes to engine weights compared to kerosene. However, when observing the take-off peak cycle temperatures, fixed core strategy provides the best temperature reduction possibilities as presented in Figure 4-17. This is then followed by fixed cycle strategy when it comes down to temperature

reduction capability. The resized core strategy maintains the peak cycle temperatures at take-off as explained earlier, hence there are no differences compared to kerosene.

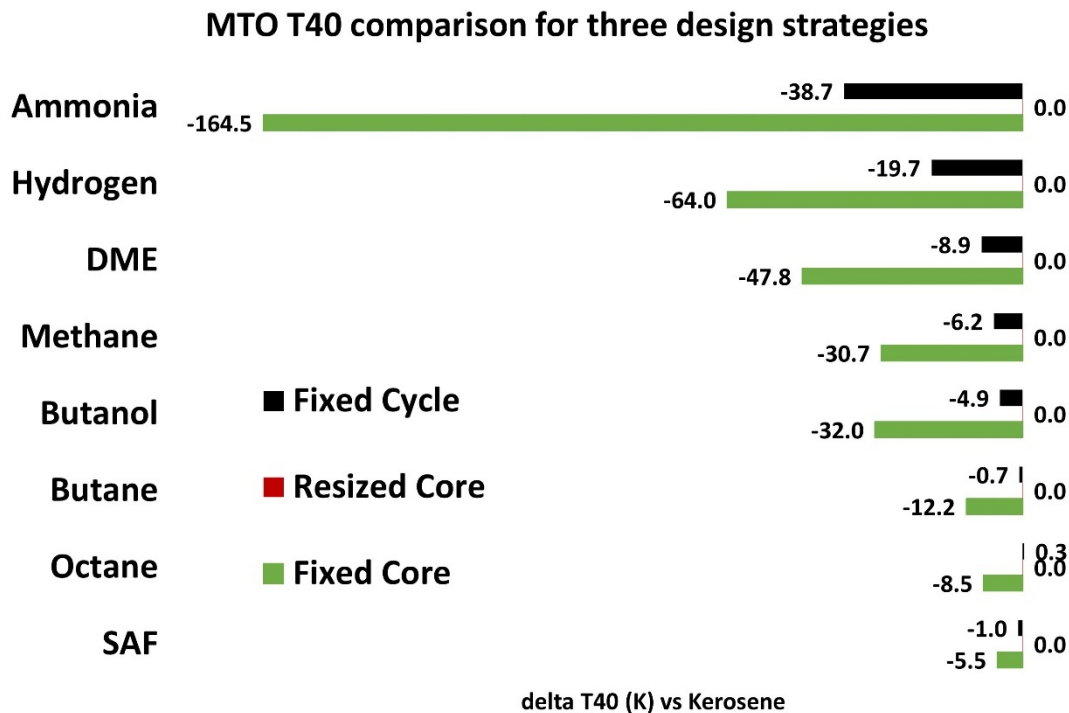


Figure 4-17: Peak cycle temperature comparison with kerosene for alternative fuels

The maximum degree of impact on engine weights is showcased by zero carbon fuel Ammonia which is then followed by Hydrogen using the fixed cycle and resized core strategy. When it comes to take-off temperature reduction capability, the maximum degree of impact is showcased by zero carbon fuel Ammonia that is followed by Hydrogen using the fixed core and fixed cycle strategy. Hence, one can qualitatively conclude that alternative fuels can affect engine weights and operating temperatures that clearly depends on the design strategy chosen. The engine weights and take-off temperatures are presented in Table 4-21 and Table 4-22. The bare engine annulus diagram for the three strategies compared to the baseline kerosene are showcased in Figure 4-18, Figure 4-19, Figure 4-20 followed by all the 3 strategies in one picture Figure 4-21 to showcase the degree of changes for the candidate alternative fuels.

Table 4-21: The bare engine weights for candidate alternative fuels (3 design strategies)

<i>Baseline kerosene bare engine weight = 2553 kg</i>			
<i>Fuels</i>	<i>Fixed Core</i>	<i>Resized Core</i>	<i>Fixed Cycle</i>
<i>SAF</i>	2544	2533	2528
<i>Octane</i>	2547	2534	2514
<i>Butane</i>	2547	2529	2506
<i>Butanol</i>	2550	2514	2455
<i>Methane</i>	2548	2515	2461
<i>DME</i>	2553	2503	2412
<i>Hydrogen</i>	2561	2489	2403
<i>Ammonia</i>	2579	2355	2048

Table 4-22: The peak cycle temperatures (take-off) for candidate alternative fuels (3 design strategies)

<i>Baseline kerosene T40 = 1877.41 K</i>			
<i>Fuels</i>	<i>Fixed Core</i>	<i>Resized Core</i>	<i>Fixed Cycle</i>
<i>SAF</i>	1871.94	1877.41	1876.42
<i>Octane</i>	1868.95	1877.41	1877.73
<i>Butane</i>	1865.22	1877.41	1876.72
<i>Butanol</i>	1845.41	1877.41	1872.51
<i>Methane</i>	1846.74	1877.41	1871.2
<i>DME</i>	1829.66	1877.41	1868.51
<i>Hydrogen</i>	1813.41	1877.41	1857.69
<i>Ammonia</i>	1712.9	1877.41	1838.75

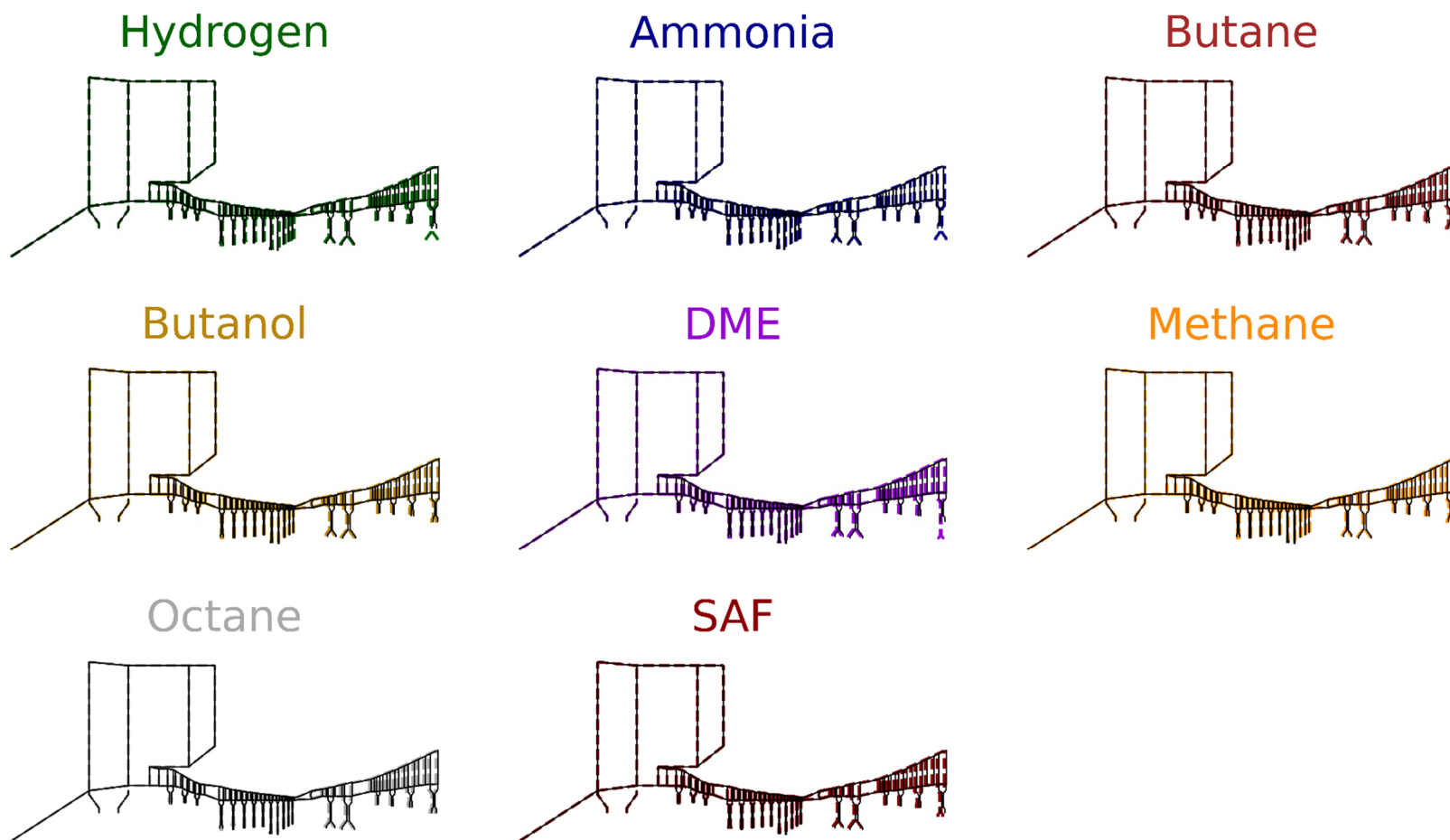


Figure 4-18: Bare engine annulus diagram for candidate fuels overlaid on baseline kerosene annulus (Fixed Core)

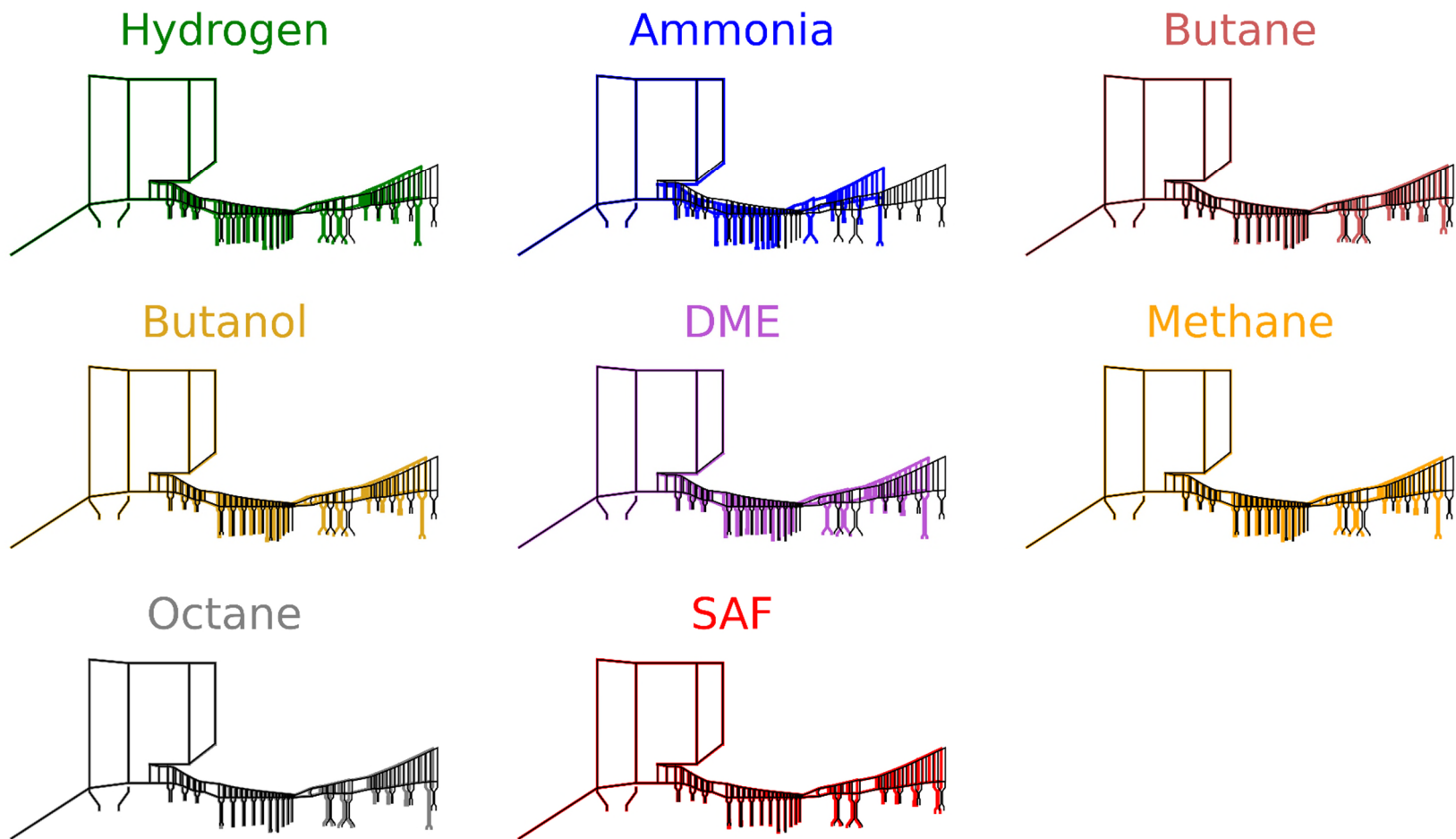


Figure 4-19: Bare engine annulus diagram for candidate fuels overlaid on baseline kerosene annulus (Resized Core)

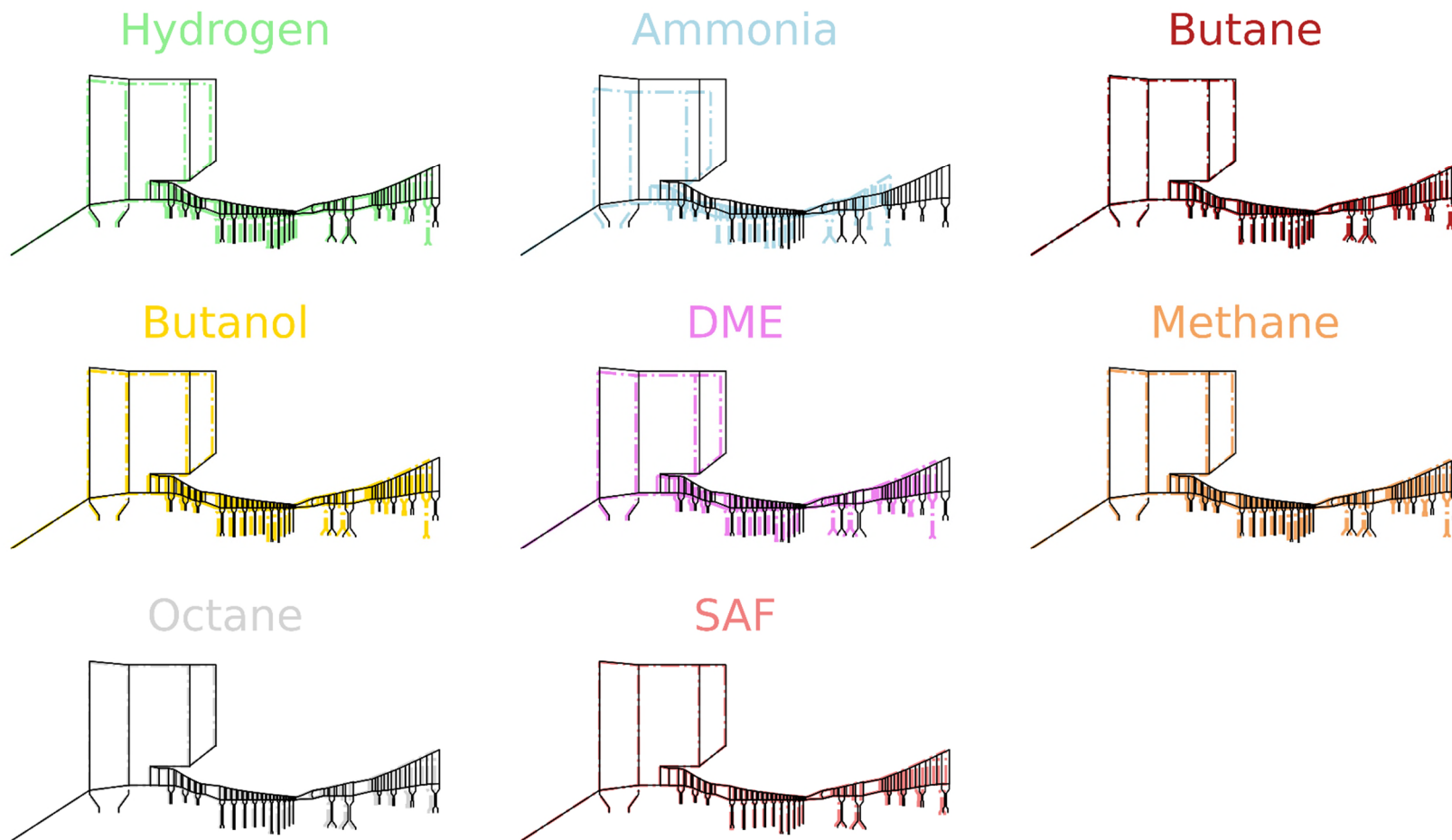


Figure 4-20: Bare engine annulus diagram for candidate fuels overlaid on baseline kerosene annulus (Fixed Cycle)

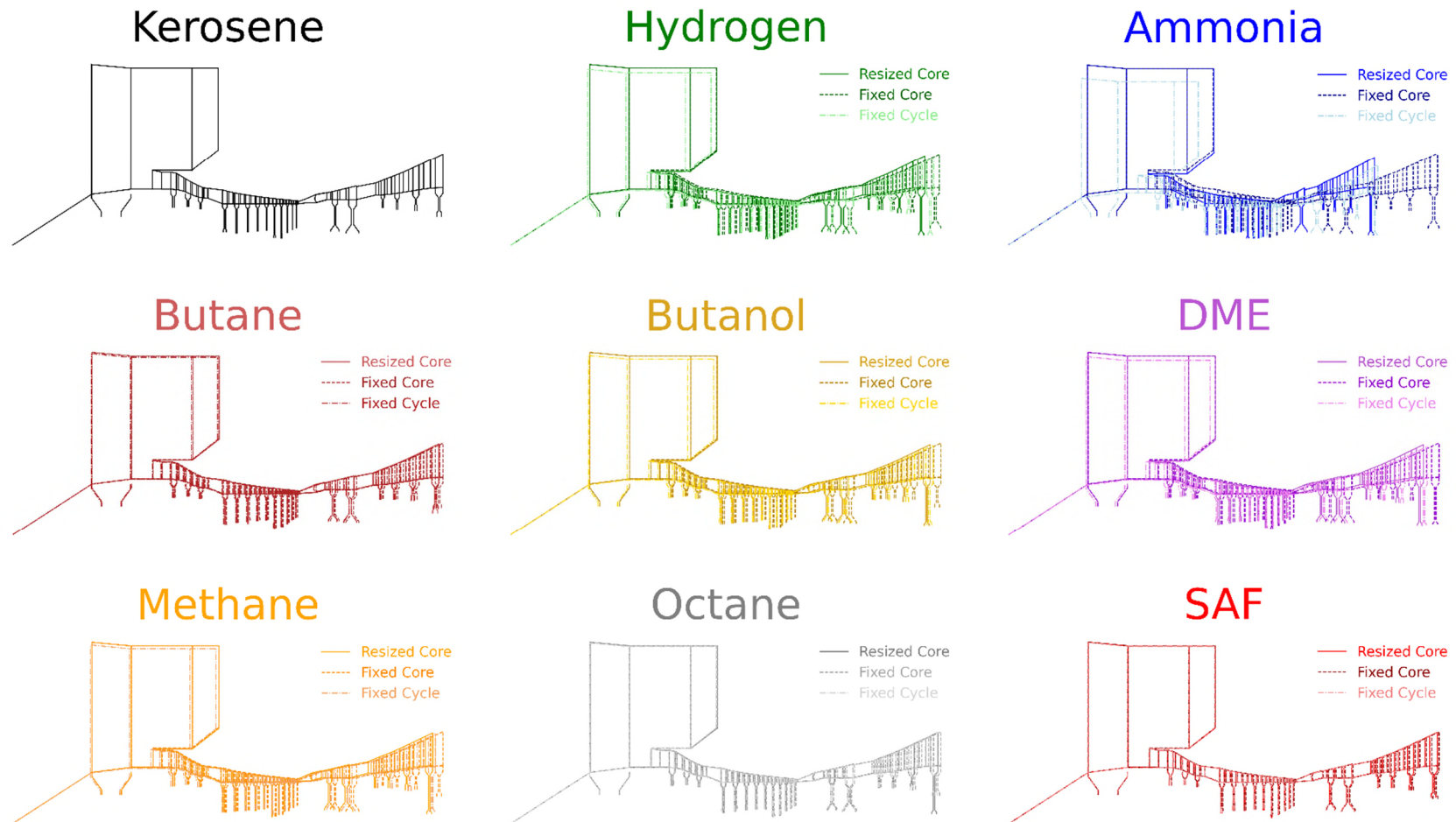


Figure 4-21: Bare engine annulus diagram for candidate fuels showcasing 3 design strategies for candidate alternative fuels

It must be noted that the simulations are performed respecting the turbomachinery constraints in terms of stage loading for turbines and de Haller number for compressors. The simulations are performed for fixed inlet and outlet axial Mach numbers, fixed fan hub/tip radius ratio and fixed geometrical ratios such space/chord ratios as well as blade aspect ratios.

Figure 4-18 showcases that maintaining the same core size when operating with candidate alternative fuels results in turbofan engines with a similar engine footprint in terms of size. As a result, there are only minor changes in engine weight as presented in Table 4-21. However, this design strategy provides the advantage of operating with the lowest possible operating temperatures as presented in Table 4-22.

Figure 4-19 showcases the changes possible to the core section (gas generator) of the turbofan engine when operating with candidate alternative fuels. It highlights that smaller cores tend to reduce the engine length. Smaller cores reduce the blade span which reduces the chord length for fixed blade aspect ratios as mentioned earlier. For fixed space to chord ratios, this leads to more compact cores. Since the core is resized for the same fan size, the changes in engine weight mainly corresponds to the changes in core section. Hence, the smallest core tends to have the lowest engine weight. Note that the core section weight is also affected by the number of stages in it. Smaller cores tend to raise the stage loading predicted by ATLAS due to differences in U parameter. This results in one less HPT stage predicted for Ammonia cycle.

Figure 4-20 provides evidence of the possibility to have a smaller engine footprint with the candidate alternative fuels when the cycle parameters are fixed as that of the baseline kerosene cycle. Since fan module weight is the biggest contributor to the bare engine weight, the reduced fan size in combination with the reduced core size makes this design strategy the most attractive option to reduce bare engine weights as presented in Figure 4-16. Same arguments stated for the resized core strategy are applicable here for engine length difference observed.

Finally, Figure 4-21 allows one to visualise the degree of impact offered by the 3 design strategies compared to kerosene engine annulus.

4.4 Integrated engine aircraft assessment

This activity aimed to explore the opportunities that can be exploited for the turbofan engines when the associated mission performance of the alternative fuelled aircraft is considered. Hence, this section presents the results of the activity followed by a discussion on the significance of the outcomes.

4.4.1 B787-3 SMR retrofit case study

In this investigation, a retrofit case study is conducted with the candidate alternative fuels for a Boeing B787-3 style aircraft. The Boeing 787-3 is a wide body aircraft capable of carrying more passengers for SMR category missions. It is considered that a wide body aircraft can provide more space for any additional fuel systems that may be needed in the future especially like cryogenic tanks for cryogenic fuels. Retrofit here denotes that the airframe dimensions are kept fixed with the same fan size compared to the baseline kerosene aircraft. Table 4-23 presents the design conditions for the modelled baseline kerosene aircraft.

Table 4-23: Kerosene aircraft design conditions

Design Conditions	
Cruise Mach	0.85
Cruise Altitude (ft)	35,000
Design Range (nm)	3050
MTOW (tons)	170.24
Maximum Fuel Capacity (tons)	38.98
PAX	330

The engine model used for the aircraft is based on a 3-spool turbofan engine architecture. Table 4-24 presents the baseline kerosene turbofan cycle performance at the design point MCR.

Table 4-24: Baseline kerosene 3-spool turbofan cycle

MCR	Values
BPR	10.29
T40 (K)	1500.03
SFC (g/kN.s)	15.185
ESFC (J/N.s)	654.84
Sp. Thrust (N.s/kg)	105.38
W (kg/s)	398.84
W_{core} (kg/s)	35.29
OPR	36.21
FPR	1.52

The pressure ratio split and the component efficiencies are the same as provided in Table 4-13. The peak cycle temperature at take-off is 1758 K, the maximum HPC exit temperature at take-off is 891 K and the top of climb mass flows which sizes the fan is 405 kg/s. Table 4-25 presents the 3-point thrust requirements for the baseline kerosene aircraft.

Table 4-25: 3-point thrust requirements for baseline kerosene aircraft

3 point thrust requirements	Values
MCR	42 kN ISA 0
MCL	50.4 kN ISA 10
MTO	178.7 kN ISA 15

The following paragraphs discuss the working assumptions that have been considered regarding the storage of the candidate fuels onboard the aircraft.

Table 4-26 is provided to help the reader be aware of the boiling points of the candidate fuels.

Table 4-26: Boiling point of candidate fuels (a: [46], b: [101])

Fuels	Boiling Point (°C) at 1 atm
Jet A-1/SAF	176 ^a
N-Octane	126 ^a
Butanol	118 ^b
N-Butane	-0.5 ^b
DME	-24.8 ^b
Ammonia	-33 ^a
Methane	-162 ^a
Hydrogen	-252 ^a

SAF is a synthetic/processed fuel that is manufactured to replace the conventional fuel Jet A-1/Jet A. Hence, it is assumed to be stored inside the wings of the aircraft.

As mentioned earlier in section 4.1.2, Octane represents the gasoline family that is used in automotive industry. Due to this fact, it is assumed that storage is not going to be a major concern and hence, it is assumed to be stored inside the wings of the aircraft.

Butanol is a liquid alternative fuel of the alcohol family which has densities very close to that of Jet A-1/Jet A. Hence, it is assumed to be stored inside the wings of the aircraft.

Hydrogen needs to be stored in a liquid state to maximize its density and reduce the volume it occupies. It exists as a cryogenic liquid at 20.35K and ambient pressure. However, it's preferable to store it at a slightly higher pressure than ambient at 1.2 bar, to prevent leakage of air into the tanks [68]. It is assumed to be stored inside the fuselage in cryogenic cylindrical tanks with hemispherical cap ends as this geometry has the least surface/volume ratio that minimizes heat

leakage [54]. The CleanSky report [91] assumes a tank gravimetric efficiency of 37% for the SMR segment while Verstraete et al [109] and Brewer [76] reported values in the ranges between 50% and 70%. Hence, two scenarios, conservative 30% and optimistic 60% values are assessed.

Like Hydrogen, Methane also needs to be stored in a liquid state to maximize its density and reduce the volume occupied. It exists as a mild cryogenic liquid at 111.55K and ambient pressure. However, it is preferable to store it at a slightly higher pressure than ambient at 1.2 bar, to prevent air leakage into the tanks. Rompokos et al [35] and Carson et al [77] reported a tank gravimetric efficiency of approximately 90%. Being conservative due to installation effects, 85% value is selected for the assessment. One should also note that liquid Methane will require lower insulation due to its higher boiling point compared to liquid Hydrogen, and this will lead to a higher tank gravimetric efficiency in comparison to liquid Hydrogen. It is also assumed to be stored inside the fuselage in a cryogenic cylindrical tank with hemispherical cap ends.

Butane can exist as a liquid under ambient temperatures and 2 atm pressures. However, it is assumed to be stored inside the wings as a subcooled liquid as this provided maximum density (601.63 kg/m^3). Since the boiling point is a high value compared to cryogenic fuels, a tank gravimetric efficiency of 97% is assumed to account for the low insulation tank weights required.

DME can exist as a liquid under moderate pressures of 4-5 atm at ambient temperatures. Its handling properties are very similar to LPG. However, it is assumed to be stored inside the wings as a subcooled liquid as this provided maximum density (735 kg/m^3). Since the boiling point is a high value compared to cryogenic fuels, a tank gravimetric efficiency of 97% is assumed to account for the low insulation tank weights required.

Ammonia can exist as a liquid under moderate pressure of 8 bar and ambient temperatures. Herein, it is assumed to be stored inside the wings as a subcooled liquid as this provided maximum density (682 kg/m^3). Since the boiling point is a high value compared to cryogenic fuels, a tank gravimetric efficiency of 97% is assumed to account for the low insulation tank weights required.

Based on methodology discussed in section 3.5 for the integrated engine aircraft assessment, the results presented here utilises turbofan engine cycles that are redesigned according to the aircraft thrust requirements. This means that the delivered power by the turbofan engine is different based on the aircraft requirements.

The assessments are made for a target design range of 3050 nm where possible and never exceeding the MTOW to be within the structural limitations of the aircraft. Figure 4-22 presents the aircraft weight breakdown along with the passenger capacity compared to the baseline kerosene aircraft.

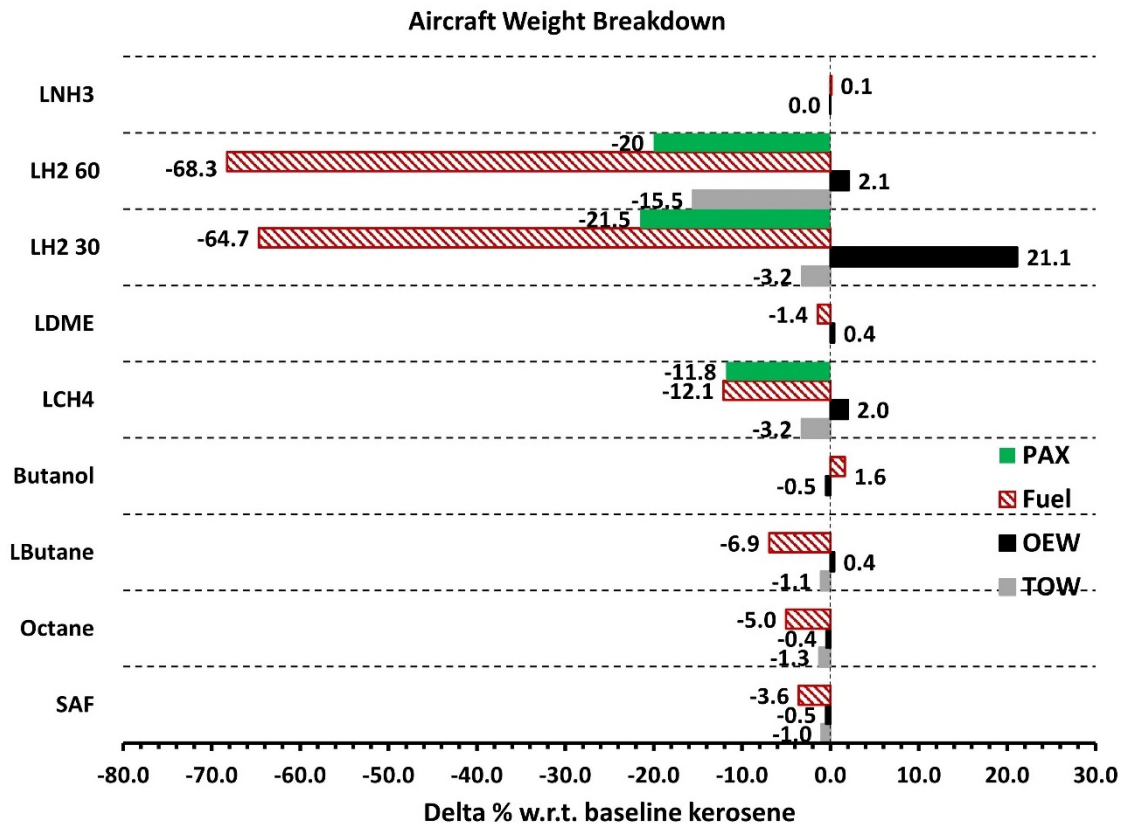


Figure 4-22: Aircraft weight breakdown

LH2 30 and LH2 60 are assessments made for Hydrogen aircraft that utilize cryogenic tanks of different technology levels. LH2 30 i.e., 30% tank gravimetric efficiency corresponds to a heavier tank and LH2 60 i.e., 60% tank gravimetric efficiency corresponds to a lighter tank. It is observed that for cryogenic fuels such as Hydrogen and Methane where the fuel is stored inside the fuselage, the

passenger capacity must be reduced to accommodate the cryogenic tanks. This is 71 and 66 passengers for LH2 30 and LH2 60 respectively whereas, for Methane, it is 39 passengers. The OEW has increased compared to baseline due to the heavy tanks associated with cryogenic fuels, but MTOW has been respected as is seen from the reduction in TOW. Note that OEW also includes the reduced engine weights, which will be demonstrated in the upcoming discussions. For higher boiling point fuels such as DME and Butane, the OEW increases are lower due to lighter tanks as the insulation requirements are lower compared to cryogenic fuels. For Ammonia, the OEW becomes approximately equal to kerosene, thanks to the reduced engine weights. The higher LHV fuels such as Hydrogen, Methane, Butane, Octane, and SAF have lower TOW and mission fuel requirements. Reduced LHV fuels such as Ammonia, DME, and Butanol are within the same MTOW as baseline kerosene to be within the structural limits for the aircraft.

Table 4-27 presents the 3-point thrust requirements obtained from the aircraft performance assessment.

Table 4-27: 3-point thrust requirements for alternative fuelled aircraft

Fuel	MCR kN	MCL kN	MTOW kN
	ISA 0	ISA 10	ISA 15
SAF	41.1	49.4	177.5
Octane	41.19	49.43	177.1
Butanol	41.44	49.73	178.7
LButane	41.3	49.58	177.3
LDME	41.44	49.73	178.7
LNH3	41	49.4	178.7
LCH4	40.9	49.1	173.9
LH2 30	42.6	46.9	174.4
LH2 60	39.1	43	152.6

Figure 4-23 presents the engine cycle differences at the design MCR operating point for the candidate alternative fuels.

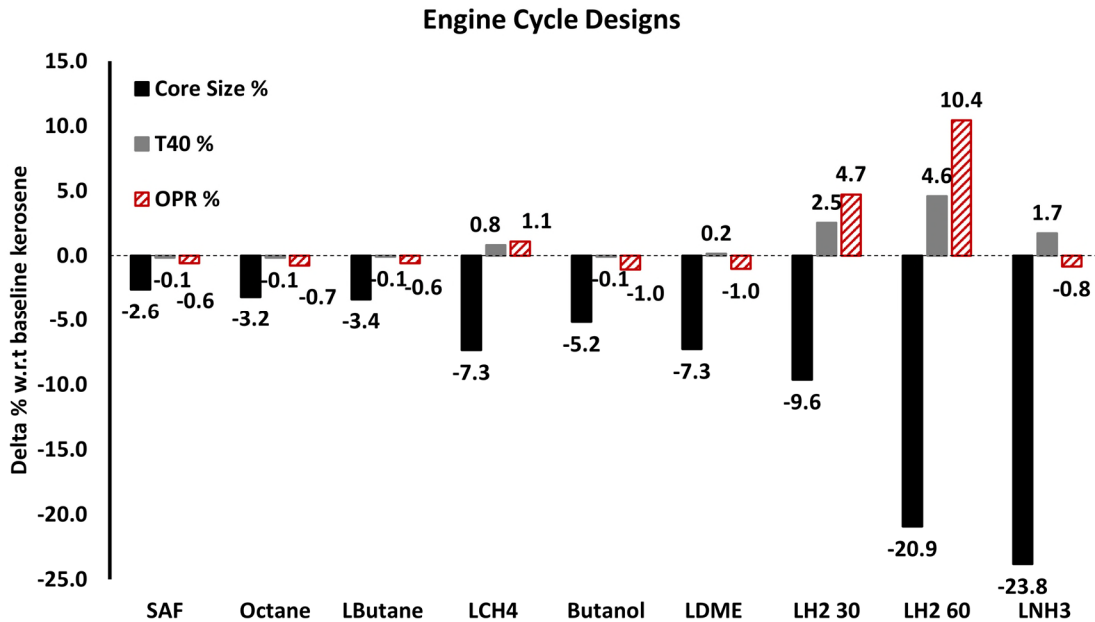


Figure 4-23: Engine cycle differences at MCR when powered by candidate alternative fuels

It is found that, for the same fan size, when powered by alternative fuels, the core size starts reducing with a maximum reduction of up to 23.8% as seen in the case of an Ammonia turbofan engine. Note that core size here refers to the core inlet flow capacities. This is followed by a 21% and 10% reduction for Hydrogen turbofan engines depending on the cryogenic tank technology. The reduction in take-off T40 when operated with alternative fuels (section 4.2.2) provides opportunities to resize the core for a given peak cycle temperature. This leads to different BPR designs for the same fan diameter. The take-off power for a given thrust-weight ratio starts to reduce due to the impact of the higher LHV fuels on TOW for a given mission range as shown earlier in Figure 4-22. This provides opportunity to downsize the core even further for a given peak cycle temperature. This applies to SAF, Octane, Butane, Methane, and Hydrogen. The differences in T40 and OPR to satisfy take-off T40 and T30 constraints can be attributed to the different thrust ratings between take-off and mid-cruise as obtained from the

mission assessment. Figure 4-24 presents the differences in specific thrust, ESFC and BPR of the turbofan engine cycles powered by alternative fuels for the MCR operating point.

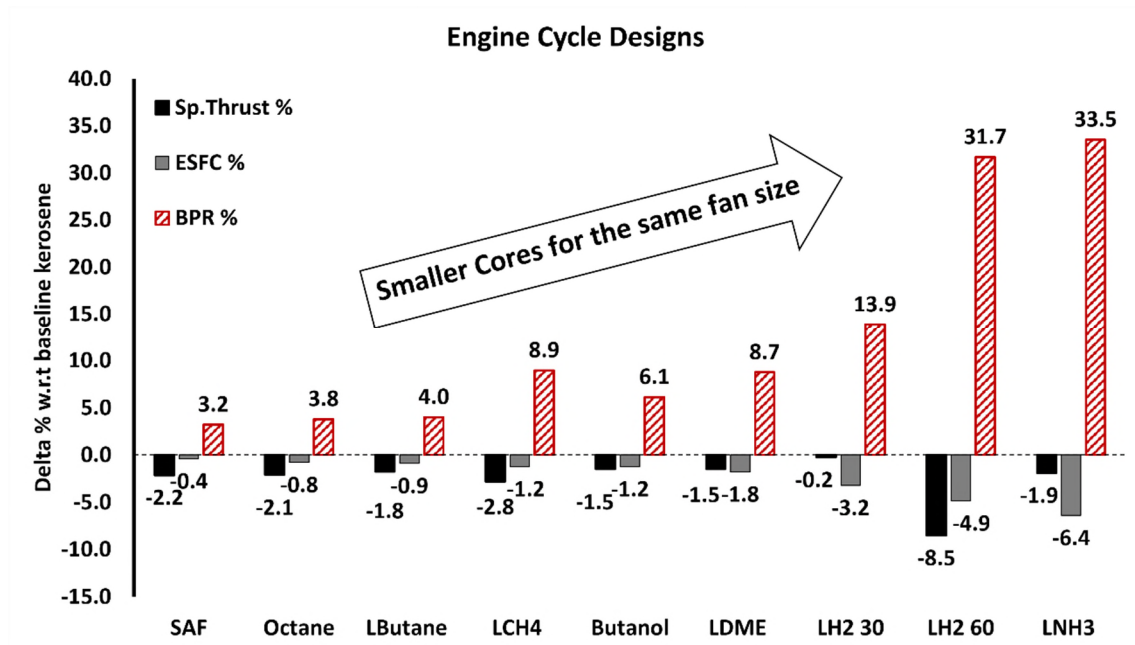
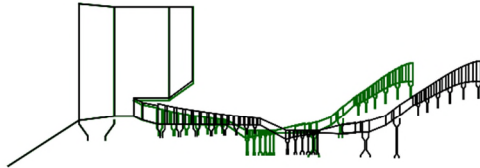


Figure 4-24: Overall efficiency of the engine cycles at mid cruise

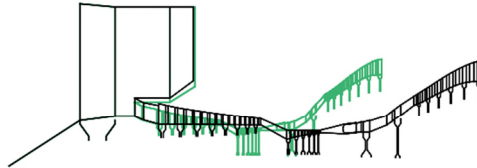
The smaller core sizes demonstrated in the previous Figure 4-23 will manifest as an increase in the BPR as demonstrated in Figure 4-24 when the fan size is kept the same. Hence, as one move towards zero carbon fuels (Hydrogen and Ammonia), the turbofan design impacts are greatly increased as can be seen from the change in BPRs. Since higher LHV fuels results in a lighter aircraft due to lower TOW, the thrust levels are reduced and as a result, when the fan size is kept the same, a lower specific thrust design is obtained. Based on the mission assessment thrust requirements, maintaining the same fan size can alter the specific thrust for reduced LHV fuels. It is found that the maximum ESFC benefit for Ammonia turbofan engine is up to 6.4% and for Hydrogen turbofan engine is 3.2% and 4.9% depending on the cryogenic tank technology. The rest of the candidate alternative fuels offer ESFC benefits providing improved overall efficiencies at the engine cycle level.

Figure 4-25 presents the size and weight differences of the 3-spool turbofan engines powered by the candidate fuels.

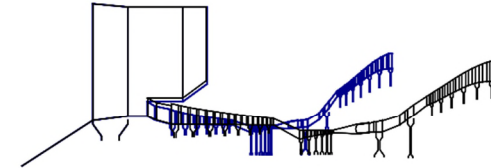
Hydrogen30 -7.4%



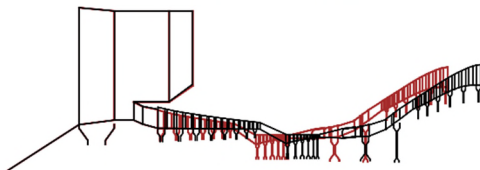
Hydrogen60 -9.9%



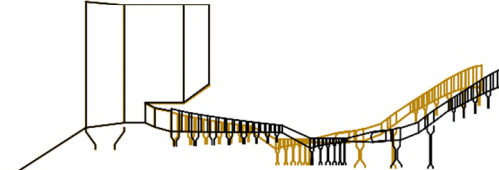
Ammonia -8.8%



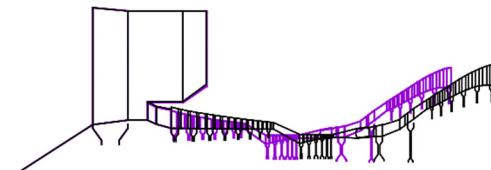
Butane -4.1%



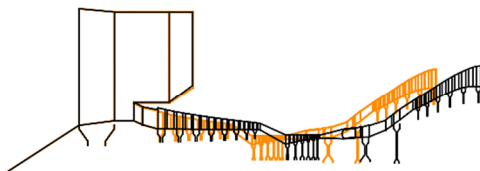
Butanol -4.5%



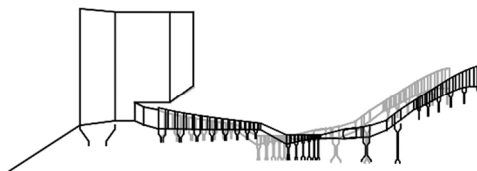
DME -5.2%



Methane -5.7%



Octane -3.9%



SAF -4.3%

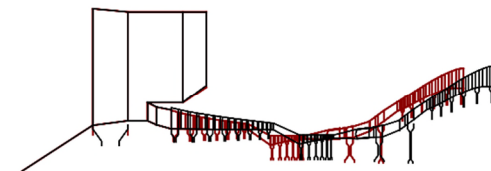


Figure 4-25: Impacts of candidate alternative fuels on engine size and weights

Note that % values refer to the weight differences compared to the baseline kerosene engine. The candidate fuels annulus diagrams are overlayed on the black kerosene engine annulus diagram. Figure 4-25 clearly demonstrates the smaller core sizes when the fan size remains fixed. Similar arguments can be made regarding the length of engine (section 4.3.2) for smaller cores. It is found that zero carbon fuels (Hydrogen and Ammonia) provide the best reduction in engine size and weights. In the case of Hydrogen, it is seen that cryogenic tank technology significantly affects the turbofan design through size and weights. 100% SAF blend also has the potential to affect the turbofan design through core size and weight reductions. Rest of the low carbon fuels also impact the turbofan design through core size and weight reductions which are clearly demonstrated.

4.4.1.1 Environmental and mission assessment

Table 4-28 presents the emission indices used for quantifying the environmental impact of the alternative fuelled aircraft.

Table 4-28: Emission indices for alternative fuels

Alternative Fuel	EICO₂ (kg/MJ)	EIH₂O (kg/MJ)
Kerosene	0.0704	0.0281
SAF	0.0699	0.0313
Octane	0.0689	0.0317
Butane	0.0663	0.0339
Butanol	0.0719	0.0367
DME	0.0664	0.0408
Methane	0.055	0.045
Hydrogen	-	0.075
Ammonia	-	0.0853

Table 4-29 presents the inflight CO₂ and H₂O emissions when operating with the candidate alternative fuels compared to baseline kerosene aircraft. Note that these values are on a per pax.nm basis.

Table 4-29: Inflight emissions of alternative fuel aircraft

Alternative Fuel	%delta vs baseline (CO₂)	%delta vs baseline (H₂O)
SAF	-2	10
Octane	-3	11
LButane	-7	19
Butanol	2	31
LDME	-5	46
LCH ₄	-14	76
LH ₂ 60	-100	194
LNH ₃	-100	198
LH ₂ 30	-100	234

It is seen that as alternative fuels are utilised, the inflight CO₂ emissions are reduced except for Butanol. This is because the emission index of CO₂ for Butanol is higher compared to kerosene as showcased in Table 4-28. However, on the downside, the H₂O emissions are increasing from long chain hydrocarbons to zero carbon fuels. Hence, the total impact of both reducing CO₂ emissions and increasing H₂O emissions are quantified into CO₂ equivalent emissions as demonstrated in Figure 4-26.

Figure 4-26 demonstrates the mission level attributes of the candidate fuels. These include range, block energy burn and global warming impact in terms of CO₂ equivalent emissions.

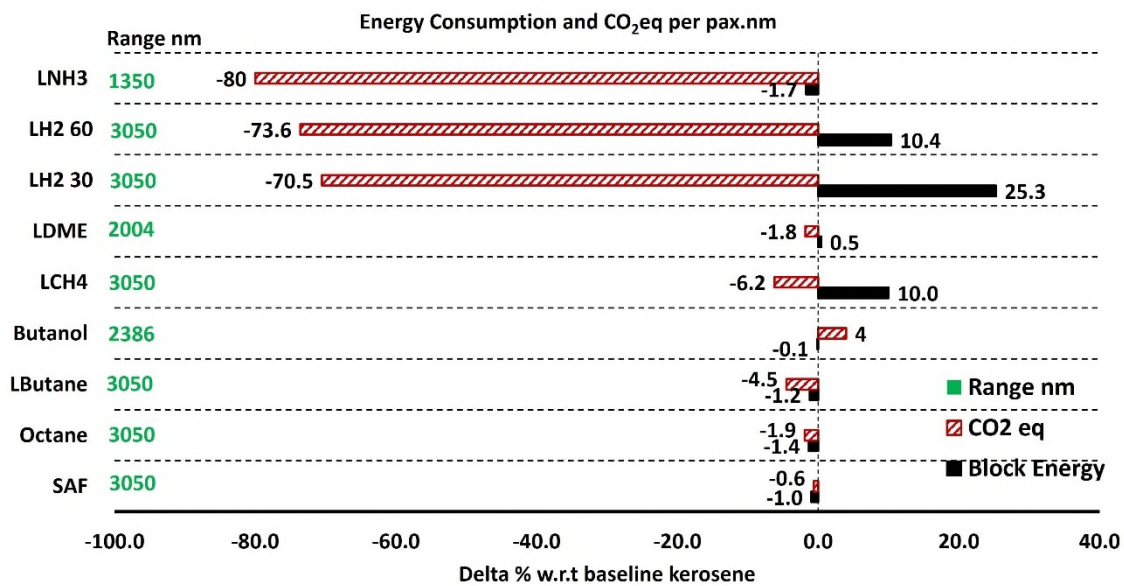


Figure 4-26: Block energy consumption and global warming impact

It is observed that zero carbon fuels, Hydrogen and Ammonia provide the least global warming impact. All other fuels provide benefits in global warming reduction except for Butanol. Cryogenic fuels, Hydrogen and Methane are penalized in block energy consumption due to the size and weight of the fuel storage system (which causes reduced passenger numbers and increased OEW). For Hydrogen, depending on the tank technology, this can be from 10 to 26%. The rest of the fuels are comparable to kerosene on block energy consumption. Fuels such as Ammonia, DME, and Butanol are penalized in mission range because of less energy in the tanks due to their reduced LHV for a fixed MTOW. The maximum penalty is seen in the case of Ammonia which is up to 56% reduced range compared to the baseline kerosene aircraft.

4.4.1.2 Impact of fan size (specific thrust) on turbofan cycle design for zero carbon fuels

From this investigation, it is seen that when it comes to the candidate fuels impact on the turbofan design, while considering their respective aircraft thrust requirements, zero carbon fuels are found to provide the highest degree of impact. Hence, an assessment is performed with Hydrogen and Ammonia to assess the impact of varying the specific thrust (varying fan diameter) on the turbofan design.

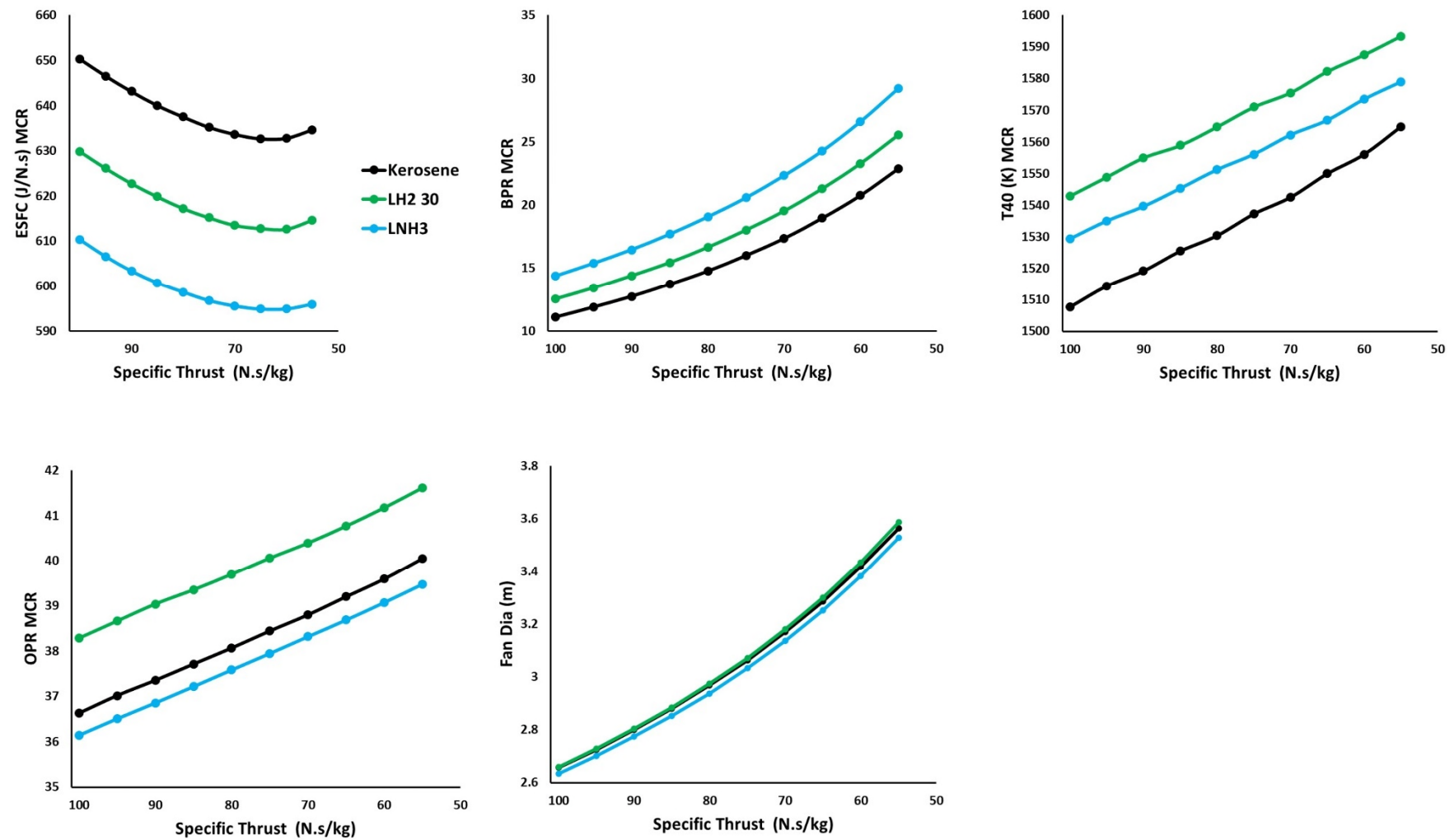


Figure 4-27: Impact of specific thrust on turbfan cycle design of zero carbon fuels

This is performed for the 3-point thrust requirements of the LH2 30 and Ammonia aircraft (Table 4-27) while maintaining the same peak cycle temperature and HPC blade exit temperature at take-off. Figure 4-27 presents the impacts of varying specific thrust on the turbofan design of zero carbon fuels Hydrogen and Ammonia.

It is found that for any given fan size (specific thrust), the impact of zero carbon fuels on turbofan design is significant which can be seen by the increment in bypass ratio. Maximum impact is observed for Ammonia fuel as the bypass ratio is highest i.e. in other words, smallest core size. This is followed by Hydrogen fuel. Reducing specific thrust under the given constraints, improves the overall efficiency in terms of ESFC benefits. This is because of improved propulsive efficiency due to reducing specific thrust and improved thermal efficiency due to higher T40 and OPR. This trend is shown by both Hydrogen and Ammonia. For any given specific thrust (fixed propulsive efficiency), thermal efficiency is higher when operating with zero carbon fuels since ESFC is lower for these fuels compared to kerosene. It is also worth noting that for very low specific thrust designs, the ESFC starts to increase. As the OPR increases, the isentropic efficiency of the compression system reduces for a given polytropic efficiency. This leads to diminishing thermal efficiencies as the specific thrust is reduced. This effect in combination with the bypass duct pressure losses start to become penalising for very low specific thrust designs. The differences in T40 and OPR levels between Ammonia and Hydrogen can be attributed to the different thrust ratings of their respective aircraft.

Similar impacts of specific thrust on turbofan design can be expected for the other candidate alternative fuels as well.

4.4.2 A350-1000 LR retrofit case study

In this investigation, a retrofit case study is conducted for a long range Airbus A350-1000 style aircraft. The Airbus A350-1000 is a wide body aircraft capable of covering distances exceeding 8000 nm with a passenger capacity in the range of 350 to 410 [110]. This retrofit case study is performed with the same set of

assumptions regarding the storage of fuels inside the aircraft (B787-3 case study of section 4.4.1). The dimensions of the airframe and fan size are kept the same as that of baseline kerosene. From the B787-3 case study of section 4.4.1, it is found that certain candidate fuels are limited in mission capability in terms of range covered. These candidate fuels are namely Ammonia, DME and Butanol. Hence, only candidate fuels that demonstrated full mission range capability are assessed. This included SAF, Octane, Butane, Methane and Hydrogen. Regarding Hydrogen aircraft assessment, only LH2 60 (lighter cryogenic tank technology) is assessed. LH2 30 (heavier cryogenic tank technology) is not assessed here because it will lead to a significant reduction of passenger capacity given the mission fuel requirements of a LR aircraft of this category and hence, make it an unrealistic aircraft. The motivation behind this investigation is to assess the impact of candidate alternative fuels on turbofan design across aircraft category by comparing SMR and LR case.

Table 4-30 presents the design conditions for the modelled baseline kerosene LR aircraft.

Table 4-30: Kerosene LR aircraft design conditions

Design Conditions	
Cruise Mach	0.85
Cruise Altitude (ft)	35,000
Design Range (nm)	8077
MTOW (tons)	316
Maximum Fuel Capacity (tons)	122.5
PAX	369

The engine model used for the aircraft is based on a 3-spool turbofan engine architecture. Table 4-31 presents the baseline kerosene LR turbofan cycle performance at the design point MCR.

Table 4-31: Baseline kerosene LR 3-spool turbofan cycle

MCR	Values
BPR	9.6
T40 (K)	1500
SFC (g/kN.s)	13.99
ESFC (J/N.s)	603.3
Sp. Thrust (N.s/kg)	119.52
W (kg/s)	540.80
Wcore (kg/s)	51.02
OPR	41.1
FPR	1.61

The pressure ratio split and the component efficiencies are provided in Table 4-32. The turbomachinery component efficiencies have been assumed to be of year 2020 based on the works of Sebastian et al [111].

Table 4-32: Pressure ratio split and component efficiencies for kerosene LR turbofan

<u>Technology</u>	<u>Value</u>
IPC/HPC pressure ratio split	1.44
$\eta_{poly,Fan}$	0.948
$\eta_{poly,IPC}$	0.917
$\eta_{poly,HPC}$	0.921
$\eta_{poly,HPT}$	0.893
$\eta_{poly,IPT}$	0.898
$\eta_{poly,LPT}$	0.924

The peak cycle temperature at take-off is 1912 K, the maximum HPC exit temperature at take-off is 963 K and the top of climb mass flows which sizes the fan is 567 kg/s. Table 4-33 presents the 3-point thrust requirements for the baseline kerosene LR aircraft.

Table 4-33: 3-point thrust requirements for baseline kerosene LR aircraft

3-point thrust requirements	Values
MCR	64.63 kN ISA 0
MCL	84 kN ISA 10
MTO	345.1 kN ISA 15

Like the SMR case (section 4.4.1), the turbofan engine cycles for the candidate fuels are redesigned according to their respective aircraft thrust requirements. The alternative fuelled aircraft is assessed for the same target design range of 8077 nm as that of the baseline kerosene LR aircraft.

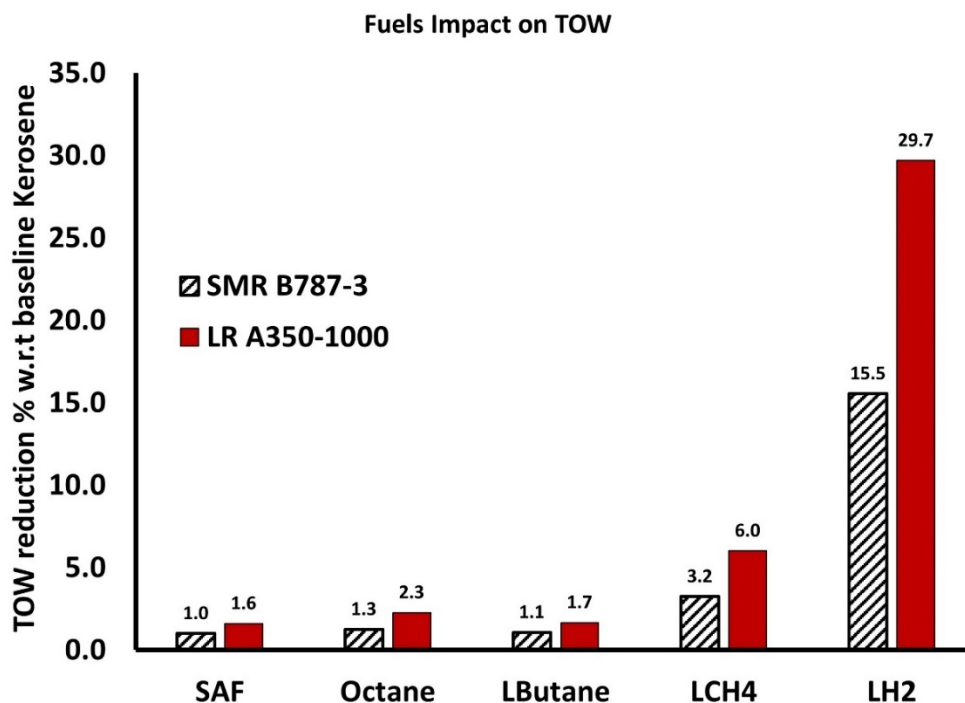


Figure 4-28: TOW impact of candidate alternative fuels (Note: Ammonia not assessed due to limitation in full mission range capability)

Figure 4-28 presents the impact of candidate alternative fuels on TOW across aircraft category. Note that the comparisons are made against the baseline kerosene aircraft of respective category (For example, kerosene SMR vs SAF SMR, kerosene LR vs SAF LR).

It presents the TOW impact of alternative fuels as aircraft class changes from SMR category to LR category. As the LHV of the fuel is increased, less fuel is needed for a given mission range. This impact is enhanced when the proportion of fuel is higher as is the case for a LR aircraft (SMR kerosene fuel = 19.4 wt % of TOW; LR kerosene fuel = 38.6 wt % of TOW). This is manifested as a higher reduction in TOW for LR aircraft. The impact of this trend is stronger as one transition to higher LHV fuels from left to right (long chain hydrocarbons to zero carbon fuels) as shown in Figure 4-28. However, it also must be noted that for cryogenic fuels (Hydrogen and Methane) due to their storage location inside the fuselage, the passenger capacity has been reduced. This is 11.8% and 33.8% respectively for Methane SMR and Methane LR while for Hydrogen SMR and Hydrogen LR, it is 20% and 62% respectively.

As a result of this impact on TOW, the aircraft is lighter and leads to lower thrust requirements. Table 4-34 presents the thrust requirements for the LR aircraft powered by candidate fuels as obtained from the mission assessments.

Table 4-34: 3-point thrust requirements for alternative fuelled LR aircraft

Fuel	MCR kN ISA 0	MCL kN ISA 10	MTO kN ISA 15
SAF	64.2	77.15	341.2
Octane	64.1	76.9	339.3
LButane	64.6	77.58	341.3
LCH4	63.15	80.8	325.8
LH2 60	55.96	67.15	245.8

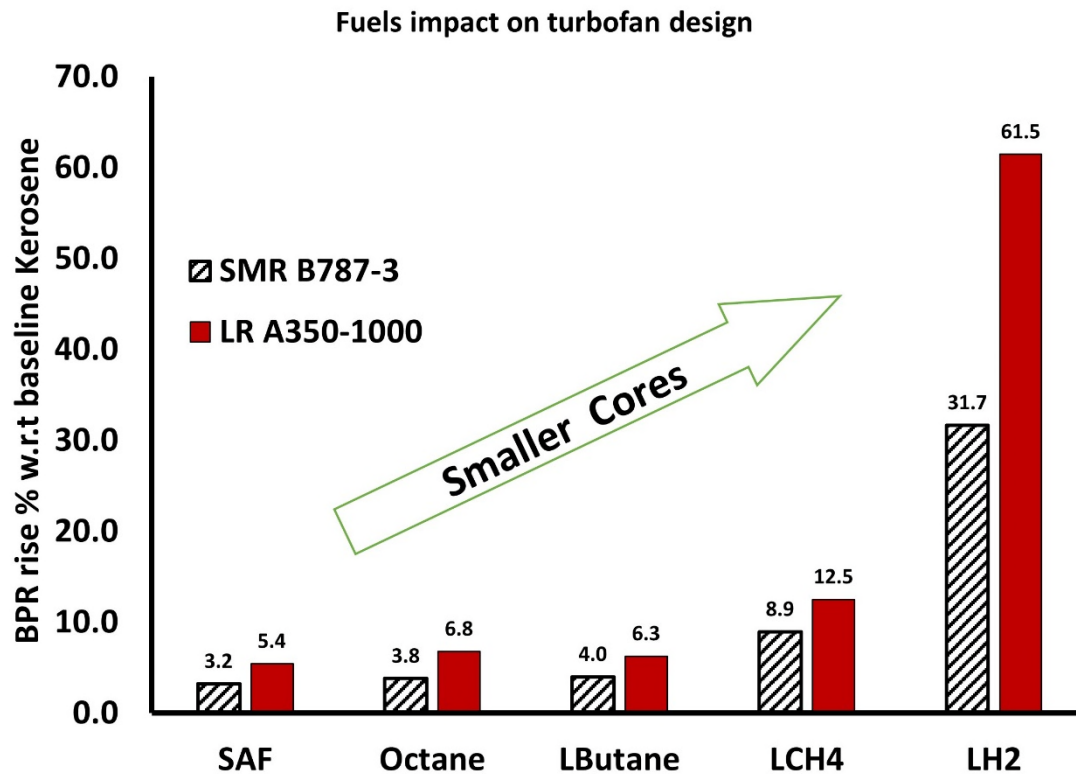


Figure 4-29: Candidate fuels impact on turbofan design across aircraft class

Figure 4-29 presents the impact of the candidate alternative fuels on the turbofan design across aircraft category. The impact on TOW when operated with alternative fuels were presented in Figure 4-28. For a given thrust/weight ratio at take-off, as the TOW reduces, the take-off thrust and power requirements also reduce. For civil passenger aircraft, as the take-off segment is where the turbofan delivers maximum power, the core is sized for take-off. Hence, the reduction in take-off power requirements allows to one downsize the core of the gas turbines. For a given fan size, this results in an increment of BPR. And due to the impact of candidate fuels on TOW across aircraft category, further downsizing of the core is possible which results in a further increment of BPR. Finally, as we transition to higher LHV fuels (long chain hydrocarbons to zero carbon fuels) from left to right, this impact of alternative fuels on turbofan design is significant.

Figure 4-30 to Figure 4-34 presents the comparison of engine size and weights across aircraft category for the assessed candidate fuels.

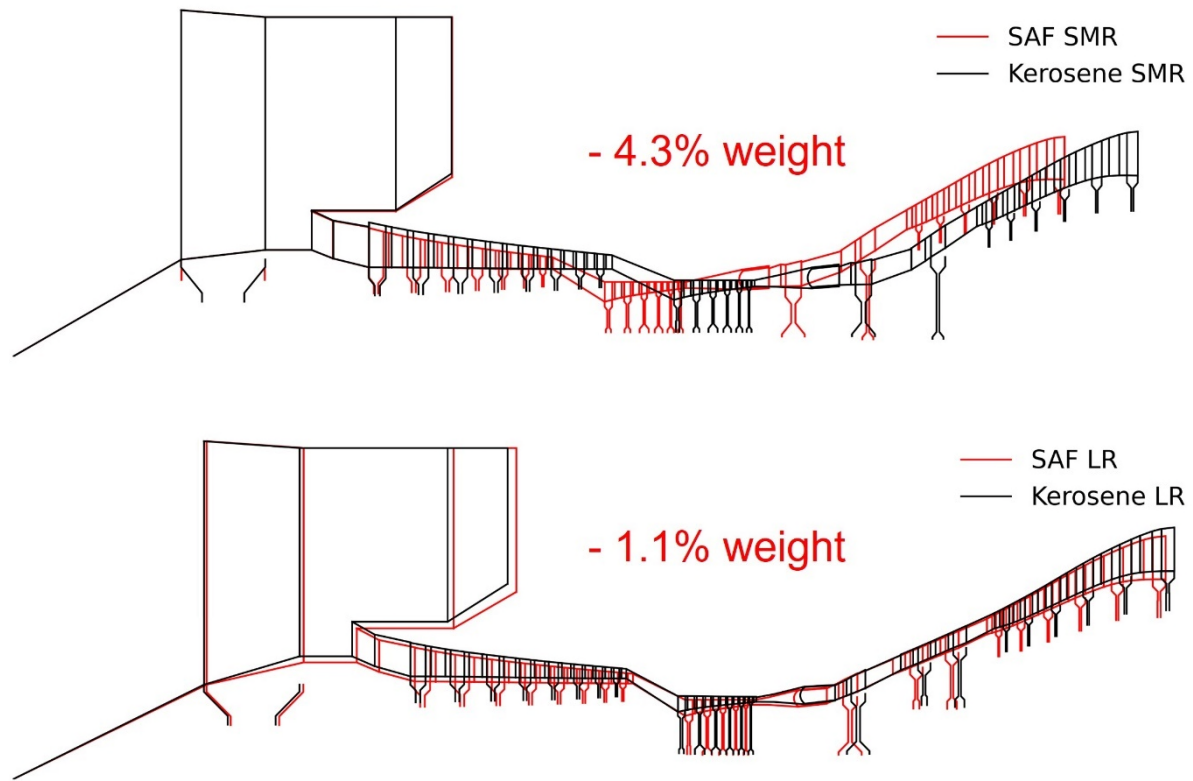


Figure 4-30: Comparison of SAF operated 3-spool turbofan across aircraft category

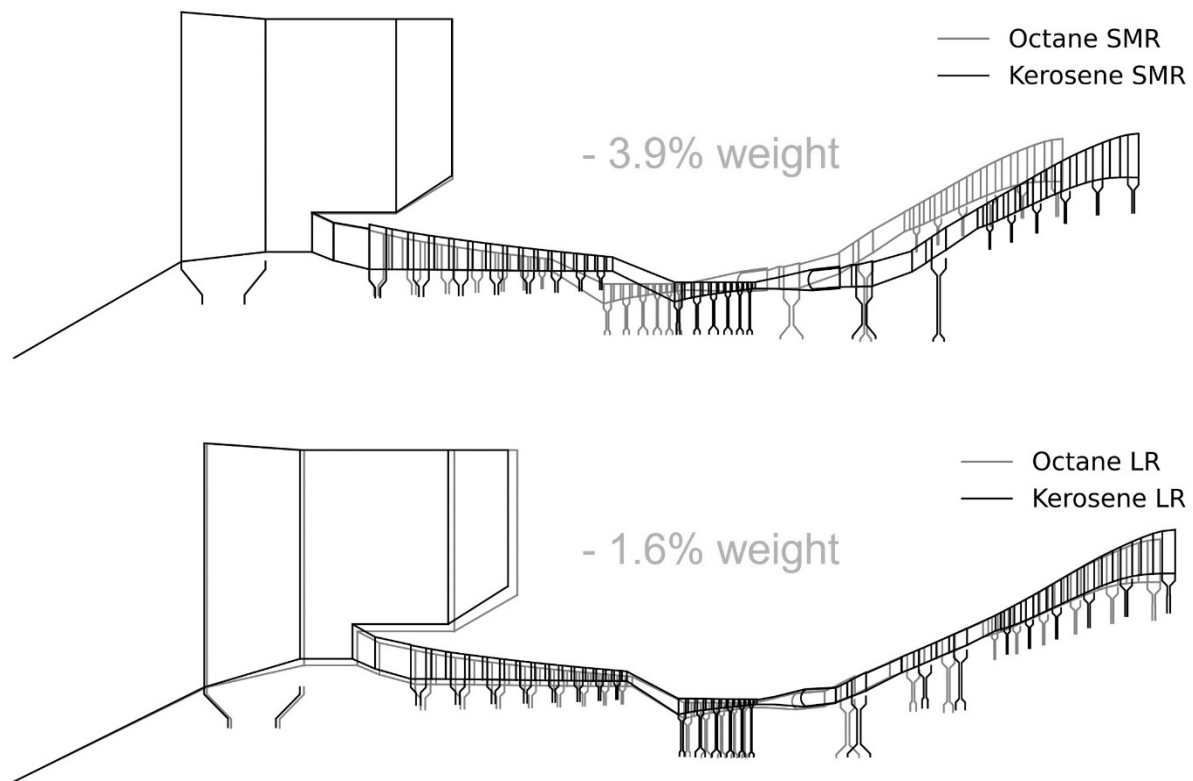


Figure 4-31: Comparison of Octane operated 3-spool turbofan across aircraft category

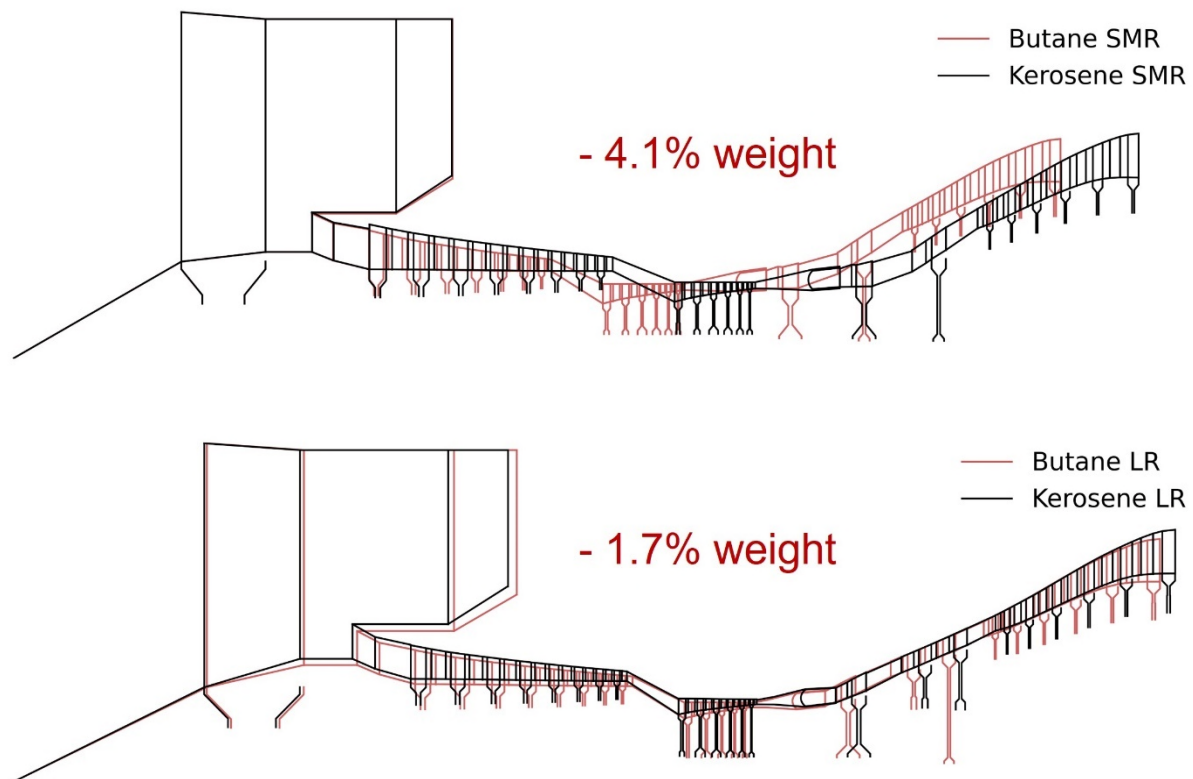


Figure 4-32: Comparison of Butane operated 3-spool turbofan across aircraft category

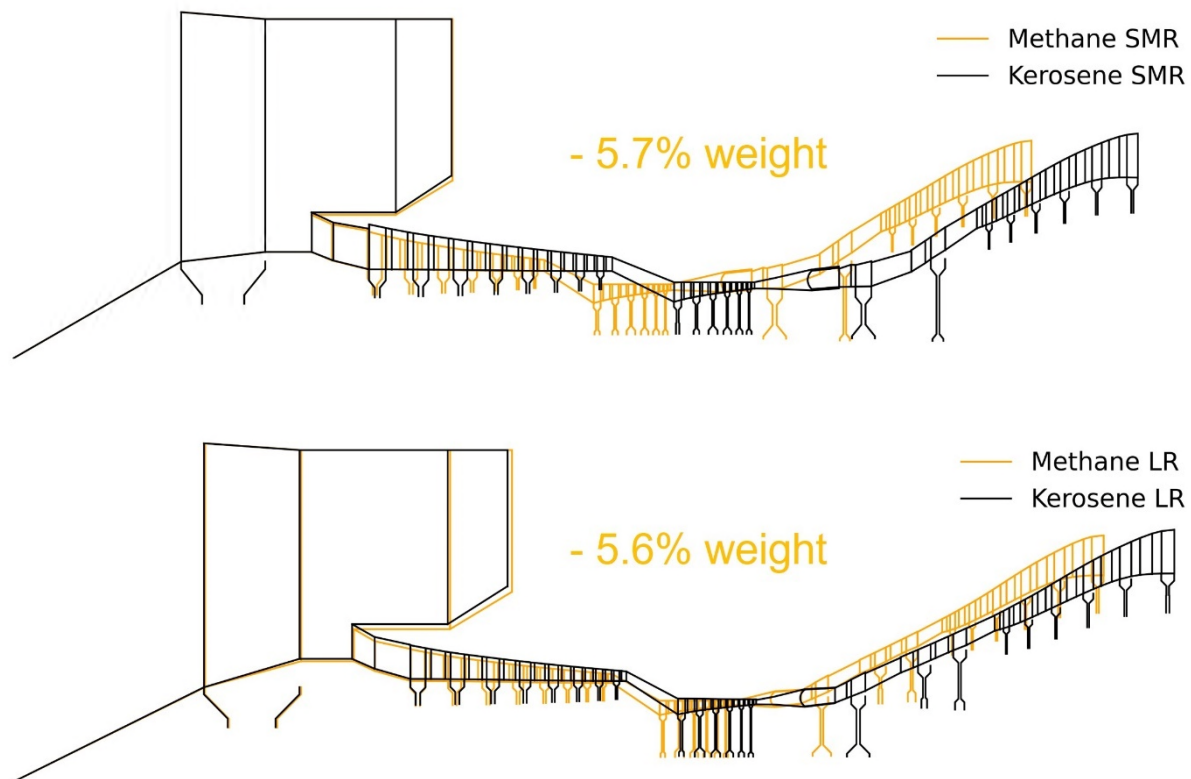


Figure 4-33: Comparison of Methane operated 3-spool turbofan across aircraft category

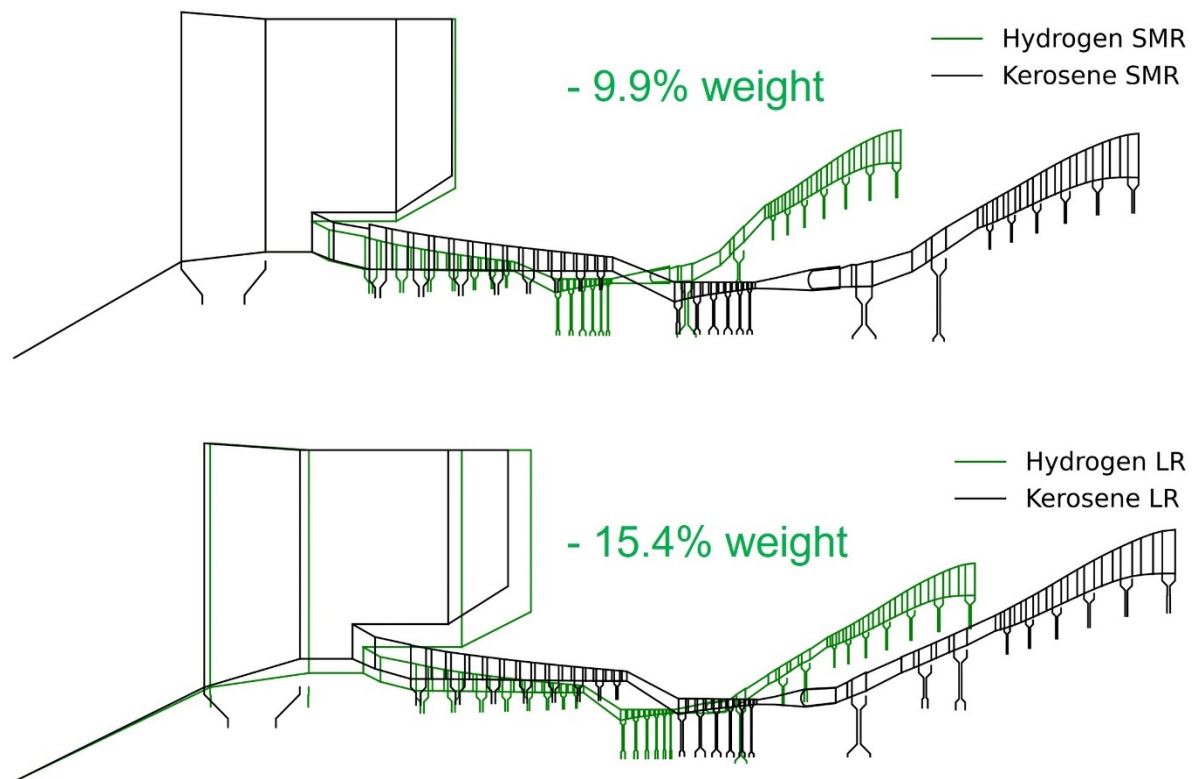


Figure 4-34: Comparison of Hydrogen operated 3-spool turbofan across aircraft category

It is observed that when comparing the annulus diagrams of engines of one category with another (SMR with LR), the BPR increment is higher for LR as opposed to the BPR increment for SMR. This can be observed in Figure 4-30 to Figure 4-34 for SAF, Octane, Butane, Methane and Hydrogen. This is in line with the findings demonstrated in Figure 4-29. At present where efforts to implement 100% SAF instead of blends is taking place, Figure 4-30 demonstrates the possible impact it can have on turbofan cycle design due to change in TOW as shown in Figure 4-28. It is important to note this effect as one could argue that since SAF is a drop in fuel, why would there be any difference. Here, this impact on TOW and consequently on engine cycle design is present due to the differences in LHV and working fluid properties of SAF which is possible in a practical application due to wide variety of feedstocks. Regarding the engine weights, in some cases (SAF, Octane, Butane, Methane), SMR category engines have a higher reduction in engine weights compared to the LR, even though LR engines have comparatively smaller cores. This is because of one less stage in the IPC section for SMR engines due to higher stage loading that is affected by the U parameter. The LR engine has one less stage in HPC section due to higher stage loading. However, IPC weights constitute a bigger proportion of engine weights compared to HPC weights and hence, overall make SMR engines lighter. One must note that for the baseline kerosene engines, the SMR engine has a fan diameter of 2.6m with BPR 10.3 whereas the LR engine has a fan diameter of 3m with BPR 9.6. Hence, the engines are of different fan and core sizes when it comes to SMR and LR modelled engines. In the case of Hydrogen engines of both categories, an additional stage is present for LPT section because of very small cores obtained and due to the fact that LPT powers the fan which generates most of the thrust and hence delivers the highest power.

Figure 4-35 presents the global warming impact of alternative fuels when operated across aircraft category. Note that it is on a per pax.nm basis. It is found that as we transition to higher LHV fuels from left to right (long chain hydrocarbons to zero carbon fuels), the global warming impact reduces. When it comes to comparisons across aircraft category for every fuel, SAF and Octane

demonstrates higher global warming reduction capability whereas Butane demonstrates approximately same levels of global warming reduction capability. In the case of Methane and Hydrogen, the global warming per pax.nm increases because the passenger capacity is reduced and hence, the reduction trend is not observed.

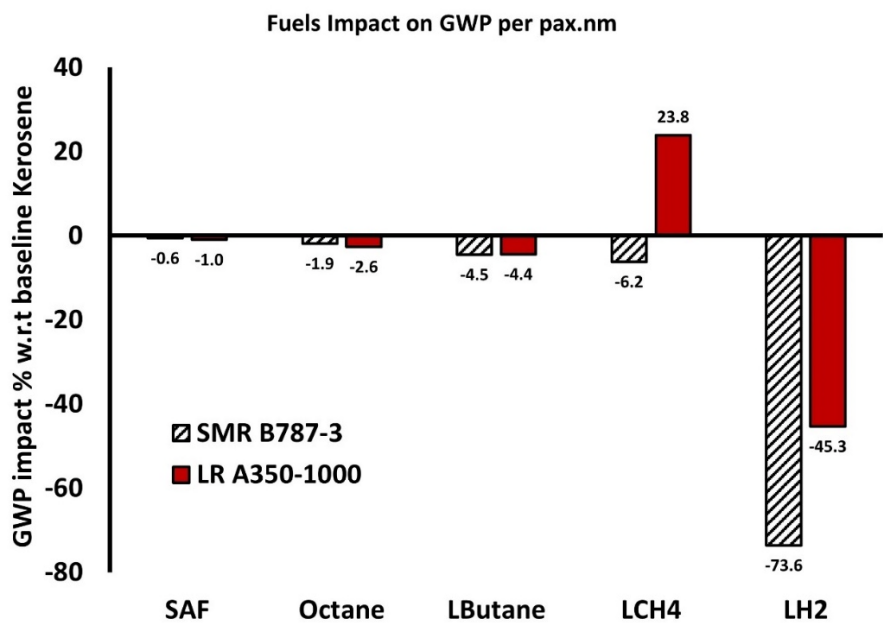


Figure 4-35: GWP impact of alternative fuels across aircraft category

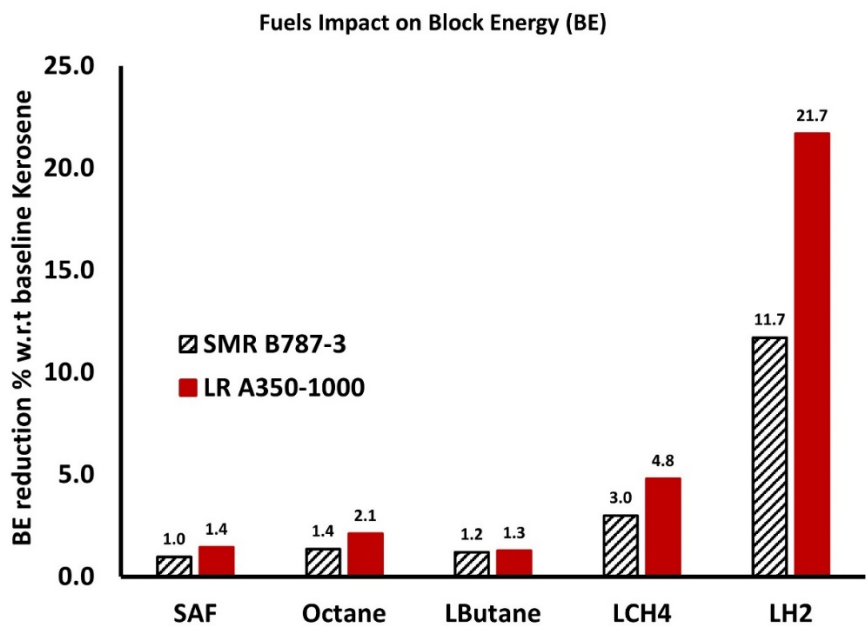


Figure 4-36: Block energy burn impact of alternative fuels across aircraft category

Figure 4-36 presents the block energy burn impact of alternative fuels across aircraft category. It is observed that across aircraft category and as we transition to higher LHV fuels (long chain hydrocarbons to zero carbon fuels), the block energy burn benefit increases. This is because lighter aircraft burns lower energy as a whole and this is what alternative fuels shown here offer. Note that this is not normalized against pax.nm. This is what the aircraft burns for the entire mission. This increasing benefit in energy consumption can be seen as an important aspect in the future especially considering an economy run by renewable energy. In that scenario, where these fuels will be likely produced using renewable energy, these candidate fuels will offer lower energy costs with lower global warming impact as demonstrated in Figure 4-35.

4.4.3 A321 SMR case study

In this investigation, a case study is conducted for an Airbus A321 style SMR category aircraft. The main motivation behind this activity is to assess the impact of cryogenic tank technology and fan size (specific thrust) on a Hydrogen aircraft. Unlike the assessments in section 4.4.1 and 4.4.2, this is not a retrofit exercise. In this assessment, the airframe is extended to accommodate the cryogenic tanks in the aft fuselage. Hence, the passenger capacity of the Hydrogen aircraft is preserved. The fan size is varied. The wing areas are changed for cases where the Hydrogen aircraft is heavier than the baseline kerosene aircraft. This is done by maintaining the same wing loading of the baseline kerosene aircraft. As a result, the airframe dimensions are different for the Hydrogen aircraft. The additional fuselage and wing weights are considered for the assessments. For the baseline kerosene aircraft, the airframe dimensions differ only because of the varying fan sizes. Regarding the cryogenic tank technology for the Hydrogen, 3 different technology factors by means of tank gravimetric efficiency have been considered. These are 35%, 65% and 95%. It must be noted that since the passenger capacity is preserved, considering a 30% tank gravimetric efficiency resulted in a very heavy aircraft and very long fuselage dimensions. As a result, a slightly higher technology level 35% is considered as a starting point for the 3 tank technology factors.

The engine model used for the assessment is based on a 2-spool turbofan engine architecture. The turbofan engine cycles are redesigned according to the aircraft thrust requirements.

Table 4-35 presents the design conditions for the modelled baseline kerosene aircraft.

Table 4-35: Modelled kerosene aircraft design conditions

Design Conditions	
Cruise Mach	0.78
Cruise Altitude (ft)	35,000
Design Range (nm)	3050
MTOW (tons)	96.5
Maximum Fuel Capacity (tons)	25.7
PAX	248

Table 4-36 presents the modelled 2-spool turbofan cycle performance at design MCR for fan diameter 1.98m.

Table 4-36: 2-spool turbofan cycle performance at design MCR

MCR	Values
BPR	11
T40 (K)	1508.4
SFC (g/kN.s)	14.35
ESFC (J/N.s)	618.91
Sp. Thrust (N.s/kg)	104.54
W (kg/s)	214.41
Wcore (kg/s)	17.86
OPR	41.96
FPR	1.483

The pressure ratio split and the component efficiencies are the same as that of Table 4-16. All the assessments are performed for a target design range of 3050 nm with the same passenger capacity.

Figure 4-37 presents the weight breakdown of the Hydrogen aircraft utilising 3 cryogenic tank technologies. Note that this is compared to the kerosene aircraft using engine model of fan size 1.98m.

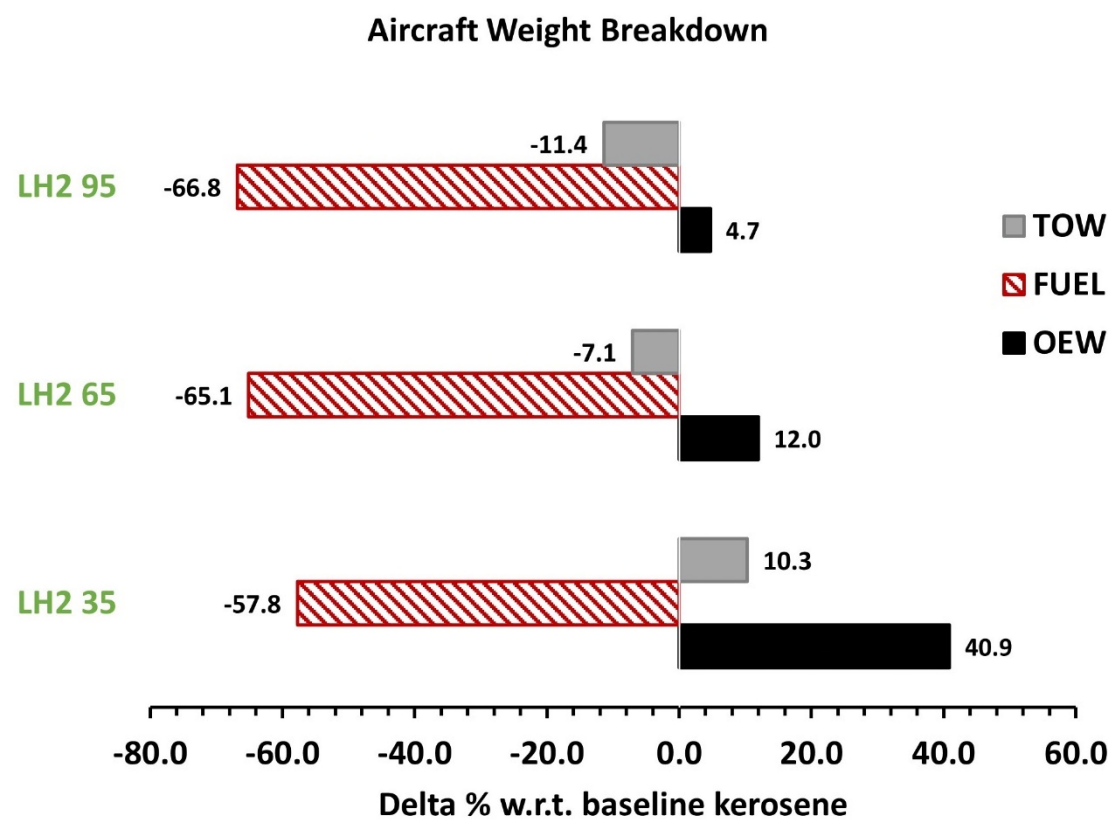


Figure 4-37: Hydrogen aircraft weight breakdown across cryogenic tank technologies

It is observed that as one moves from heavier tank technology to lighter tank technology (LH2 35 to LH2 95), the fuel requirements reduce, OEW increment reduces, and finally the TOW reduces. The heavier tank technology LH2 35 leads to aircraft that is heavier than kerosene for a given mission range. As a result of the weights of the aircraft, the thrust requirements are presented in Table 4-37.

Table 4-37: 3-point thrust requirements for A321 style aircraft (1.98m fan dia)

Fuel	MCR kN	MCL kN	MTO kN
	ISA 0	ISA 10	ISA 15
Kerosene	22.4	29.14	109.7
LH2 35	27	33.2	121.5
LH2 65	22.7	27.9	104.2
LH2 95	21.6	27.7	99.3

Because LH35 aircraft is heavier than the kerosene aircraft, the requirements from the turbofan are higher comparatively whereas the lighter LH2 65 and LH2 95 aircraft demands lower requirements from the turbofan.

Figure 4-38 presents the impact of fan sizes on mission fuel burn across cryogenic tank technology. Note that the differences are compared to their respective aircraft with a fan size of 1.78m.

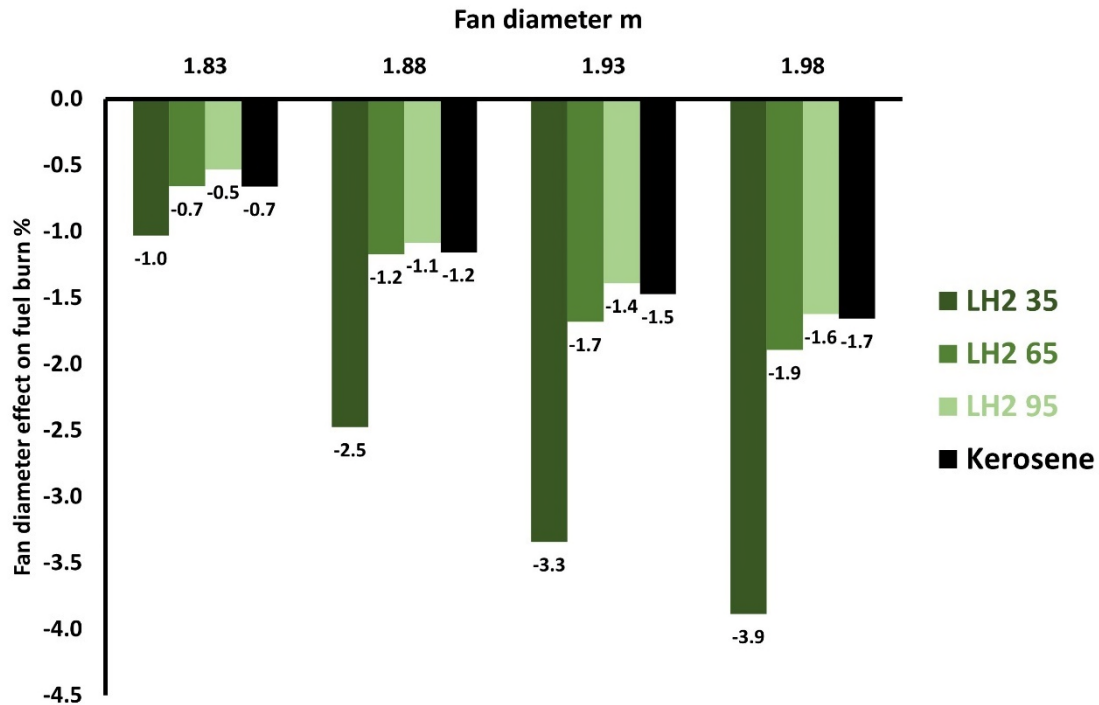


Figure 4-38: Fan diameter effect on mission fuel burn

It is observed that when the fan size is increased, a Hydrogen aircraft behaves like a kerosene aircraft. This is because as the fan size is increased (lower specific thrust and better fuel efficiency), the fuel burn for the Hydrogen aircraft reduces similarly to the kerosene aircraft.

It is also observed that LH2 35 is more sensitive to changes in fan size when compared to LH2 65 and LH2 95. This is due to the fact that the tanks constitute a bigger proportion of the weights in LH2 35 and hence, any savings in fuel burn from increasing fan size, leads to a comparatively higher change in tank weight which in turn affects TOW and energy requirements (snowball effects).

Figure 4-39 presents the mission energy comparison against baseline kerosene aircraft for different fan sizes. Note that the comparison is made for a given fan size for each case (For e.g., LH2 35 (fan size 1.98m) vs kerosene (fan size 1.98m)).

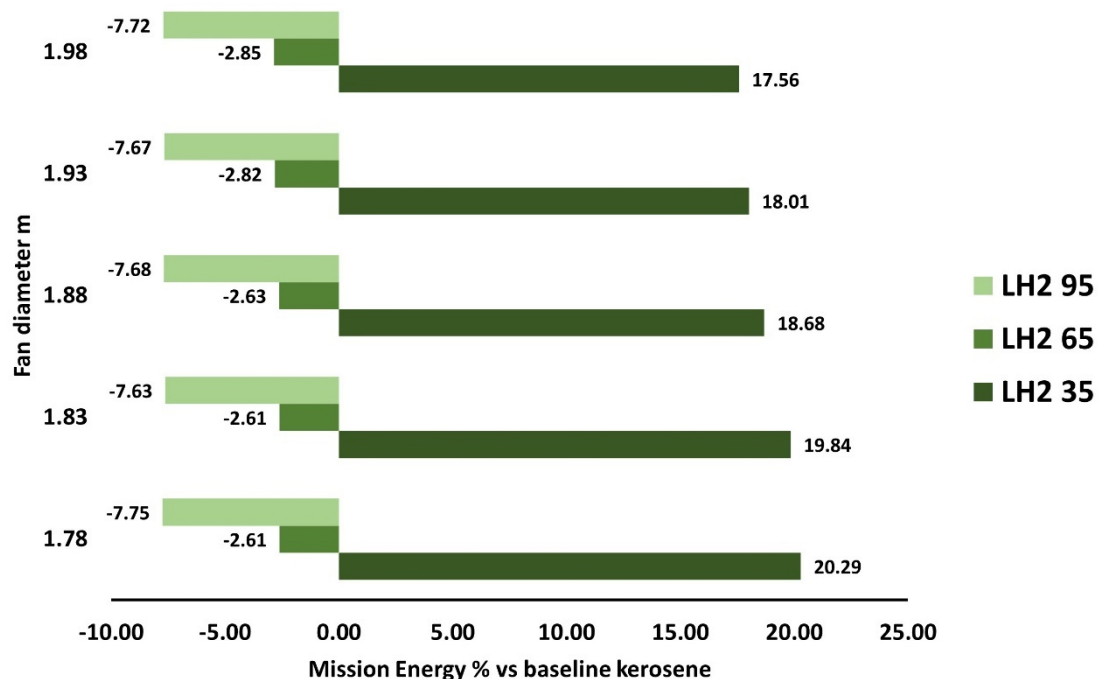


Figure 4-39: Mission energy comparison against baseline kerosene aircraft

It is observed that the heavier LH2 35 aircraft burn significantly more energy than the baseline kerosene aircraft approximately in the region of 20%. However,

when considering the lighter variants LH2 65 and LH2 95 aircraft, they burn comparatively lower energy. This is in the region of 2% and 7% respectively. It is also worth noting that increasing the fan size for LH2 35 aircraft helps in reducing the significantly high energy burn penalty from 20% to 17% approximately. This is because of the high sensitivity of LH2 35 aircraft to fan size as demonstrated in Figure 4-38. A similar effect is observed for LH2 65 aircraft with lower impact. Regarding LH2 95 aircraft, the sensitivity to fan size change is the lowest and is lower than a kerosene aircraft as demonstrated in Figure 4-38. As a result, when comparing like to like between LH2 95 and kerosene aircraft, increasing fan size does not always reduce energy consumption. However, this is not so important since it already consumes roughly 7% lower energy at aircraft level. Hence, this demonstrates that cryogenic tank technology is a major driver for aircraft energy consumption as compared to fan size change for a Hydrogen aircraft.

Figure 4-40 provides an idea of the weight evolution across the flight for Hydrogen and kerosene aircraft. Note that this is a case for fan size of 1.98m.

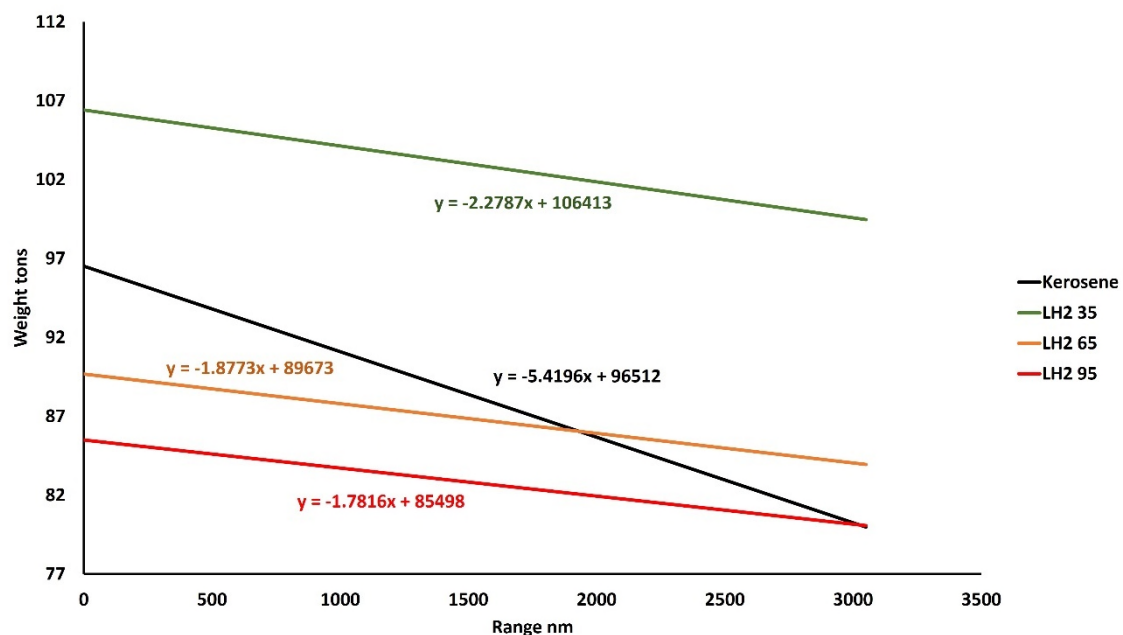


Figure 4-40: Weight evolution across the flight

When observing the trends, it is clear that for Hydrogen aircraft, because it has very little fuel mass compared to kerosene aircraft, the change in weight across the flight is lower than that of a kerosene aircraft. This can also be confirmed by

examining the slopes of the lines where kerosene aircraft has a more negative slope compared to all the Hydrogen aircraft. When it comes to Hydrogen aircraft using different cryogenic tank technologies, on examining the slopes, the heavier tank LH2 35 aircraft have the highest slope whereas the lightest tank aircraft LH2 95 has the lowest slope. This is because the heavier LH2 35 aircraft require more fuel which results in more weight change as opposed to the lighter LH2 95 aircraft that requires less fuel which can lead to lower weight change possibilities. As a result, as one moves from heavier tank to lighter tank for Hydrogen aircraft, the degree of weight change reduce. Because of these reasons, a Hydrogen aircraft will have less difference in turbofan requirements across flight as opposed to a kerosene aircraft's turbofan requirements. Among the Hydrogen aircraft using different tank technology, the lighter aircraft will have the lowest difference in turbofan requirements across flight. What this means is that for a Hydrogen powered turbofan, due to the aircraft characteristics, there will be lower degree of off-design operations, which means that the turbofan will operate closer to its design point most of the time providing maximum efficiency compared to a kerosene aircraft's turbofan.

Figure 4-41 presents the turbofan engine cycles and their weights used in the assessment. Note that the engine cycles are redesigned for the same peak cycle temperature and HPC exit temperature at take-off, while maintaining the core pressure ratio split. The peak cycle temperature and HPC exit temperature at take-off are 1877K and 952K respectively.

It is observed that the cryogenic tank technology is a design driver of the specific thrust of the Hydrogen turbofan. This is because, for any given fan size, thrust required for the aircraft is significantly affected by the tank technology level and hence, the design specific thrust of the system changes. Since, LH2 35 is the heaviest aircraft while LH2 95 is the lightest, the specific thrust is highest for LH2 35 and lowest for LH2 95. As demonstrated earlier in Figure 4-40, the weight change across the flight will be minimal for lighter LH2 95 aircraft compared to LH2 35 aircraft. As a result, the turbofan non-dimensional thrust/power requirements at mid-cruise will be closer to those at take-off, for lighter LH2 95

aircraft compared to heavier LH2 35 aircraft. Hence, the MCR OPR and T40 are the highest across fan sizes for the lighter LH2 95 aircraft's turbofan compared to the heavier LH2 35 aircraft's turbofan. In contrast to Hydrogen aircraft, kerosene aircraft characteristics cause the turbofan non-dimensional thrust/power requirements at mid-cruise to be further away from those at take-off, and hence demonstrate the lowest MCR OPR and T40 across fan sizes among all the cases. When it comes to MCR BPR, for any given fan size, BPR is highest for the lighter LH2 95 aircraft since the core which is sized for take-off is the smallest due to the lowest take-off thrust/power requirements among all the cases. Since LH2 35 aircraft is the heaviest, the core size is the biggest for delivering higher take-off thrust/power and hence, the BPR is the smallest across the fan sizes.

Generally, across all the cases, ESFC reduces (indicating increased overall efficiency) as specific thrust reduces. This is due to the increasing propulsive efficiency associated with the reduction in specific thrust and the increasing thermal efficiency associated with the increasing T40 and OPR. The ESFC is lowest for the lightest LH2 95 aircraft's turbofan (highest overall efficiency) whereas ESFC is highest for the kerosene aircraft's turbofan, although at smaller fan sizes LH2 35 aircraft's turbofan catches up due to very high specific thrust.

When it comes to engine weights, the general trend of increasing engine weights as the fan size is increased can be observed across all cases. However, for any given fan size, the lightest engine is possible for LH2 95 aircraft whereas the heaviest engine is seen for LH2 35 aircraft. This is mainly due to the core size differences highlighted in Figure 4-42.

Figure 4-42 presents the impact of cryogenic tank technology on Hydrogen turbofan design for a given fan size. It highlights the larger core size with an additional LPT stage needed to deliver a higher power for the heavier LH2 35 aircraft. This leads to a bigger engine footprint for the heavier Hydrogen aircraft compared to kerosene. The lightest LH2 95 aircraft has the smallest engine footprint in terms of size and length, and hence, this figure provides evidence of the role that tank technology can play in affecting the engine design and dimensions.

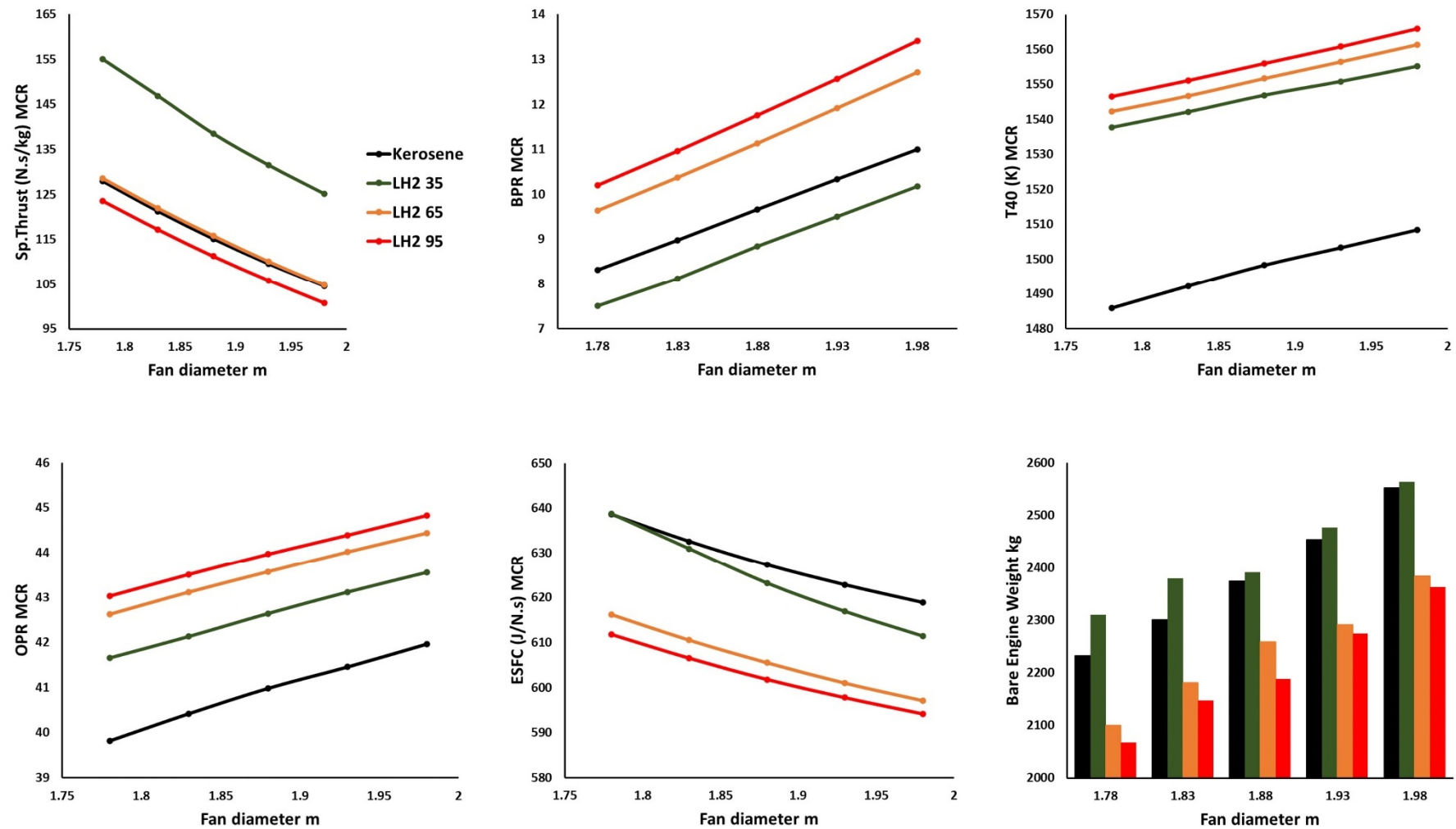


Figure 4-41: Turbofan engine cycles and weights

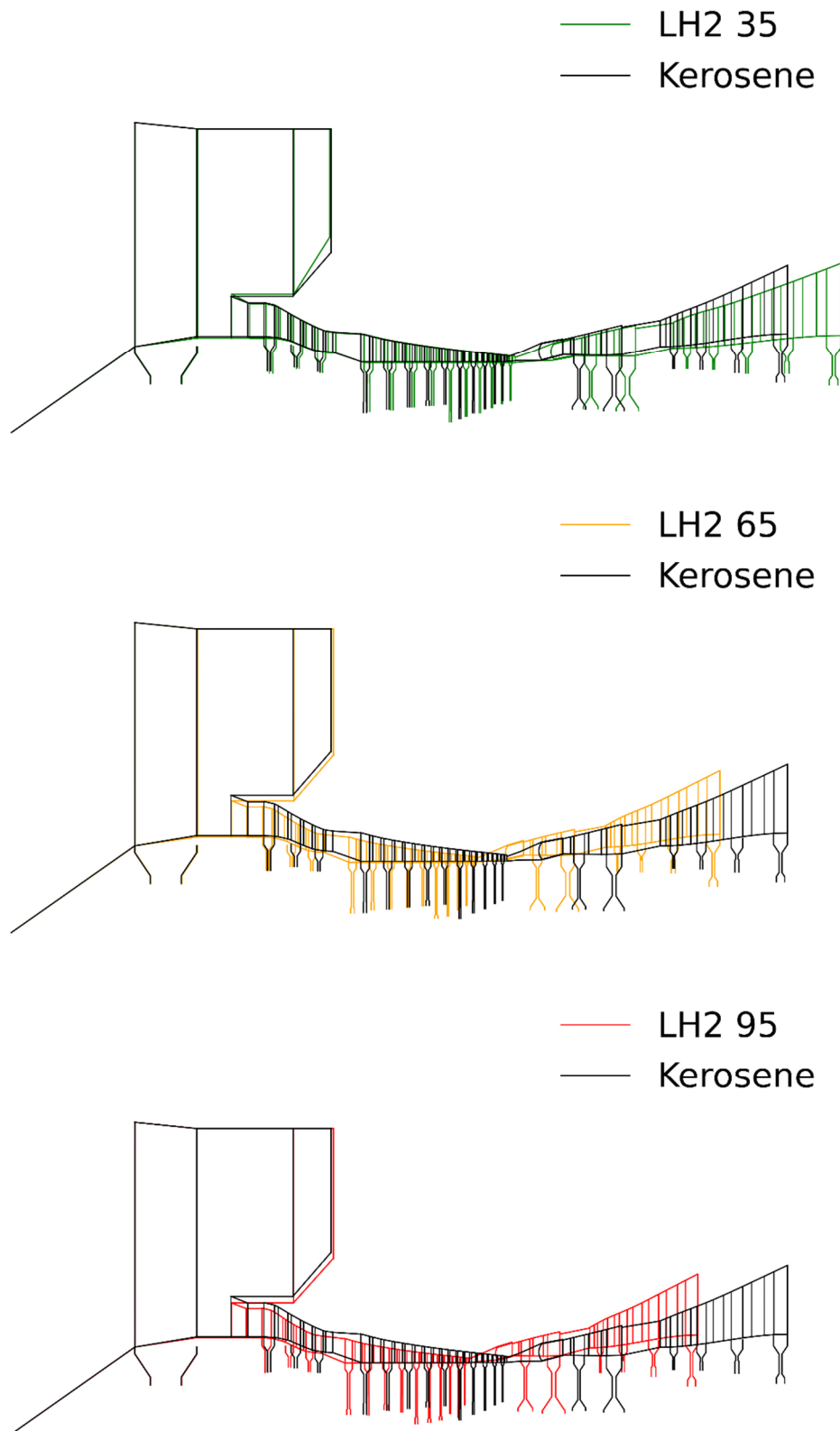


Figure 4-42: Impact of cryogenic tank technology on Hydrogen turbofan design (1.78m fan diameter)

4.5 Advanced cycles investigation

This activity aimed to identify the fuel conditioning requirements in terms of heat loads for the candidate alternative fuels and finally, assess the impact of fuel conditioning on cycle design for the most demanding fuels in terms of heat loads.

Hence, this section presents the results of the activity followed by a discussion on the significance of the outcomes.

4.5.1 Identification of fuel conditioning requirements

In this investigation, the fuel conditioning requirements are assessed for the candidate alternative fuels. The operating condition selected for the assessment is take-off since it is a reasonable starting point as it is one of the critical points of the flight envelope. The test case selected for this investigation is the study presented in section 4.4.1 (787-3 SMR Retrofit). The turbofan fuel flow rates and core operating pressures P30 are based on the turbofan cycles of the study. The boundary conditions assessed are those referring to the case of delivering the fuel from the storage tanks to combustor. Hence, for liquid fuels, the delivery pressure into the combustor is assumed to be 25% more than the HPC exit pressure P30 whereas for gaseous fuels, it is assumed to be 2 times the P30 based on the study in [68]. Gaseous fuels such as Ammonia, DME, and Butane exist in a subcooled liquid state for the turbofan operating conditions. Hence, they are injected into the combustor at pressures 25% more than the HPC exit pressure. Jet A-1 is assumed to be injected at temperatures lower than its boiling point to avoid coking of the fuel. This is also the case assumed for SAF. For liquid fuels, Octane and Butanol, it is assumed to be injected at their boiling points. The injection temperatures for gaseous fuels have been considered to be 300K (25°C) to ensure stable combustion. Hydrogen is assumed to be injected at a slightly lower temperature of 250K based on the works of Haglind and Singh [64]. The tank storage conditions are based on the study of section 4.4.1 (787-3 SMR Retrofit).

Table 4-38 presents the fuel storage and delivery conditions used for the assessments.

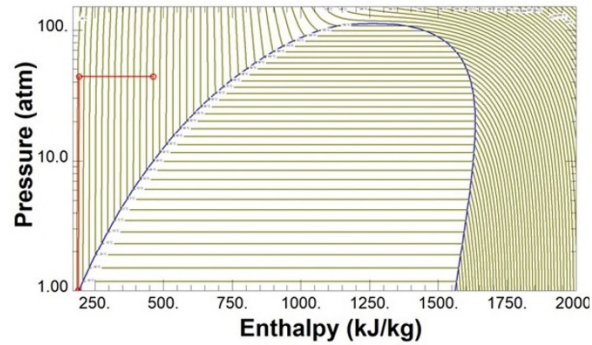
Table 4-38: Fuel storage and delivery conditions for take-off operating point

Fuel	P_{storage} (atm)	T_{storage} (°C)	P_{injection} (atm)	T_{injection} (°C)	Fuel Flows (kg/s)
Jet A-1	1	25	43.97	120	1.85
SAF	1	25	43.98	120	1.77
Octane	1	25	43.99	126	1.75
Butanol	1	25	44.00	118	2.38
LButane	1	-0.6	44.00	25	1.71
LDME	1	-25.1	43.99	25	2.72
LNH3	1	-33.9	44.10	25	3.98
LCH4	1.18	-159.4	70.32	25	1.59
LH2 30	1.18	-252.3	70.27	-23.15	0.61
LH2 60	1.18	-252.3	69.83	-23.15	0.51

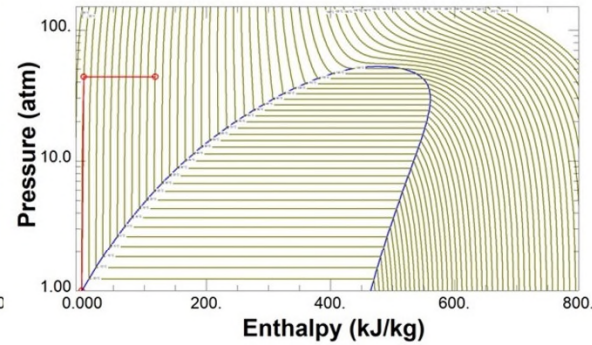
It allows one to observe the differences between the storage conditions and delivery conditions for the candidate alternative fuels. In terms of differences in temperatures and pressures, cryogenic fuels (Hydrogen and Methane) showcase the highest degree of difference.

Figure 4-43 presents a pressure - enthalpy diagram to demonstrate the possible working state of the fluid. It represents an idealised way of the required compression and heating, where the fuel initially is compressed and then heated to the requirements. Note that only gaseous fuels (Hydrogen, Methane, Ammonia, DME, and Butane) are presented since liquid fuels are not expected to change their phase during operation.

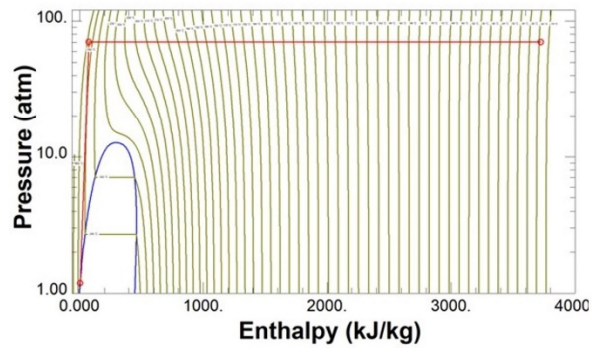
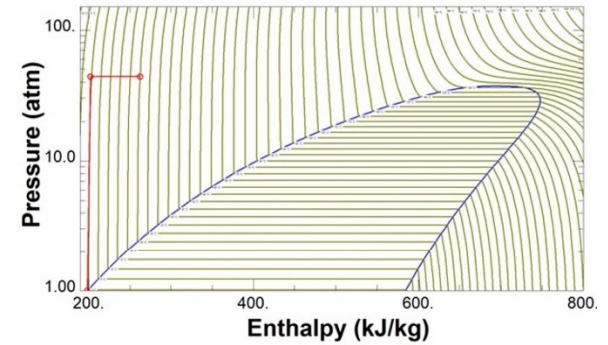
Ammonia



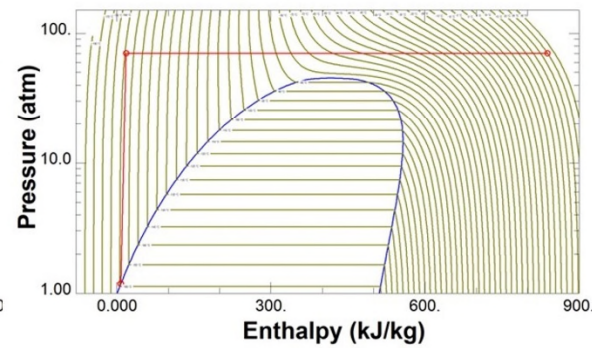
DME



Butane



Hydrogen



Methane

Figure 4-43: Pressure vs Enthalpy diagram of gaseous candidate alternative fuels at take-off operating point

The golden lines in the image represent lines of constant temperature. The blue line represents the saturation line which acts as a boundary for the 2 phase fluid state inside. This is also called a vapour dome. Left side of this dome depicts fluid in a subcooled liquid state. Right side of this dome depicts fluid in a superheated vapor state. Above this dome depicts fluid in a supercritical state since the topmost point of the vapor dome denotes the critical point. The red line denotes the ideal representation of compressing/pumping the fuel and then heating it to the required conditions stated in Table 4-38.

It is observed that the high boiling point gaseous fuels such as Ammonia, DME and Butane exist as a subcooled liquid whereas the cryogenic fuels such as Hydrogen and Methane exist in supercritical state. This provides useful evidence of the state of the fluid under the turbofan operating conditions which can be helpful when thinking about the fuel management system design for these candidate alternative fuels. Fuels existing in a liquid state could be considered favourable when it comes to fuel management, whereas those existing in supercritical state may be challenging. Figure 4-44 presents the thermal power required to condition the fuel for satisfactory performance of the turbofan under the conditions presented in Table 4-38.

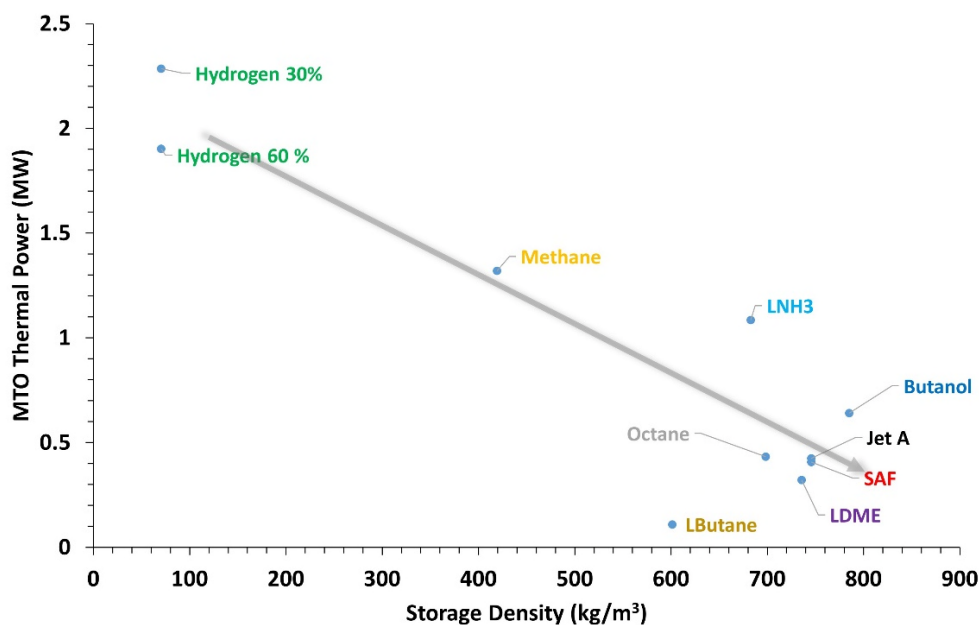


Figure 4-44: MTO thermal power required for fuel conditioning vs storage density

Note that the graphical arrow simply acts as a guideline and is not based on any equation. It is observed that as the storage density in the aircraft increases, the thermal power requirement to condition the fuel decreases. It is observed that that cryogenic fuels such as Hydrogen and Methane require 2.2 MW and 1.3 MW of thermal power respectively. Ammonia requires 1 MW of thermal power with rest of the candidate fuels demanding similar needs to that of Jet A. To put into perspective, Jet A requires 425 KW of thermal power which means Hydrogen, Methane and Ammonia requires roughly 5.3, 3.1 and 2.5 times of Jet A fuel conditioning thermal power respectively. As a result, there exist scope for a significant amount of thermal power exchange in the turbofan when it is fuelled by Hydrogen, Methane and Ammonia. Hence, these three fuels are identified as the most demanding fuels for fuel conditioning and selected for the next stage of assessment.

4.5.2 Impact of fuel conditioning on cycle design

In this investigation, the impact of fuel conditioning on cycle design is assessed for the most demanding fuels. Hence, Hydrogen, Methane and Ammonia are assessed. The assessment is performed for fixed 3-point thrust requirements of the respective alternative fuelled aircraft that is obtained from the mission assessments. The engine cycles are redesigned for the same fan size and core engine compressor pressure ratio split, while maintaining T40 and T30 at take-off. The comparisons are made against turbofan engine cycles that do not consider fuel conditioning. The turbofan engine architecture is based on a 3-spool system.

4.5.2.1 Hydrogen

Figure 4-45 presents the impact of fuel conditioning on cycle design for a Hydrogen fuelled turbofan engine, explored through the various strategies of fuel conditioning described in the previous chapter. The differences are presented for the design MCR operating point compared against a hydrogen turbofan cycle that does not consider fuel conditioning. It is observed that precooling strategy appears to be the most promising in terms of thermodynamic performance (energy consumption benefit i.e SFC reduction), while intercooling strategy

provided the least penalising performance in terms of SFC increment. In case of precooling strategy, IPC and HPC compressor work is reduced due to cooled air in front of the core engine. As a result, more power is produced for a given core size. Since, the thrust is kept the same, the core size is reduced which is observed. Similar effect is applicable to the intercooling strategy, however, since only HPC work is reduced, and due to the assumption of a total pressure loss of an installed heat exchanger, the core size is increased to maintain the same thrust.

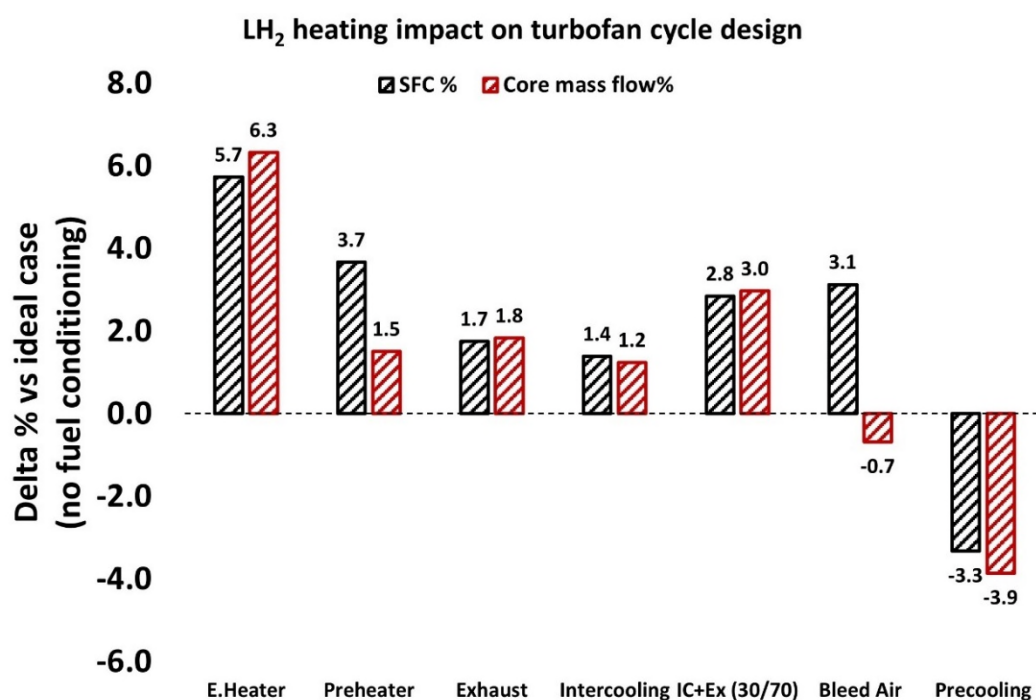


Figure 4-45: LH₂ fuel conditioning impact on turbofan cycle design (design MCR point)

Since the fan size is maintained, the BPR is increased for the precooling strategy whereas for intercooling, its reduced. The Electric heating strategy causes the worst performance in terms of SFC with the highest increase in core size. As a result, the BPR is the lowest with this strategy. Bleed air heating strategy reduces the cooling flows due to colder cooling flows. As a result, the core produces more power and hence, for a given thrust, the core size is reduced. However, since the cooling flow fraction reduction is much greater than the core size reduction (3.5% vs 0.7%) combined with the fact that FAR is not affected due to negligible change

in T40, the air mass flow into the combustor is higher which increases the fuel flows and hence, the SFC for the same thrust. Preheater strategy causes to increase the core size because core power is reduced due to air bleed after the IPC for the preheater setup. As a result, the SFC is higher. Note that the SFC calculations include the Hydrogen fuel flow required for the preheater setup. Exhaust heating strategy causes the thrust to be reduced since exhaust velocity is affected by total temperature and total pressure loss. As a result, the core size is increased with SFC penalty to maintain the same thrust. Finally, a combination of fuel conditioning from cold and hot ends with help of two heat exchangers introduces higher pressure losses when compared to strategies that use only one. As a result, the core size is increased with SFC penalty to maintain the same thrust. Note that this is assessed where 30% heat load is extracted from the cold side while 70% extracted from the hot side for fuel conditioning.

Table 4-39 showcase the differences in turbofan cycle performance of the various strategies explored to condition Hydrogen fuel. It is observed that as mentioned earlier, precooling and bleed air heating strategies lead to an increase in BPR. Rest all of the strategies lead to a reduction in BPR. When core temperature T40s are observed, generally bigger core sizes lead to reduced T40s. However, in the case of Intercooling, since OPR is higher, higher T40s are observed for bigger cores. Intercooling and Precooling, cool the air and allow higher OPR for the same take-off T30. The specific thrust remains approximately the same for all the strategies since the fan size and thrust requirements are fixed. As a result, the propulsive efficiency remains unchanged. The SFC changes showcased in Figure 4-45 are consequence of changes happening to the thermal efficiency. When observing the fuel conditioning requirements of Hydrogen fuel for the three operating points namely MCR, MCL and MTO, the thermal power ranges from 1 MW to 3 MW respectively.

Figure 4-46 presents the impact of total pressure loss due to HEX on the cycle design with fuel conditioning for Hydrogen fuel. This is assessed for Intercooling and Exhaust heating strategy as they are representatives of fuel conditioning from the cold and hot ends of the engine respectively.

Table 4-39: Turbofan cycle performance differences of various strategies for Hydrogen fuel conditioning

<i>MCR</i>	<i>Electric Heater</i>	<i>Preheater</i>	<i>Exhaust</i>	<i>Intercooling</i>	<i>IC+RC (30/70)</i>	<i>Bleed Air</i>	<i>Precooling</i>
<i>FN (kN)</i>	56	56	56	56	56	56	56
<i>T40 (K)</i>	-4.39	-0.69	-0.63	1.38	-0.76	-0.04	6.27
<i>OPR (%)</i>	-0.23	0.06	-0.02	13.32	1.34	0.04	40.55
<i>BPR (%)</i>	-6.29	-1.59	-1.99	-1.30	-3.12	0.73	4.23
<i>Sp. Thrust (%)</i>	-0.04	0.01	0.07	0.00	0.05	0.00	0.04
η_{prop}	0.01	0.00	-0.01	0.00	-0.01	0.00	-0.01
η_{therm}	-5.42	-3.53	-1.71	-1.37	-2.76	-3.03	3.45
<i>HEX P_{loss}</i>	-	-	4%	4%	8% (4%+4%)	4%	4%
ϵ_{HEX}	-	-	0.36	0.44	0.25	0.59	0.88
<i>Fuel (MW)</i>	1.01	0.968	0.988	0.982	0.997	0.993	0.932
<i>MCL</i>							
<i>FN (kN)</i>	67.1	67.1	67.1	67.1	67.1	67.1	67.1
<i>Fuel (MW)</i>	1.26	1.2	1.23	1.21	1.24	1.23	1.1
<i>MTO</i>							
<i>FN (kN)</i>	245.8	245.8	245.8	245.8	245.8	245.8	245.8
<i>Fuel (MW)</i>	3	2.85	2.95	2.86	2.97	2.92	2.7

Note: These differences are compared against baseline Hydrogen turbofan cycle that do not consider Hydrogen fuel conditioning. Heat exchanger effectiveness is calculated for heating Hydrogen fuel to 250K.

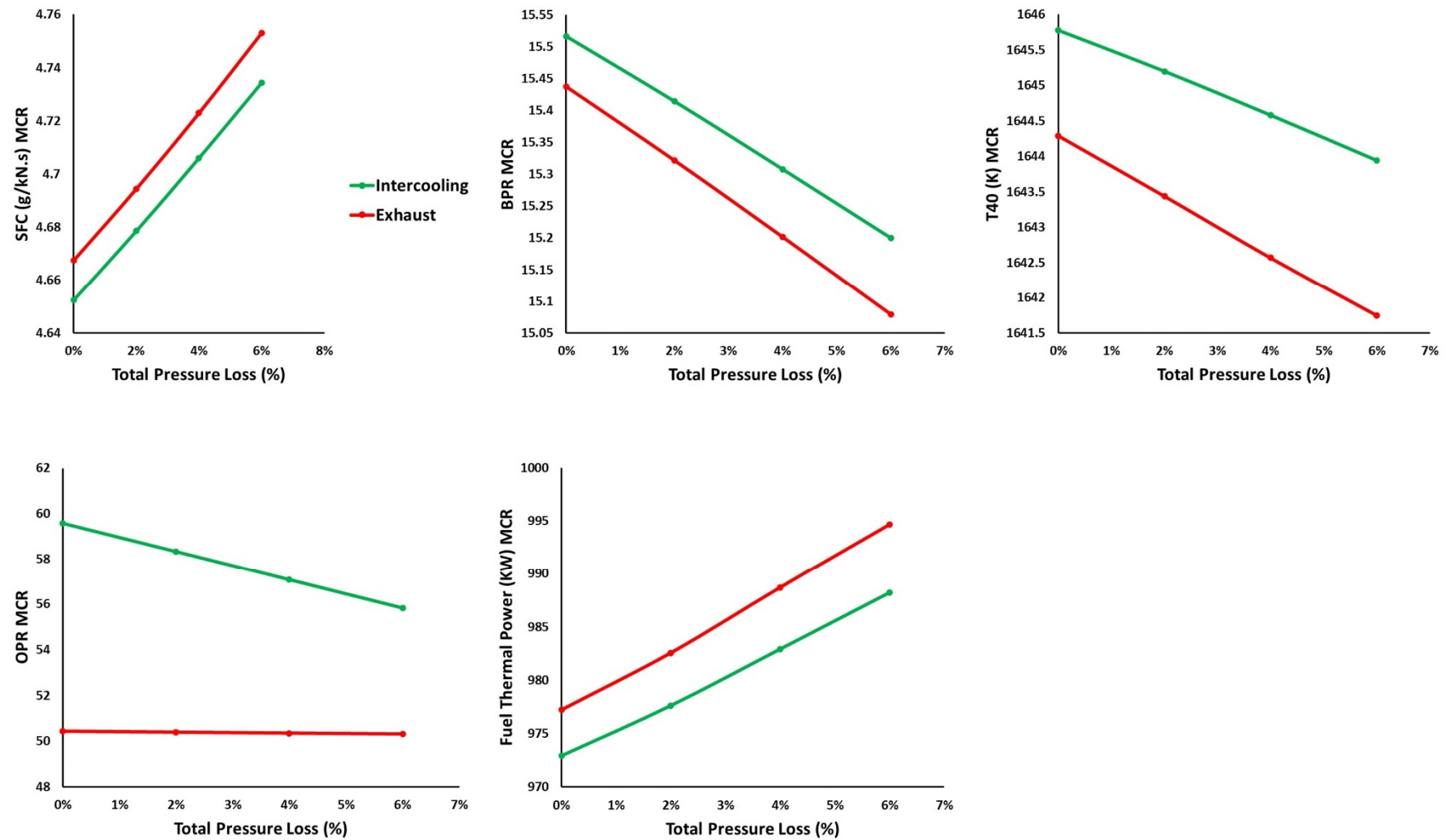


Figure 4-46: Impact of total pressure loss due to HEX on cycle design with fuel conditioning for Hydrogen fuel

It is observed that SFC increases for both strategies with increase in total pressure loss. Exhaust heating strategy causes more energy consumption (SFC) than the intercooling strategy. The BPR for the same fan size, reduces for increasing total pressure loss. This indicates a bigger core size requirement for the same thrust when pressure losses increase. Exhaust heating strategy results in relatively bigger core sizes compared to intercooling strategy. The core operating temperature T_{40} reduces with increase in total pressure loss. Due to the pressure loss, the temperature difference between cruise and take-off operating point increases. As the cycles are redesigned for the same take-off T_{40} , the core temperature at cruise reduces as a result. The cruise OPR reduces with increase in total pressure loss. At take-off, the engine spools up because of pressure loss and leads to a higher difference in OPR between cruise and take-off which in turn increases take-off T_{30} . As the cycles are also redesigned for the same take-off T_{30} , the OPR at cruise is reduced. It's interesting to note that the intercooling strategy's OPRs is more sensitive to pressure loss when compared to exhaust heating, even though OPR is still higher for intercooling strategy. The pressures between the IPC and HPC are higher when compared to exhaust pressures and as a result, the pressure losses are higher for intercooling compared to exhaust strategy for any given percentage of total pressure loss due to HEX. Finally, increase in total pressure loss increases the fuel conditioning requirements for both the strategies because of increasing fuel consumption.

4.5.2.2 Methane

Figure 4-47 presents the impact of fuel conditioning on cycle design for a Methane fuelled turbofan engine, explored through various strategies of fuel conditioning. Note that precooling is not assessed as there does not exist enough temperature margin to heat Methane to 300K from the inlet of core engine during cruise. Similar trends like those of Hydrogen fuel in section 4.5.2.1 are observed in the case of Methane fuel as well. Intercooling strategy provides the least penalising thermodynamic performance in terms of SFC increment. Electric heating strategy provides the worst thermodynamic performance in terms of SFC

increment. Table 4-40 showcase the differences in turbofan cycle performance of the various strategies explored to condition Methane fuel.

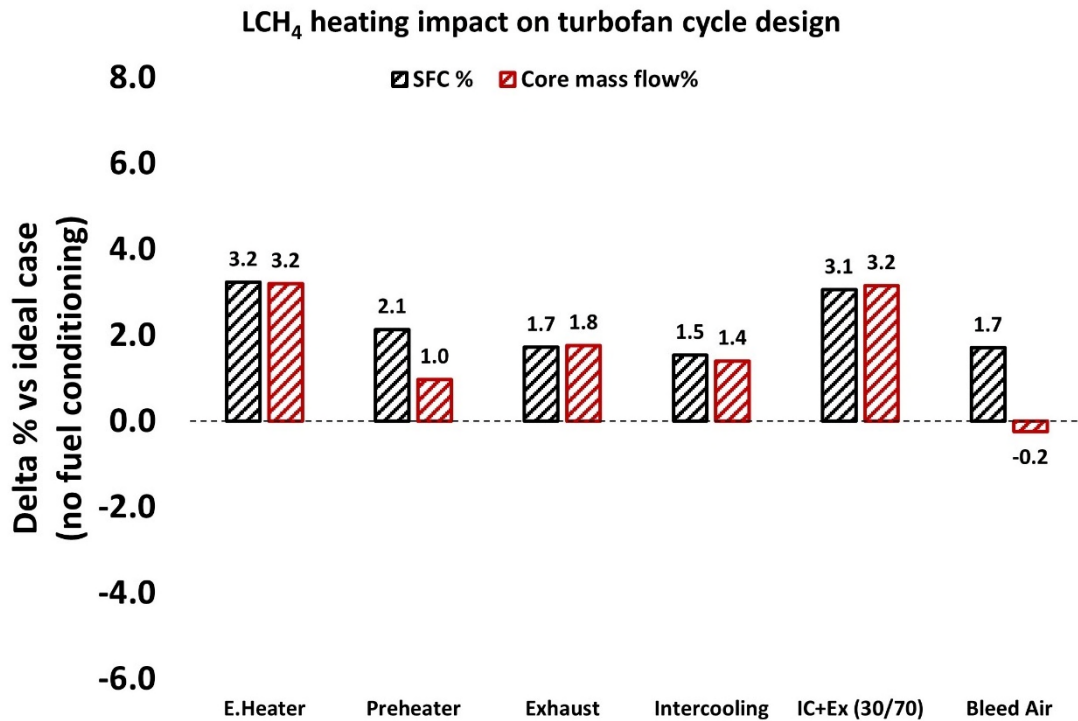


Figure 4-47: LCH₄ fuel conditioning impact on turbofan cycle design (design MCR point)

It is observed that generally, bigger core sizes lead to lower core T40s. Intercooling is an exception here since the OPR is increased. Except for bleed air heating strategy, all the other strategies lead to reduced BPRs for the same fan size. Since the specific thrust difference is minimal, the impact on propulsive efficiency is negligible. As a result, all the penalty in SFC arises due to deterioration of thermal efficiency because of fuel conditioning. In contrast to Hydrogen fuel conditioning requirements, Methane fuel conditioning requirements in terms of thermal power range from 0.65 MW at cruise to 2.28MW at take-off approximately. As a result, the degree of impact of Methane fuel conditioning compared to Hydrogen fuel conditioning on cycle design, is relatively lower which can be inferred from Figure 4-47 (the y-axis bounds are fixed). It is also worth noting the thrust class difference between the two fuels as these thrusts are based on aircraft requirements of section 4.4.2.

Table 4-40: Turbofan cycle performance differences of various strategies for Methane fuel conditioning

<i>MCR</i>	<i>Electric Heater</i>	<i>Preheater</i>	<i>Exhaust</i>	<i>Intercooling</i>	<i>IC+RC (30/70)</i>	<i>Bleed Air</i>
<i>FN (kN)</i>	63.1	63.1	63.1	63.1	63.1	63.1
<i>T40 (K)</i>	0.03	-0.54	-0.30	0.36	-0.98	0.91
<i>OPR (%)</i>	-0.10	0.03	0.01	3.09	-1.81	0.01
<i>BPR (%)</i>	-3.35	-1.06	-1.94	-1.51	-3.38	0.27
<i>Sp. Thrust (%)</i>	-0.03	0.01	0.04	0.00	0.04	0.00
η_{prop}	0.01	0.00	-0.01	0.00	-0.01	0.00
η_{therm}	-3.14	-2.09	-1.68	-1.51	-2.96	-1.68
<i>HEX P_{loss}</i>	-	-	4%	4%	8% (4%+4%)	4%
ϵ_{HEX}	-	-	0.65	0.94	0.32	0.36
<i>Fuel (MW)</i>	0.67	0.65	0.66	0.65	0.65	0.66
<i>MCL</i>						
<i>FN (kN)</i>	80.8	80.8	80.8	80.8	80.8	80.8
<i>Fuel (MW)</i>	0.89	0.87	0.89	0.87	0.88	0.88
<i>MTO</i>						
<i>FN (kN)</i>	325.8	325.8	325.8	325.8	325.8	325.8
<i>Fuel (MW)</i>	2.28	2.22	2.28	2.23	2.22	2.24

Note: These differences are compared against baseline Methane turbofan cycle that do not consider Methane fuel conditioning. Heat exchanger effectiveness is calculated for heating Methane fuel to 300K.

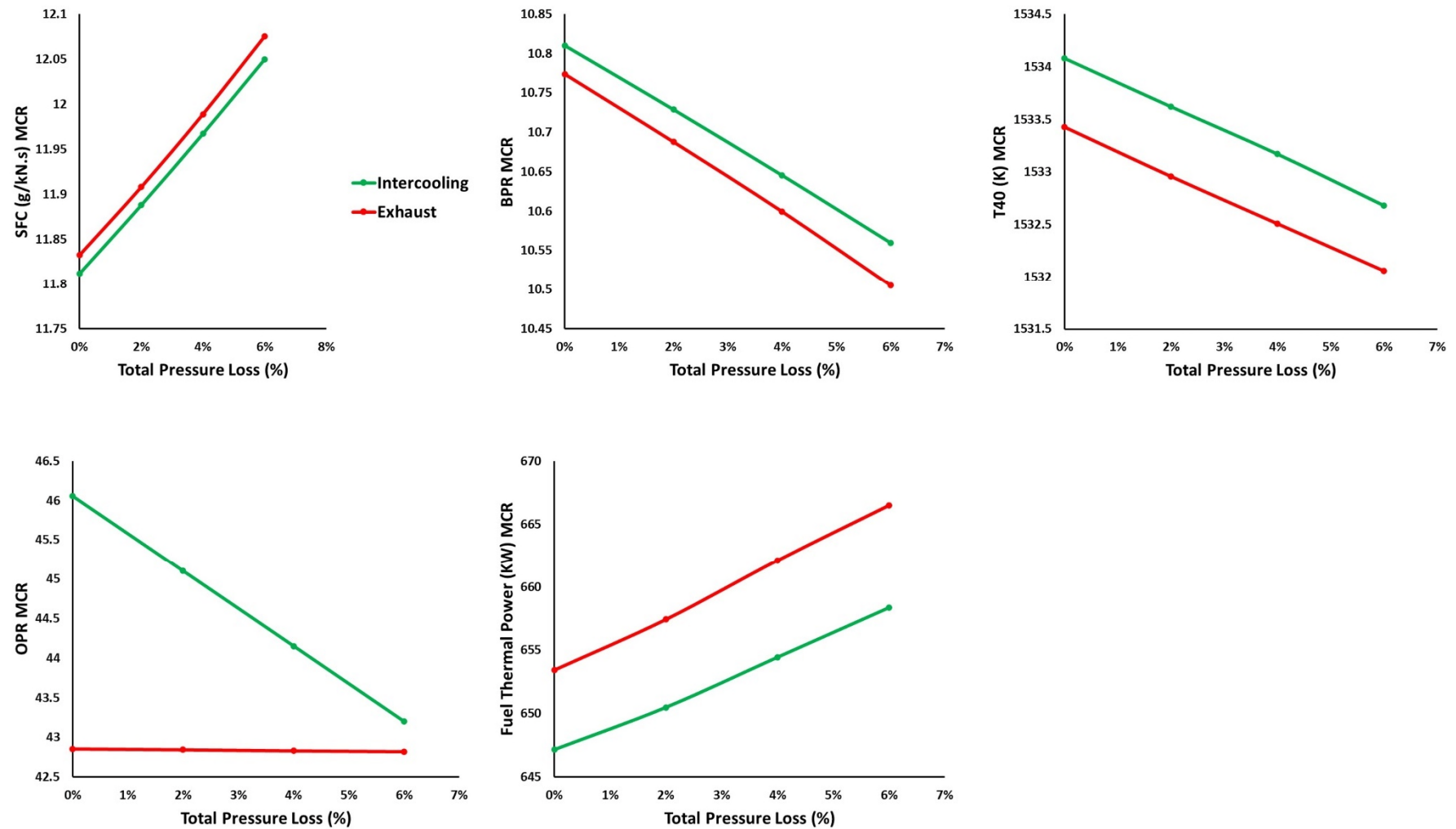


Figure 4-48: Impact of total pressure loss due to HEX on cycle design with fuel conditioning for Methane fuel

Figure 4-48 presents the impact of total pressure loss due to HEX on the cycle design with fuel conditioning for Methane fuel. This is assessed for Intercooling and Exhaust heating strategy. Similar trends of Figure 4-46 on the impact of total pressure loss on cycle design are observed in this case as well. As the total pressure loss increase, all the design features of the turbofan (BPR, T40, OPR, fuel conditioning requirements, SFC) are negatively affected.

4.5.2.3 Ammonia

Figure 4-49 presents the impact of fuel conditioning on cycle design for an Ammonia fuelled turbofan engine, explored through various strategies of fuel conditioning. Note that precooling is not assessed as there does not exist enough temperature margin to heat Ammonia to 300K from the inlet of core engine during cruise.

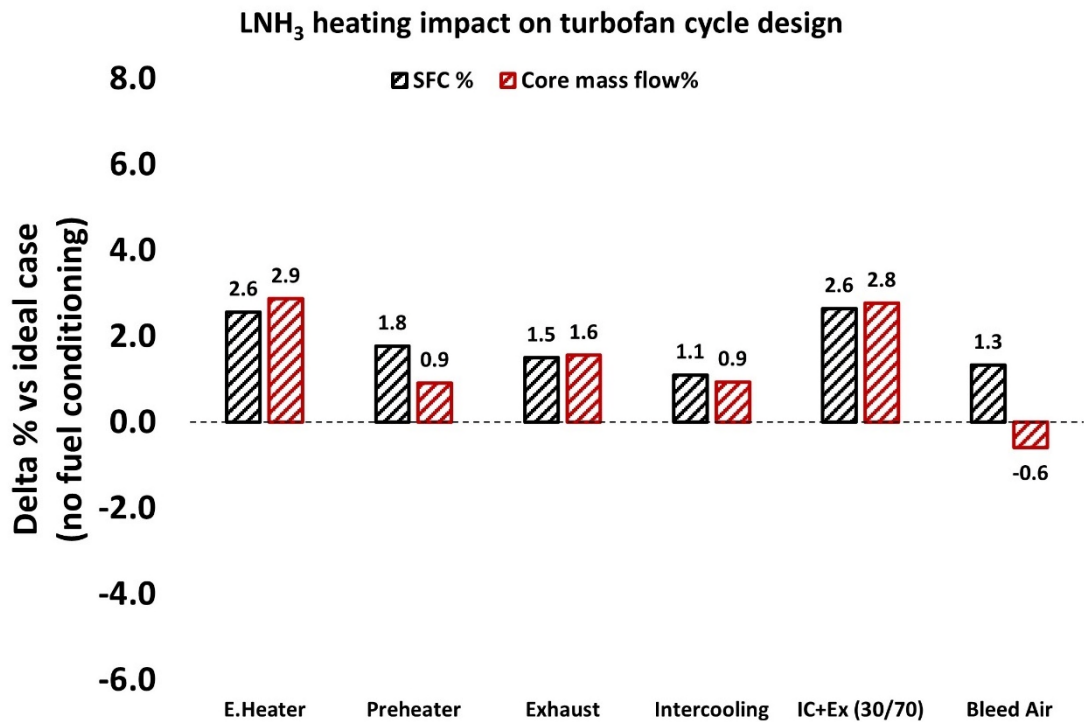


Figure 4-49: LNH₃ fuel conditioning impact on turbofan cycle design (design MCR point)

Similar trends observed in the previous sections 4.5.2.1 & 4.5.2.2, are observed for Ammonia as well. Intercooling strategy is the least penalising option when

thermodynamic performance in terms of SFC is considered. The electric heater and the combination of fuel conditioning from cold and hot ends (IC+Ex) strategy both appear to be the worst option in terms of SFC increment. It is worth noting that the degree of impact of Ammonia fuel conditioning on cycle design is lower when compared to Methane fuel conditioning due to the lower fuel conditioning requirements of Ammonia fuel. Ammonia fuel conditioning requirements in terms of thermal power range from 0.53 MW at cruise to 2.2 MW at take-off. This is demonstrated in Table 4-41. It is worth noting the relatively higher thrust requirements of Ammonia compared to Methane. The thrust requirements for Ammonia aircraft are based on a A350-1000 LR retrofit case study, which will be demonstrated in upcoming section 4.6. Table 4-41 showcases the differences in turbofan cycle performance of the various strategies explored to condition Ammonia fuel. Except for bleed air strategy, all other strategies result in turbofan designs of reduced BPRs for the same fan size. Intercooling strategy leads to higher core operating temperature T40 due to higher OPRs. Propulsive efficiency is approximately the same due to negligible changes in specific thrust. Hence, thermal efficiency changes are directly affecting the cycle efficiencies in terms of SFC. Figure 4-50 presents the impact of total pressure loss due to HEX on the cycle design with fuel conditioning for Ammonia fuel. This is assessed for Intercooling and Exhaust heating strategy. As the total pressure loss increase, all the design features of the turbofan (BPR, T40, OPR, fuel conditioning requirements, SFC) are negatively affected.

The interesting outcome from this investigation for Hydrogen, Methane and Ammonia fuel is that, even after considering fuel conditioning requirements, the BPRs are higher when compared to kerosene design. This is demonstrated in Table 4-42 for electric heating strategy since it provided turbofan designs with maximum increment in core size. Hence, this provides evidence of the possibility of having smaller cores for the same fan size even after considering the fuel conditioning requirements. Its highly likely that this holds true for the other candidate alternative fuels since this assessment was performed for the most demanding fuels.

Table 4-41: Turbofan cycle performance differences of various strategies for Ammonia fuel conditioning

MCR	Electric Heater	Preheater	Exhaust	Intercooling	IC+RC (30/70)	Bleed Air
FN (kN)	64.1	64.1	64.1	64.1	64.1	64.1
T40 (K)	-1.66	-1.01	-0.46	1.55	-1.08	0.06
OPR (%)	0.13	-0.03	-0.06	3.57	-3.15	0.00
BPR (%)	-2.97	-1.00	-1.64	-1.01	-2.88	0.64
Sp. Thrust (%)	-0.03	0.03	-0.01	0.01	-0.02	0.00
η_{prop}	0.01	-0.01	0.00	0.00	0.00	0.00
η_{therm}	-2.51	-1.74	-1.48	-1.09	-2.58	-1.31
HEX P_{loss}	-	-	4%	4%	8% (4%+4%)	4%
ϵ_{HEX}	-	-	0.12	0.14	0.08	0.31
Fuel (MW)	0.54	0.53	0.54	0.53	0.54	0.53
MCL						
FN (kN)	83.3	83.3	83.3	83.3	83.3	83.3
Fuel (MW)	0.75	0.73	0.76	0.74	0.76	0.74
MTO						
FN (kN)	345.1	345.1	345.1	345.1	345.1	345.1
Fuel (MW)	2.14	2.09	2.19	2.1	2.2	2.1

Note: These differences are compared against baseline Ammonia turbofan cycle that do not consider Ammonia fuel conditioning. Heat exchanger effectiveness is calculated for heating Ammonia fuel to 300K.

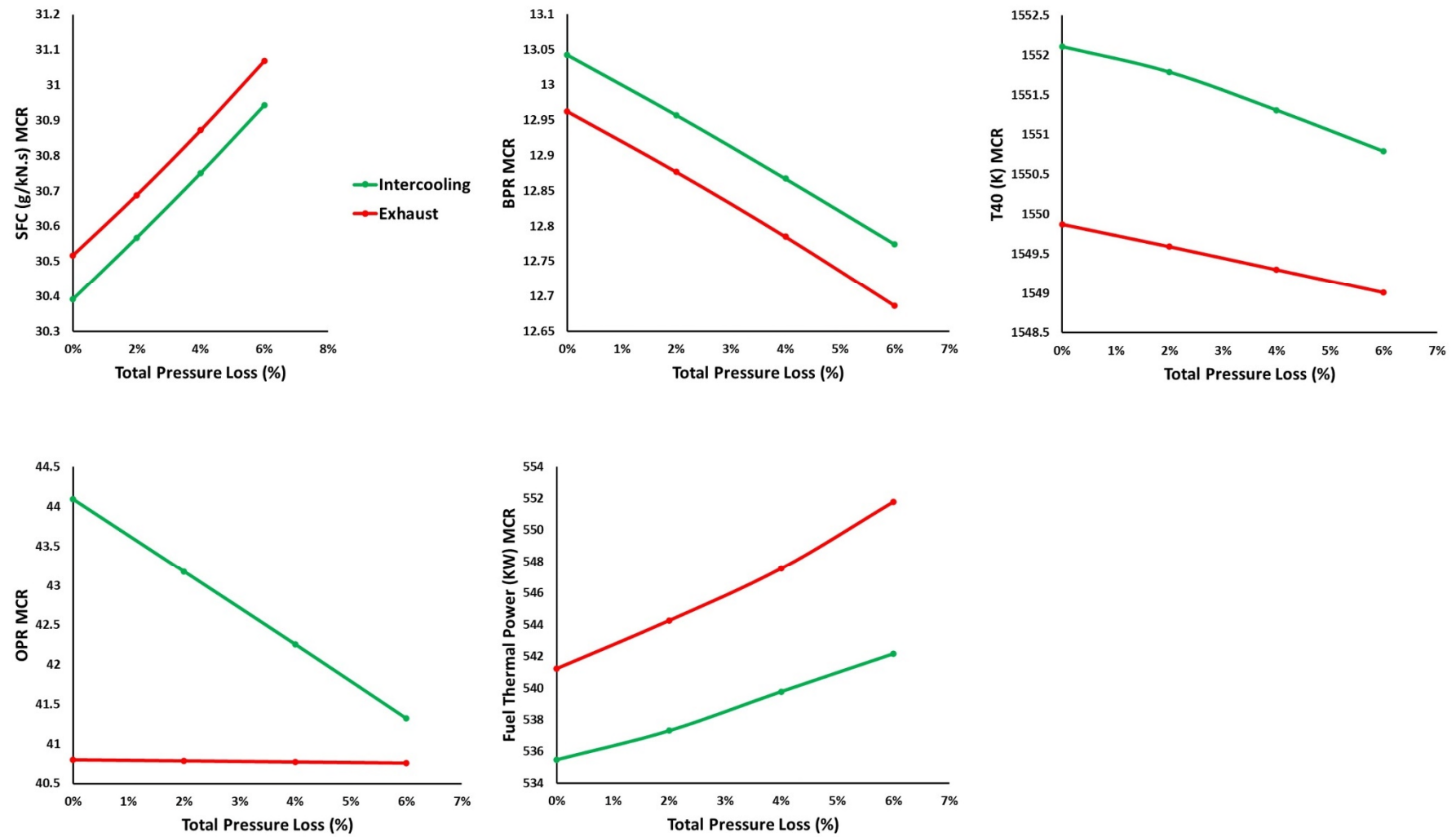


Figure 4-50: Impact of total pressure loss due to HEX on cycle design with fuel conditioning for Ammonia fuel

Table 4-42: Maximum impact on turbofan cycle BPR with fuel conditioning requirements

Fuel	MCR BPR
Kerosene	9.6
Hydrogen	14.53
Ammonia	12.61
Methane	10.44

Note: Kerosene is the reference case for comparison purposes.

4.6 Ammonia as a hydrogen carrier

Ammonia aircraft, as demonstrated previously, is limited in mission capability due to its range limitations. As a result, this investigation aimed to assess the application of Ammonia as a Hydrogen carrier for civil aviation. The implications of such an application are assessed at mission level and for the turbofan engine.

Hence, this section presents the results of the activity followed by a discussion on the significance of the outcomes.

4.6.1 A350-1000 LR retrofit

The assessment platform chosen for the investigation is an Airbus A350-1000 LR style aircraft. This is an extension to the work done in section 4.4.2 for Ammonia aircraft. Hence, the airframe dimensions are unchanged with the turbofan engine cycles redesigned for the same fan size. Same assumptions regarding storage of Ammonia inside the aircraft are used (section 4.4.1). Two cases are assessed. One case where the Ammonia carried in the wings is combusted in an Ammonia fuelled turbofan. Second case where the Ammonia carried in the wings is cracked (decomposed) into 100% gaseous Hydrogen before combusting it in a Hydrogen fuelled turbofan. A study by the US department of energy [112] has reported that commercial cracking reactors for producing Hydrogen from Ammonia typically weigh around 2-5 tons and occupy 3-6 m³ of space while accounting for the cracking system efficiencies. These systems require catalysts and operating

temperatures typically in the range of 500°C. More recently, Yuan et al [113], [114] developed a photocatalytic technique which utilized LEDs at room temperatures to extract Hydrogen from Ammonia. Due to the preliminary nature of the assessment, the weight and efficiencies of such cracking systems have not been considered as this is a field of continuous development.

Table 4-43 compares the Ammonia and Hydrogen turbofan engines at MCR condition.

Table 4-43: Hydrogen and Ammonia turbofan comparison

MCR	Hydrogen	Ammonia
BPR	10.7	13.0
ESFC (J/N. s)	588.1	566.0
SFC (g/kN. s)	4.9	30.42
T40 (K)	1519.9	1549.8
OPR	41.0	40.8
MCR (kN)	64.1	64.1
MCL (kN)	83.3	83.3
MTO (kN)	345.1	345.1

It can be observed that Ammonia turbofan has higher BPR meaning smaller core size compared to Hydrogen turbofan for the same fan size. There is also 3.7% ESFC benefit for the Ammonia turbofan compared to Hydrogen turbofan showcasing better energy efficiency of the Ammonia turbofan.

However, when examining the mission level performance, the aircraft burning Hydrogen fuel appears to provide an additional range capability (8.73%). This is demonstrated in Table 4-44. The difference in OEW is due to the engine weights.

Table 4-44: Mission level performance of ammonia as a hydrogen carrier

	NH₃ as H₂ carrier	NH₃	Units
MTOW	316.8	316.8	tons
OEW	162.7	161.6	tons
PAYLOAD	35	35	tons
FUEL	119	120.2	tons
Range	3847.5	3538.6	nm

The reason for the additional range is that when Ammonia is used as a Hydrogen carrier, more energy is available in the tanks than when pure Ammonia is considered. To explain this, energy density(MJ/L) of the two cases are compared. Energy density of ammonia is 12.7 MJ/L. Ammonia contains 3/17 mass ratio of Hydrogen in it. The density of Ammonia at its boiling point is 0.682 kg/L. Hence, Ammonia contains 0.120 kg/L of Hydrogen which translates into 14.4 MJ/L. This highlights the higher energy carrying capacity of Ammonia as a Hydrogen carrier and Ammonia's higher Hydrogen content per volume compared to pure liquid Hydrogen whose density is only 0.071 kg/L.

Since this positive aspect of additional range capability is identified, it is interesting to assess the range obtained once the energy needed to crack Ammonia into Hydrogen is considered. Ammonia cracking (decomposition) into Hydrogen is given by the Equation (4-4).



From the above equation, it is understood that for one mole of Ammonia, 46 kJ of endothermic energy is required to crack Ammonia into 1.5 moles of Hydrogen i.e 30.6 kJ is required for every mole of Hydrogen consumed by the Hydrogen turbofan.

Following this philosophy, the impact of Ammonia cracking energy on the cycle design of Hydrogen turbofan is assessed through two strategies namely, electric heater drawing power from high pressure turbine and exhaust heater utilizing a heat exchanger with a 4% total pressure loss in the flow path. The Hydrogen turbofan cycle is redesigned for the same fan size. The 3-point thrust requirements are maintained the same to examine the impact on the cycles while delivering the same thrust. Ammonia cracking energy impact on Hydrogen turbofan design along with the 3-point thermal power requirements to crack Ammonia is presented in Table 4-45.

Table 4-45: Ammonia cracking impact on Hydrogen turbofan design

MCR	Hydrogen (Baseline)	Electric Heater	Exhaust Heater
BPR	10.7	7.8	10.2
ESFC (J/N. s)	588.1	762.6	612.7
SFC (gr/kN. s)	4.9	6.3	5.1
T40 (K)	1519.9	1502.2	1524.1
OPR	41.0	41.3	41.3
MCR (kW)	-	6231	4984
MCL (kW)	-	8491	6935
MTO (kW)	-	24967	19591

It can be observed that taking energy from the exhaust is least penalising in terms of SFC when compared to the electric heating variant. As a result, the change in Hydrogen turbofan cycle is less for the exhaust heating variant.

Significant thermal power requirements to crack Ammonia into Hydrogen are observed for the 3 operating points namely MCR, MCL and MTO. This is highest for the electric heating variant since the fuel consumption are highest.

The interesting aspect observed from this assessment is that the thermal power for the cracking process is higher by an order of magnitude when compared to the fuel conditioning requirements of Hydrogen, Methane and Ammonia as demonstrated in the earlier section 4.5.2. This highlights the significant energy requirements to crack Ammonia into Hydrogen and its impact on the turbofan design as presented in Table 4-45.

As a result of the increased SFC which accounts for the energy needed to crack Ammonia into Hydrogen, the electric heating variant results in 17.2% loss in range compared to a pure Ammonia burning aircraft. The exhaust heating variant reduces the additional range capability from 8.73% to 4.2%. However, it must be noted that the additional cracking systems weight and efficiency are not considered in this preliminary assessment which might highly likely negate this range benefit compared to the pure Ammonia burning aircraft.

5 CONCLUSIONS & FUTURE WORK

This research work enabled novel alternative fuels to be investigated in the context of civil turbofan engines for future applications. This chapter aims to provide the reader with a summary of the research along with the key learnings from the findings. Finally, future work section presents potential work to be explored as part of continued research and development.

5.1 Summary and conclusions

This section aims to summarise the research with key learnings from each section of the Chapter 4 RESULTS & DISCUSSION. They are summarised in order of the sections of Chapter 4.

The research summary with key learnings is as follows:

- ❖ Thanks to the exploratory nature of this research, novel alternative fuels such as Hydrogen, Ammonia, Methane, Butane, DME, Butanol and Octane are proposed for civil aviation in the future. Drop-in fuel SAF is already being used with up to 50% blends with Jet A-1 in the current civil airplanes. Efforts and active flight tests are underway to push the certification limits all the way to 100% blends of SAF. Identification and application of novel fuels is a perpetual process. The candidate fuels identification phase of the project highlighted the fact that adopting a fuel for aviation is not a straightforward process. This is understood from the several stringent ASTM D1655 Jet fuel requirements as demonstrated and compared in the section 4.1. This is also supported by the fact that SAF which is very similar to conventional Jet fuel, is only allowed to be blended with Jet A in limited quantities and must go through numerous testing procedures before getting the green signal for a 100% blend. However, recent aggressive efforts to introduce Hydrogen as an alternative fuel for civil aviation shows that the aviation systems and culture around it can be changed and adopted. This provides additional confidence in the proposed alternative fuels in the study.

- ❖ The preliminary engine cycle design space study highlighted the potential impacts of the proposed alternative fuels on turbofan engine designs. A 3-spool architecture of the turbofan engine is selected for the assessment. The assessment is performed for same thrust requirements as that of the kerosene turbofan engine. The study showcased that transitioning from long chain hydrocarbons to zero carbon fuels improves the thermal efficiency of the turbofan engine cycles for a given OPR. The combined effect of different working fluid mass flow rates and working fluid thermodynamic properties on the expansion turbines causes the improved thermal efficiency. The optimum specific thrust levels are found to increase when transitioning from long chain hydrocarbon fuels to zero carbon fuels. As a result of this effect, smaller engine sizes could be envisaged for a given set of thrust requirements and technology constraints. Alternatively, if the same specific thrust as kerosene is desired which could essentially mean the same fan size, the engines can be operated at lower core temperatures for the same core size or the engines can be designed to have smaller cores operating with the same temperatures translating into higher BPR turbofan designs. Thanks to varying working fluid mass flow rates and thermodynamic properties, transitioning from long chain hydrocarbon fuels to zero carbon fuels, provides a benefit (reduction) in peak cycle temperatures at take-off for civil turbofan engines. Maximum impacts in the design space are observed for zero carbon fuels Hydrogen and Ammonia with 3% and 6% ESFC benefits compared to kerosene respectively. At take-off, a maximum temperature reduction of 20K and 40K is observed in the design space for Hydrogen and Ammonia respectively. When assessing the influence of OPR on the design space of zero carbon fuels, it is brought to light that apart from having lower core operating temperatures for the same core size or smaller cores for the same operating temperatures all for the same fan size, a higher OPR can be envisaged for the same core size and operating temperature as that of the kerosene engine. This shows that for a given set of technology constraints in the form of specific thrust and core operating temperature,

due to the higher potential of working fluid, a higher OPR can be driven thereby boosting the thermal efficiency of turbofan engines further. This trend should be applicable to other proposed alternative fuels as well with a lower degree of impact. Finally, for any given specific thrust (fan size), the proposed alternative fuels for aviation offer a wider turbofan design space when compared to kerosene with maximum opportunities seen for zero carbon fuels Hydrogen and Ammonia.

- ❖ The study performed to investigate the impacts of the proposed alternative fuels on turbofan engine size and weights brought light to potential insights. The study is performed for a 2-spool turbofan engine architecture. Three turbofan cycle design strategies are devised to proceed with the investigations. These strategies devised are based on the trends identified from the design space study in section 4.2. The strategies are resized core for the same take-off T40 and T30 as kerosene cycle, fixed core size as kerosene cycle and fixed cycle as the kerosene cycle. The turbofan engine cycles are assessed for identical 3 point thrust requirements so that the turbomachinery components are sized for identical delivery power throughout the flight phases. The impacts of alternative fuels on turbofan engine weights and operating temperatures are found to clearly depend on the design strategy chosen. This is understood from the study since maximum reduction in engine weights is achieved for fixed cycle strategy with only moderate reduction in take-off temperatures whereas no reduction in engine weights is achieved for fixed core strategy but maximum reduction in take-off temperatures. The resized core strategy for the same take-off temperature was found to offer only moderate reduction in engine weights but offered best reduction in ESFC. Hence, this indicates qualitatively that there exists a core sizing trade-off for fuel efficiency, engine weights and operating temperatures (engine life). The bare engine annulus diagrams enable one to appreciate the opportunity offered by alternative fuels to produce short and compact cores with smaller engine footprint. The degree of impact on engine size, weight and fuel efficiency

increases as one transitions from long chain hydrocarbons to zero carbon fuels. For the case study assessed, the maximum benefits in weight and take-off temperatures are 20% and 164K respectively for Ammonia cycles whereas for Hydrogen cycles, it is 6% and 64K respectively.

❖ The integrated engine-aircraft study performed to explore potential opportunities for the turbofan engines operating with alternative fuels shed light to some interesting aspects. Three case studies are performed namely B787-3 SMR retrofit, A350-1000 LR retrofit and A321 SMR case study. The learnings from the studies are summarized as follows:

- B787-3 SMR retrofit case study: This study allowed one to identify potential implications of the proposed alternative fuels at aircraft mission level in terms of range and payload. Fuels having higher LHV than kerosene resulted in a lighter aircraft for a given mission range after considering the fuel storage implications on the aircraft. This enabled reduction in take-off thrust requirements for fixed thrust-weight ratio. As a result of the reduced thrust, there existed opportunity to reduce the core size of the turbofan engine which manifests as increased BPR for a given fan size. It must be noted that core size can already be reduced due to reduced take-off T40 effects as demonstrated in Figure 4-8 and resized core strategy in Figure 4-19. Hence, the mission requirements of higher LHV fuelled aircraft offer additional opportunities to reduce the core size or increase the BPR further. This is envisaged for high LHV fuels such as SAF, Octane, Butane, Methane and Hydrogen. In general, the degree of impact on turbofan design due to the aircraft mission increases as one transitions from long chain hydrocarbons to zero carbon fuels as shown in Figure 4-24 with maximum impacts showcased by zero carbon fuels. The study identified the dependence of Hydrogen powered turbofan design on the cryogenic tank technology level since lighter tank enabled turbofan

designs with higher BPR compared to heavier tank. The preliminary environmental assessments highlighted that after accounting for water vapor emissions (not contrails), zero carbon fuels provided the best reduction in global warming impact. Although Butanol did not appear to provide environmental benefits from this preliminary assessment, literature studies ([47], [52]) highlighting their operational emission benefits provides confidence to use them. Since zero carbon fuels provided the highest impact on the turbofan designs, the effect of varying specific thrust (fan size) is assessed. Apart from the overall efficiency benefits due to changes in specific thrust, the assessment highlighted the significant turbofan design changes possible in terms of BPR, T40 and OPR as shown in Figure 4-27. It is found that Ammonia fuel always provided the highest BPR when compared to Hydrogen fuel.

- A350-1000 LR retrofit case study: This study demonstrates the potential implications of the proposed alternative fuels on turbofan design across aircraft category. The alternative fuels that are able to demonstrate full mission range capability are assessed. These include SAF, Octane, Butane, Methane and Hydrogen. The study showcased that across aircraft category, the impact of alternative fuels on TOW is higher and as a result, the opportunity to redesign the turbofan engines increases. As one transitions from long chain hydrocarbon to low/zero carbon fuels, the turbofan engine redesign opportunities across aircraft category are significant. Mission energy burn differences indicated that across aircraft category, the energy burn benefit increases and for low/zero carbon fuels, the impacts are significant. This benefit in energy consumption can be considered an important aspect since in the future, if these fuels are going to be produced by renewable energy, there can similar energy cost savings which can be an important attribute to take note of.

- A321 SMR case study: The study sheds light on the potential impacts of cryogenic tank technology and fan size for a Hydrogen aircraft. The airframe of the Hydrogen aircraft is extended to accommodate the cryogenic tank in the fuselage aft. The wing areas are modified for the same wing loading as kerosene aircraft for cases where Hydrogen aircraft is heavier than kerosene aircraft. Three tank gravimetric efficiency is assessed which are 35%, 65% and 95%. On assessing for the same mission range as kerosene, the heavier tank technology led to the heavier Hydrogen aircraft for any given fan size compared to a lighter tank technology. Hydrogen aircraft behaves similarly to kerosene aircraft when the fan size is increased regardless of the cryogenic tank technology. Overall, for both kerosene and Hydrogen aircraft, mission fuel burn is reduced when fan size is increased due to lower specific thrust turbofan designs. The heavier tank technology Hydrogen aircraft is more sensitive to changes in fan size compared to the lighter tank technology variant. The mission energy burn comparison showcased the high impacts of tank technology on energy burn of the Hydrogen aircraft where the heaviest tank led to a mission energy burn penalty of around 20% compared to the lightest tank causing an energy burn benefit of around 7%, all compared to kerosene aircraft. Since the tank technology largely dictated the heaviness of the Hydrogen aircraft, it also dictated the thrust requirements for the Hydrogen aircraft for any given fan size. As a consequence, the specific thrust of turbofan designs is significantly affected. Due to the energetic nature of Hydrogen fuel, the fuel requirement for a given mission is very less compared to kerosene fuel. As a result, the weight change throughout the flight is less for Hydrogen aircraft which enables Hydrogen turbofan engines to operate closer to their design conditions compared to a kerosene turbofan engine. Tank technology has a role to play in the fuel

requirements for a given mission where the heavier tank aircraft requires more fuel compared to lighter tank. All this leads to relatively less weight change across the flight for the Hydrogen aircraft with lighter tank compared to a heavier tank and hence, causes the turbofan engines to operate more closely to its design conditions for the lighter tank compared to the heavier tank. The combination of specific thrust change and weight evolution across the flight significantly impacts the design of turbofan engines operating with Hydrogen fuel. The study also highlights the role tank technology plays in the turbofan engine footprint where the heavier tank technology led to engine with a larger engine footprint and weight compared to a lighter tank.

- ❖ The investigation performed to study the fuel conditioning requirements of the alternative fuels and its impact on the turbofan cycle design provided some interesting insights. Of the gaseous fuels considered among the proposed alternative fuels, the study identified that high boiling point fuels such as Ammonia, DME and Butane existed in a liquid state whereas Hydrogen and Methane existed in supercritical state for the fuel injection under the turbofan operating conditions. This is believed to provide useful insights when thinking in terms of fuel handling for the engine. Most of the proposed alternative fuels required similar fuel conditioning requirements to Jet A fuel in terms of thermal power. The outliers are Hydrogen, Methane and Ammonia mainly attributed to their higher specific heat capacity of the fuel itself. Hydrogen requires significantly more thermal power to condition the fuel which is then followed by Methane and then Ammonia. As a result, several fuel conditioning strategies are investigated that utilised the turbofan engine as the power/energy source to condition the fuel (Hydrogen, Methane and Ammonia). The strategies assessed in this PhD are electric heating using the power drawn from the HPT, preheating the fuel in an external system using air bled from the compression unit, heating the fuel using exhaust heat after the LPT,

intercooling between IPC and HPC thereby heating the fuel in the process, a combination of both intercooling and exhaust heating to heat the fuel, using the hot bleed air from HPC that's used to cool the HPT NGV blades and finally, precooling similar to intercooling but the cooling process done upstream of the core section of the engine. For Hydrogen fuel, precooling strategy appears to be the most promising in terms of thermodynamic performance resulting in smaller cores and SFC benefit whereas intercooling turned out to be the least penalising strategy resulting increased core size and SFC penalty. For precooling strategy, the reduction in both the IPC and HPC work appears to dominate the total pressure loss of the heat exchanger and hence provide the turbofan design benefits. For intercooling, the reduction of HPC work does not appear to dominate the total pressure loss and as result does not provide the turbofan design benefits like precooling strategy. Electric heating strategy is found to provide the worst performance both in turbofan design and SFC indicating drawing direct power from the turbines to be not so desirable. The impact of total pressure loss due to HEX on cycle design highlighted the significant drawback it has on the turbofan designs as the fuel heating requirement increased, SFC increased (decreased thermal efficiency as T40 and OPR decreased) and BPR for the same fan size decreased. For Methane and Ammonia, precooling strategy is not assessed as there isn't enough temperature margin between the core inlet and fuel inlet during cruise. Similar impacts between the strategies are observed as that observed for Hydrogen fuel. Intercooling is the least penalising option in terms of design and performance. However, because the fuel conditioning requirements are reduced for Methane and Ammonia compared to Hydrogen, the impact fuel conditioning has on cycle design in terms of increase in core size and SFC is also reduced. The study also highlights that the fuel conditioning requirements are not significant enough to lead to turbofan designs that have BPRs lower than kerosene which indicates that the turbofan designs operating with alternative fuels are highly like to have smaller and compact cores.

- ❖ The study performed to assess the potential of using Ammonia as a Hydrogen carrier for civil aviation brought to light some insights. The limited mission capability of Ammonia aircraft in terms of range flown is the main driver behind this assessment to look for additional ways to improve the range performance. Initial range estimates of using Hydrogen contained in liquid Ammonia showed promise as additional range is obtained when compared to an aircraft burning pure Ammonia in the engines. However, this additional range capability did not account for the energy required to crack (decompose) Ammonia into Hydrogen. Hence, it is necessary to account for it and as a result, two strategies are investigated to derive the cracking energy using the Hydrogen burning turbofan engines as the power/energy source. These two strategies are using exhaust heat after the LPT and an electric heater drawing power from the HPT. The study brought to light the significant thermal power required to crack Ammonia into Hydrogen which interestingly came to be about an order of magnitude higher than the fuel conditioning requirements of fuels such as Hydrogen, Methane and Ammonia. Consequently, the impacts of such high thermal power requirements on the Hydrogen turbofan cycle design are drastic which led to designs with lower BPRs for the same fan size compared to the one without cracking impact. Although there is still a slight additional range benefit for the strategy deriving cracking energy from the exhaust, if the cracking systems weight and efficiency are considered, this additional range benefit might be negated.

5.2 Future work

The main recommendations for future work to be explored as part of continuous research and development are listed below:

- ❖ **Improve the fidelity of the investigation using dissociated combustion chemistry fluid model.** This can be interesting since the combustion of novel alternative fuels considered in this project can lead to different reactive species of combustion products upon dissociation and ultimately affect the thermodynamic properties of the working fluid passing through the hot expansion turbines. CEA can be used to generate the dataset from which tables or polynomial form can be applied in TURBOMATCH to test the effects.
- ❖ **Investigate the impacts of turbofan architectures on the preliminary design space exploration study.** This PhD performed the design space exploration for a 3-spool architecture. Additional architectures such as 2-spool and a geared configuration should be assessed to investigate and compare between all the architectures whether there are any differences in the design space boundaries for any given technology and thrust constraints. As an additional step, the compressor pressure ratio split could be varied to identify if any, the impacts of pressure ratio split on take-off T40 benefits compared to kerosene.
- ❖ **Preliminary investigation of NO_x and soot emission characteristics from novel alternative fuels.** Since NO_x and soot emissions are dangerous pollutants which can indirectly lead to global warming, their generation from the combustion of novel alternative fuels proposed in this research is important to be quantified at an upper level. It can be interesting for Hydrogen fuel since there can be NO_x emission benefits because it can be combusted at a very fuel lean equivalence ratio compared to all other fuels. This can then be used to design turbofan

cycles with minimum identified pollutants and SFC in a multi-objective optimisation platform. A simplified reactor model using these fuels with appropriate combustion reaction mechanism is envisaged as a first step in developing this capability after which further detailed development maybe pursued if the turbofan cycle results seem interesting.

❖ **Continued investigations of fuel conditioning using turbofan engines.**

Through this research work, the impact fuel conditioning has on turbofan cycle design is highlighted. As a result, further investigation into additional critical operating points (idle, top of descent, high altitude relight) could bring out potential implications/showstoppers in identifying which strategy could be the best to condition the fuel using the engines. The strategy using electric heating drawing power from turbines could be investigated on IPT or LPT depending on the architecture chosen. The bleed port/location to supply the air for the preheater strategy could be changed to further upstream or downstream the compression system. Further to it, since SFC penalty is observed for fuel conditioning, it will be interesting to perform an integrated engine aircraft study accounting for the fuel conditioning requirements. For Hydrogen and Methane aircraft, this is expected to make the aircraft heavier for a given mission range which in turn will lead to higher thrust requirements for any given fan size resulting in turbofan designs of higher specific thrust. The extent to which the shift in turbofan design occurs should be the matter of interest due to the varying degree of snowball effects on the aircraft mission by the different fuel conditioning strategies.

❖ **Increased turbofan cycle design integration with ATLAS.**

Since through this research the possibility of having smaller compact core has been identified, the fidelity of the turbofan cycle design process could be improved further and the cycle design code can be extended, by including the ATLAS component efficiency estimation capability in the solver of cycle design. Further to it, as a next step, an additional case study involving the

assessment of higher OPR for the same core size and temperature is suggested which can be interesting to assess.

❖ **Transient performance assessment of the turbofan cycles with smaller cores.** Since the PhD work focussed on steady state performance modelling, additional transient performance modelling is suggested. This is because it is thought that since the core size and weight are smaller as identified from size and weight estimation study, its associated inertias could also be lower. This could have interesting implications when assessing the time taken to achieve a desired value of thrust and potentially affect flight handling qualities.

❖ **Sensitivity analysis of weightings in decision matrix.** For supporting the generation of candidate fuels for civil aviation, the decision matrix was developed with certain relevant fuel properties for aviation and turbofan engines. Weightings are applied to these properties to prioritise them within the scope of the work. With the considered fuel properties, as a first step, the weightings can be varied to identify how the final scores between fuels among families change. It will be interesting if fuels other than those already considered comes out with a higher score. This should be investigated for Alcohol and Ether family since only fuels from these families were selected based on the final scores. If a different fuel with higher score is observed, it will be worth conducting all the technical investigations with that fuel that includes design space exploration, engine weight estimation, integrated engine aircraft assessment and finally, advanced cycles investigation (fuel conditioning assessment study).

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