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GREEN HYDROGEN REVOLUTION IN AVIATION:
REQUIREMENTS AND POSSIBILITIES

School of Aerospace Transport and Management
MSc by Research in Aerospace (Part-Time)

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Academic Years: 2021 - 2023

Supervisor: Dr. Nalianda
Associate Supervisor: Professor Pericles Pilidis
1st May 2023

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ABSTRACT

This work investigates the case for sustainable aviation for the Asia Pacific region and focusses on Hong Kong. Hong Kong presently generates 50% of its energy from coal. The aim is to remove carbon from aviation fuels for Hong Kong and replace it with green hydrogen. This is a viable choice of sustainable aviation fuel but switching it from kerosene would require the overcoming of some challenges.

This thesis comprises of three parts: firstly, the modelling and simulation of the Trent-XWB-97 jet engine as a baseline combusting Jet-A fuel. Its aircraft performance is then compared to a cryogenically fuelled green hydrogen engine. Secondly, the reference engine is then fitted with an intercooler with the gain of aircraft performance benefits in mind as well as to utilise it as a heat exchanger to vapourise the liquid hydrogen and thirdly, large-scale green hydrogen production using renewables is envisaged as part of a Green Hydrogen Hub network encompassing a green hydrogen logistical supply chain paving the way for a future aviation hydrogen micro-economy. It was discovered that relative to the Jet-A fuelled engine, the engine with a constant net thrust for ODP (Take-Off) and DP (Cruise) conditions decreased the ESFC for both baseline and intercooled engines. For the reference case at ODP this drop in ESFC was (1.71%) and (1.3%) for the intercooled scenario. There was also an accompanying decrease in TET; for the baseline engine this was 47K and for the intercooled engine this was 50K. The addition of the intercooler achieved the greater aircraft thrust requirement of 448kN and also vapourised the cryogenic hydrogen to high enough temperatures. These were calculated to be 536K and 296K for the ODP and DP respectively. The results showed that the baseline engine carried the greatest payload of 31866 kg with a block fuel burn of 36267 kg and a flight duration of 11.83 hours. The intercooled engine yielded a maximum carried payload of 27184 kg and the block fuel burn was 43349 kg and a flight time of 11.97 hours. The study also discovered that the 43.4 tonnes of green hydrogen can be generated in Hong Kong using wind and solar power and that its usage reduced the civil aviation carbon footprint of Hong Kong by 11.6%.

Keywords:

Green hydrogen, Turbomatch, Trent-XWM-97, aircraft performance, Hong Kong.

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LIST OF ABBREVIATIONS

HKIA	Hong Kong International Airport
LGW	London Gatwick Airport
AAHK	Airport Authority of Hong Kong
CAD	Civil Aviation Department of Hong Kong
RPK	Revenue Passenger Kilometres
HKO	Hong Kong Observatory
GHG	Greenhouse Gas Emissions
AEDT	Adopted Aviation Environmental Design Tool
ERF	Effective Radiative Forcing
ASTM	American Section of the International Association for Testing Materials
ICAO	International Civil Aviation Organisation
OECD	Organisation for Economic Cooperation and Development
SMR	Steam Reforming
ATR	Auto Thermal Reforming
CCUS	Carbon Capture Use and Storage
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
WACC	Weighted Average Cost of Capital
AEC	Alkaline Electrolysis Cells
PEMEC	Proton Exchange Membrane Electrolysis Cells
SOEC	Solid Oxide Electrolysis Cells
OPR	Overall Pressure Ratio
BPR	Bypass Ratio
LH ₂	Liquid Hydrogen
DEWA	Dubai Electricity and Water Authority
LHV	Lower Heating Value
NO _x	Nitrogen Oxides
WAsP	Wind resource Assessment, siting & Power yield
GUI	Graphical User Interface
TET	Turbine Entry Temperature
COT	Combustor Outlet Temperature
NT/F _N	Net Thrust
ST	Specific Thrust

FF	Fuel Flow
SAF	Sustainable Aviation Fuels
FAR	Fuel-Air Ratio
SWH	Solar Water Heating
PV	Photovoltaic
BIPV	Building Integrated Photovoltaic
ODP	Off-Design Point
DP	Design Point
FTHE	Fin-Tube Heat Exchangers
C	Heat Capacity
q	Amount of heat transferred
T	Temperature
ϵ	Intercooler effectiveness
P	Pressure
W	Mass flow
ESFC	Energy Specific Fuel Consumption
SFC	Specific Fuel Consumption
PR	Pressure Ratio
H	Hydrogen
N	Nitrogen
O	Oxygen
HPRPM	Higher Pressure Compressor Revolutions Per Minute
ROC	Rate of Climb
L/D	Lift-to-Drag Ratio
ETRW	Energy Per Passenger Kilometre
IC	Intercooler

Subscripts

c	Cold
h	Hot
in	Inlet
o	Outlet
min	Minimum
max	Maximum
m	Medium

C_p	Specific Heat Capacity at constant pressure
2,3,4,5...	Number of atoms
1,2,3,4,5.....	Engine component numbering

Superscripts

0	Degrees
2	Squared
3	Cubed

Units

Mega tonnes	Mt
mt	Metric tonnes
kgH ₂	Kilogram of hydrogen
kWH ₂	Kilowatt of Hydrogen
kWh	Kilowatt hour
MJ/kg	Megajoules per kilogram
Kg/m ³	Kilograms per metres cubed
GJ/m ³	Gigajoules per metres cubed
kg/s	Kilogram per second
K	Kelvin
g/kN/s	grams per Kilonewton per second
J/N/s	Joules per Newton per second
Ns/kg	Newton-seconds per kilogram
m	metres
nm	Nautical miles
m/s	Metres per second

1 INTRODUCTION

Recently, during the Asia-Pacific climate week (2021), it was stated that ‘the Asia-Pacific region has emissions greater than those of half of the world’s greenhouse emissions and has a very large percentage of the worldly population. This area also has many regions with cities closer to sea-level and smaller islands that are vulnerable to flooding. The same convictions have been agreed to by countries in the African green hydrogen conference and most recently at the COP26.[19], as were originally at the Paris Climate Summit (12th December 2015), which is to cap the rise in Earth’s temperature to 1.5°C (by 2100) and the attainment of resultant zero greenhouse gas emissions by 2050. [15]

Hong Kong is not only the eastern financial, tourism and connection Hub but it is also a coastal city and thus, has immense potential for the application of renewable energy sources and as such offers a promising prospect of structuring a green hydrogen-based aviation economy in Hong Kong, with a single goal of reducing the CO₂ emissions. Analysis of Passenger Data between (2018-2019-pre-Covid levels), from United Kingdom to Hong Kong, amalgamates to (166735) passengers, this suggests a good case for green hydrogen for UK-HKIA-UK flights since there are also connections from Hong Kong to Eastern Asia, Southeast Asia, and Northeast Asian markets.[25]

Hong Kong’s potential of renewable energy sources specifically wind power (Off-shore and rural) and solar energy can be utilised in the generation of green hydrogen [22], moreover, technologies such as Alkaline Electrolysis and Proton Exchange Membrane Electrolysis can be studied and their applicability to Hong-Kong Seawater evaluated. [30]

This research is inspired as part of the first innovation wave as mentioned in [35], that aims to investigate, compare, and simulate the direct combustion and performance of green hydrogen as an alternative fuel to kerosene in a three-shaft high by-pass turbofan engine (Trent-1000(XWB-97)) [24]. This engine is chosen for its installations on long-range airliners such as the A380, the A350 (employed by Hong Kong’s national carrier Cathay Pacific), and on a Cranfield University

hydrogen powered concept aircraft named the HVLER. [31]. The thesis further, explores the addition of an intercooler to this baseline engine to simulate the necessary vapourisation of the cryogenically stored liquid hydrogen, for an improved net thrust, a lower TET and a lower ESFC, when integrated on the HVLER aircraft. The research also discusses some of the challenges which must be overcome in burning the green hydrogen in the combustion chamber, e.g., pressure and temperature increase of the fuel from the cryogenic storage tanks as part of a fuel distribution system.

Three engines were simulated at the same operating point for ODP and DP conditions (for both the baseline and intercooled engine architectures) in Turbomatch, the original Jet-A fuelled, a second one with constant COT and the third one where the Net Thrust was kept the same.

The engine with the lowest ESFC and TET was selected and then modelled in the Orion aircraft performance program and the aircraft performance simulations for both the baseline and intercooled engines were conducted. The fuel burn obtained from these then informed further explorations into the green hydrogen production potential in Hong Kong. It assessed the suitability of its current modelled renewable infra-structure power yields and recommended electrolysis plants in producing and sustaining the required green hydrogen generation. The research also calculates the reduction in CO₂ emissions by the use of green hydrogen in the test case as well as its cost of production in Hong Kong.

1.1 Thesis Aim Hypothesis and Objectives

Aim

The aim of this research is to architect a case for sustainable civil aviation in the Asia-Pacific region.

Hypothesis

Is green hydrogen an efficient and a sustainable aviation fuel alternative for Hong Kong?

Objectives

1. Explain the need for sustainable aviation fuels for the Asia-Pacific region, specifically Hong Kong.
2. Justify the selection of green hydrogen as a sustainable aviation fuel.
3. Analyse the renewable energy production potential for Hong Kong.
4. Compare quantitatively the performance parameters of an intercooled propulsion system combusting kerosene or green hydrogen as an alternative aviation fuel.
5. Justify the aircraft performance benefits with the intercooled engine for the test case mission.
6. Evaluate the production feasibility of the required green hydrogen for the test case.
7. Investigate a possible design of a green hydrogen hub for Hong Kong.

2 Literature Review

2.1 Hong Kong- A Major Aviation Transportation Hub

Hong Kong's International Airport (HKIA) is strategically positioned in the Asia-Pacific region, it is a passenger hub, has a trans-shipment area and is a gateway to other Chinese cities. Prior to the COVID-19 pandemic, in 2019, it served 120 airlines and 200 international destinations.. In 2019, HKIA managed 71.5 million passengers, 4.8 million tonnes of air freight and 420,000 in air traffic. (Please see Table B-1 and Figure A-1) [1]

Hong Kong's Civil Aviation Department (CAD) certifies all aircraft registered in Hong Kong. The Airport Authority grants operating licences to all airports.

The south and the north runways of HKIA (see Figure 1) are 3,800 metres long and 60 metres wide, this will enable the landing and take-off of the A380 and A350 aircraft which is a requirement for the Cranfield concept the HVLER modelled in this thesis. There are also eight aircraft stands which can service the A380. [1]

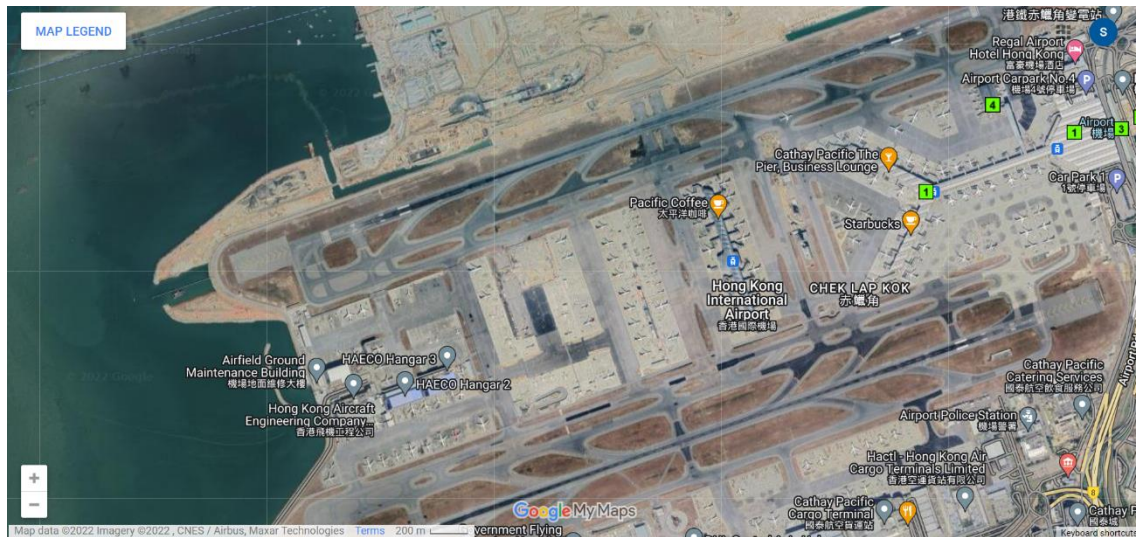


Figure 1 The North and South Runways of HKIA [1]

2.1.1 Geographical Location

Hong Kong is situated in the heart of Asia [1], it is four hours away by air to most important Asian markets and is within reach to more than half of the world's population in a matter of five hours. (Figure 4), including some 40 destinations in the Mainland, China.

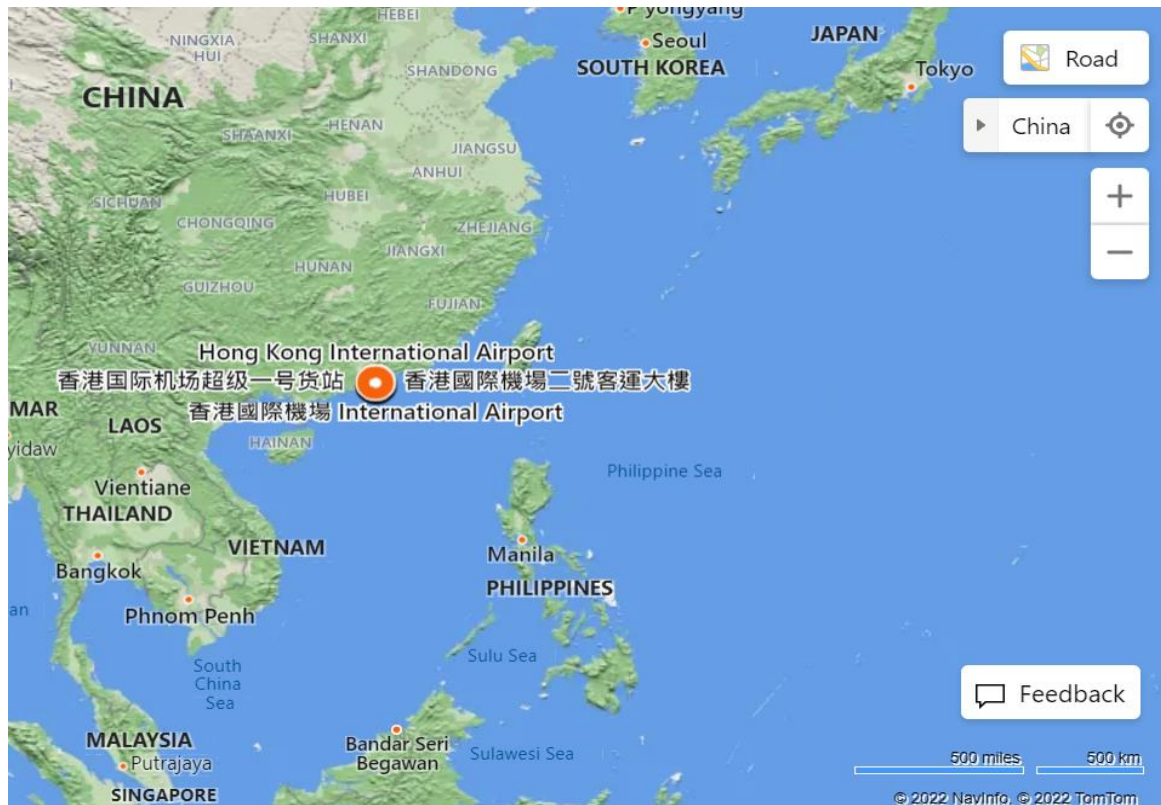


Figure 2 Map of the geographic location of Hong Kong International Airport [2]

The HKIA is the busiest international cargo network and has the world's fourth ranked international airport by passengers (after Dubai, London Heathrow, and Amsterdam).

Figure 3 (below) shows the position of the third runway which is planned to commence operations in 2024, upon the full operation of the three-runway facility, the HKIA will have the increased capacity to handle annual passenger and cargo volume of around 100 million passengers and 9 million tonnes of cargo respectively.[3]



Figure 3 Hong Kong's International Airport with third runway on far side [3]

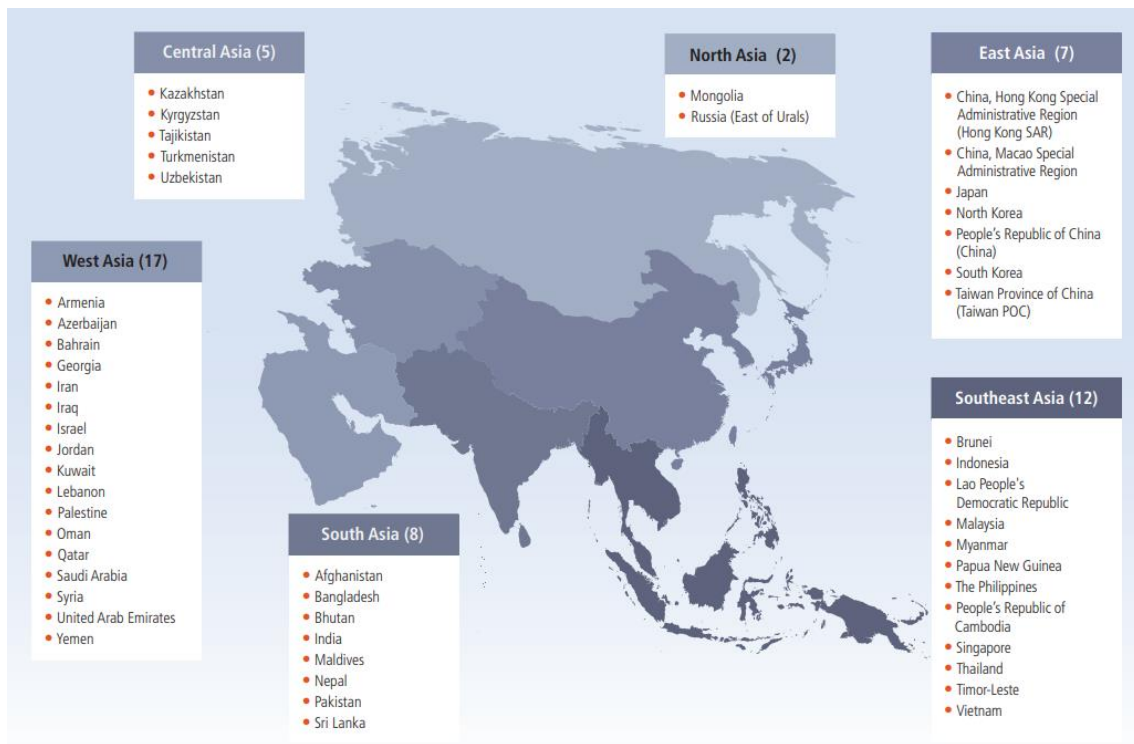


Figure 4 The land and territories of 51 countries/regions in Asia. [4]

2.1.2 Asia-Pacific CO₂ Emissions and Hong Kong

The Asia Pacific region releases just over half of the world's greenhouse gases and is one of the most rapidly developing parts of the world with a large proportion of world population. It contains most of the global near sea-level cities and small island states that are prone to flooding.[4]

This area has four out of the ten nations with the highest aviation RPK's (China, Japan, India, and Australia as shown in (Table-B1.2).

2.1.3 Asia-Pacific Emissions

Between 2010-2019, domestic and international aviation grew at average annual rates of +3.3% and +3.4%.

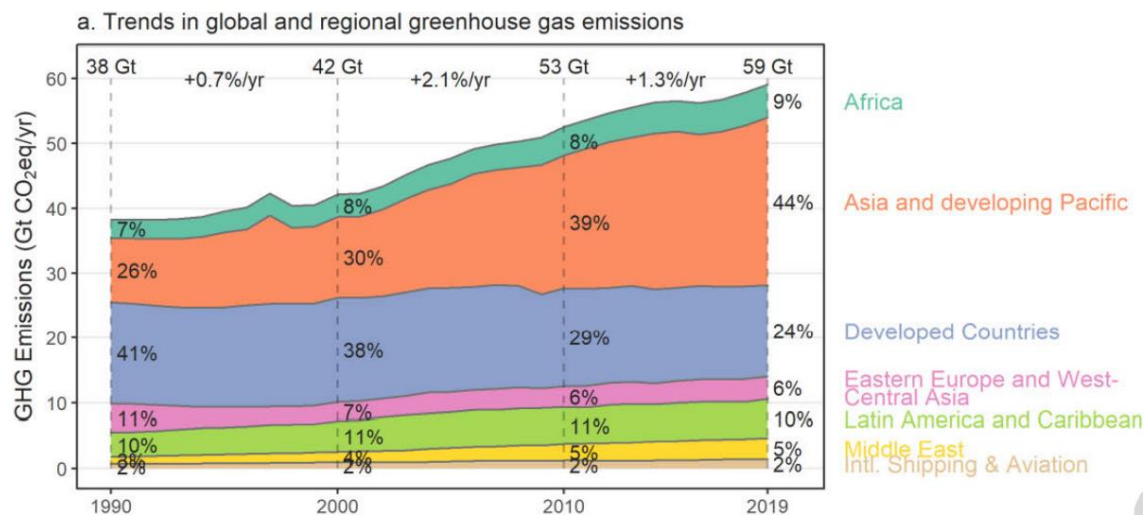


Figure 5 Trends in global and regional greenhouse gas emissions [4]

Evidence highlights that there is an unequal GHG emission in aviation, although only 2-4% of world population flew in 2018, 1% of the global population emitted half of the of CO₂ from commercial airlines (Gössling and Humpe 2020).

2.1.4 Climate Change in Hong Kong

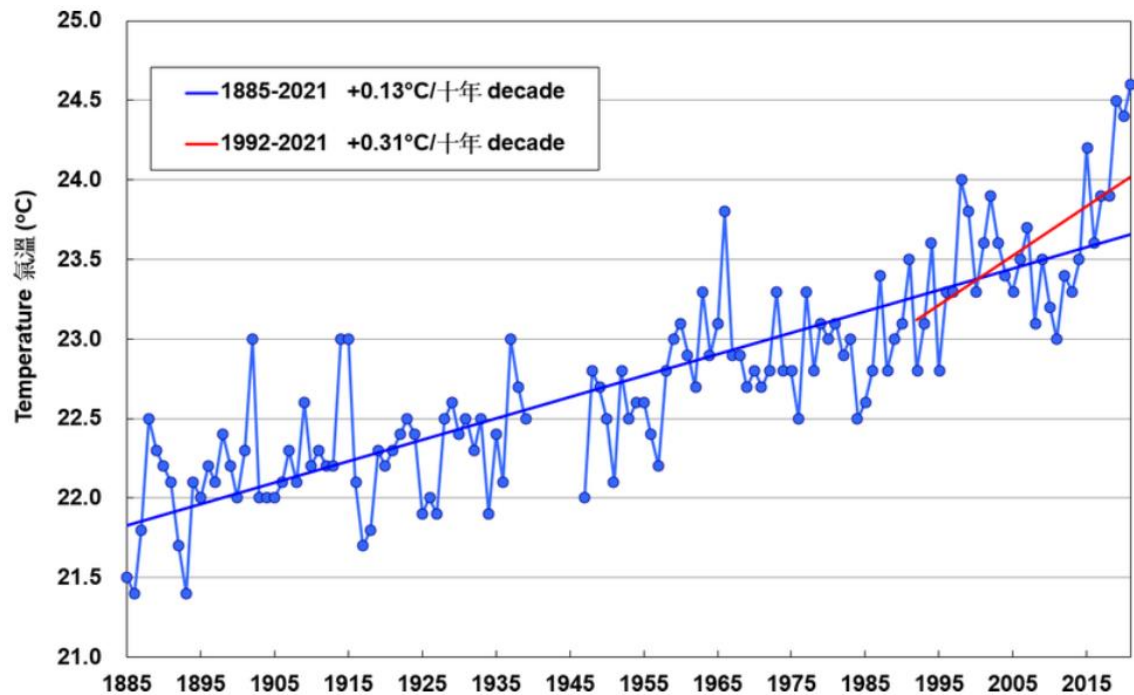


Figure 6 Annual mean temperature for Hong Kong (1885-2021) [5]

After analysing the data from Hong Kong's observatory of its annual mean temperature from 1882-2021, it showed an average increase of 0.13°C per decade. In the latter half of the twentieth century this increase became faster and reached 0.31°C per decade during 1992-2021. [5]

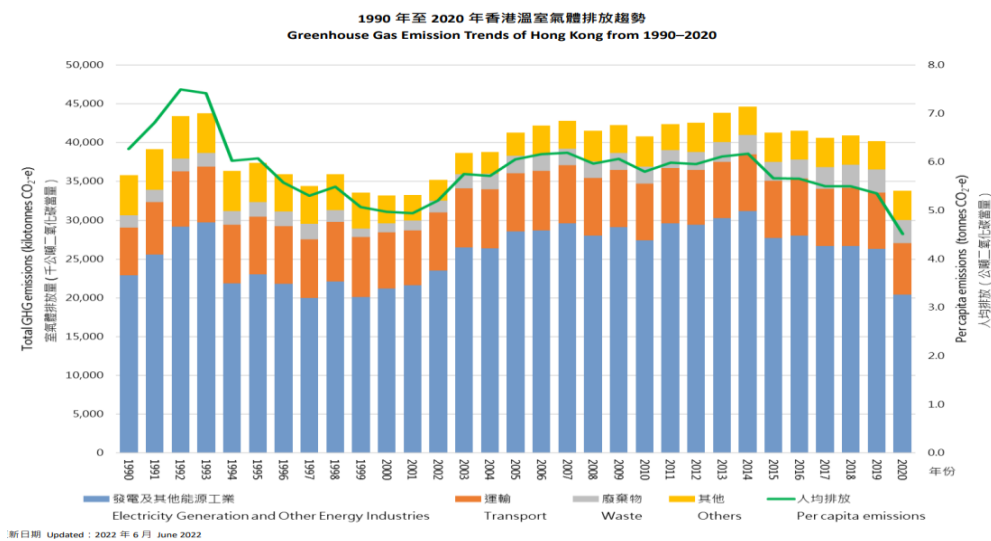


Figure 7 Greenhouse gas emission trends in Hong Kong from 1990-2020 [6]

The total GHG (CO₂) emissions in Hong Kong were above 40MT on average in the past decade, there is a downward trend on emissions per capita, but 80% of these emissions are as a result of energy and transport sectors.

In 2019, Hong Kong emitted 10.5Mt of CO₂ from civil aviation, moreover, the average CO₂ intensity of flights leaving mainland China, Hong Kong and Macau was 2% higher than the global average.(Figure 8). [8]

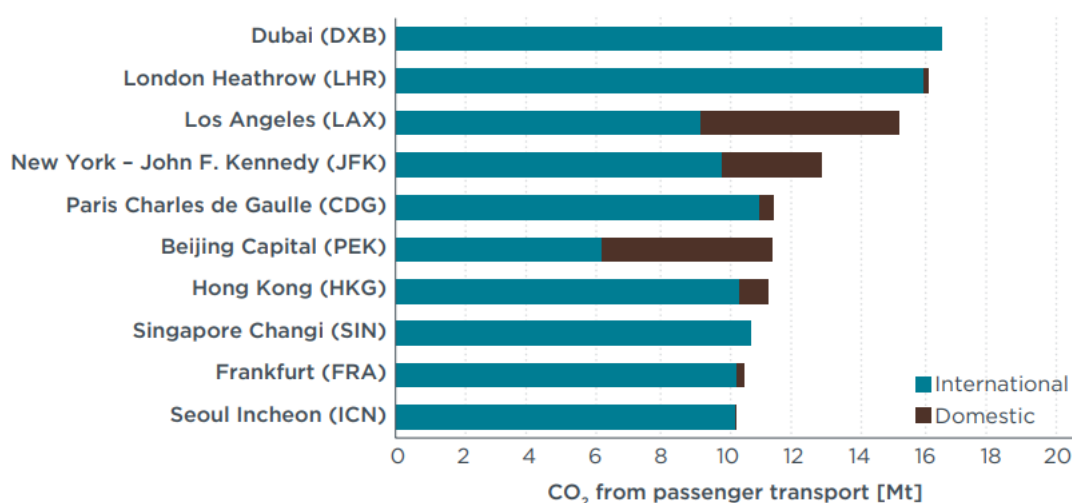


Figure 8 Passenger CO₂ emissions in 2019 of Top 10 departure airports [8]

In 2019, CO₂ emissions from international civil aviation were 61% of total transport emissions, this is a significant reason for the mitigation and reduction of the carbon footprint in this area. Flights from mainland China, Hong Kong and Macau were 9% of total global transport emissions. Within mainland China alone 66Mt of CO₂ was emitted in 2019 and 747 billion RPKs were travelled.[8]

For each passenger transported, A widebody aircraft flight like the A380 or A350, with an average range of 4675 km emits 416 kg of CO₂ per passenger while return travel CO₂ emissions were two times greater. The Airbus A380 has the highest CO₂ intensity in excess of 100g CO₂ per RPK, on the other hand, aircraft in the class, e.g., the Airbus A350-900, which is more fuel-efficient and has a CO₂ intensity of 75g CO₂ per RPK, as shown in (Table B-1.3)

In 2019, Hong Kong's civil aviation emitted approximately 9% air pollutants as compared to the total local air pollutants. The air traffic increased by 113%, with a corresponding increase in NO_x emissions of 101%. [9]. These were estimated using the Adopted Aviation Environmental Design Tool (AEDT) version 2c. The total carbon pollutant emissions from civil aviation for the year 2019 were 4,260 tonnes and the corresponding NO_x emissions were 6,310 tonnes respectively.[9]

The CAD adopts the standards as set out at Annex 16 to the Convention on International Civil Aviation, Volume II, Part III, Chapter 2 to certify the engines installed on aircraft using the HKIA in order to reduce their emissions. (See Figure 9)

Sectoral analysis for “Civil aviation”

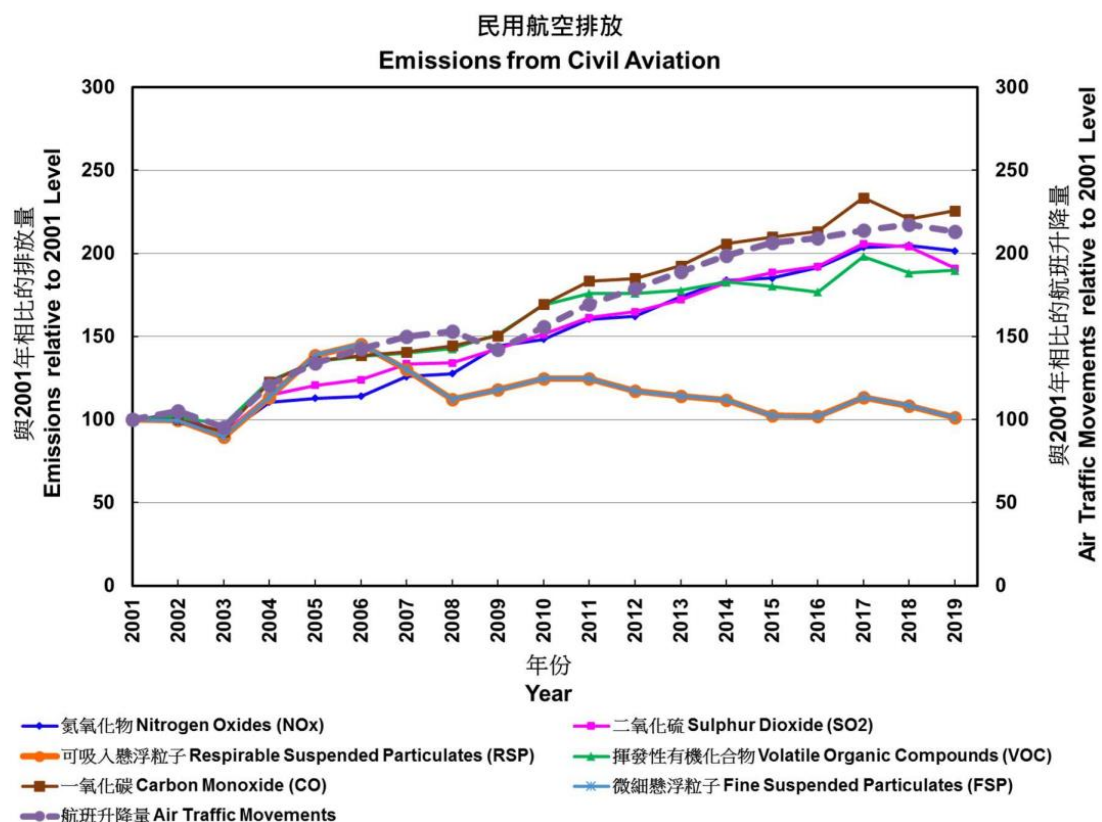


Figure 9 Emissions from Civil Aviation in Hong Kong. [9]

2.1.5 Hong Kong Energy Usage (Renewables and non-Renewables)

Hong Kong consumed 286,488 TJ of energy in 2019, 56% of this was generated using coal, natural gas, wind, and solar power, 17% using Town Gas and LPG and 27% using Oil and Coal Products. (Please see Figure A-2).[10]

Hong Kong produces a small percentage of renewable energy, these include, solar, wind, biogas, and biodiesel energies. In 2019, 2,442 TJ of renewable energy was generated and used by the end-users in Hong Kong. Out of these 3.0% was Solar, 0.6% Wind and Hydropower, 11.4 % Biodiesel (made from recycled oil) and 84.9% Waste-to-energy. The total contribution of all types of renewables in Hong Kong is 0.9% of the overall consumption of energy. (See Tables B-2). [11]

2.1.6 Hong Kong Climate Model Predictions

The mean temperature in Hong Kong was recorded by the HKO for the period 1992-2014 was found to be 23.4°C. According to the intermediate greenhouse gas emission scenario (SSP5-4.5), the average temperature would have risen by 2.0 °C and with reference to (SSP5-8.5) GHG emission scenario, by 3.6 °C for the time frame between 2081-2100 in Hong Kong. (See Figure A-2.1). [12]

Under the same two scenarios, the annual rainfall in Hong Kong during 2081-2100 is predicted to increase by about 7.0% and 9.0% respectively, when compared to the average of 2456mm (at the HKO) between 1995-2014.

Under the same two model predictions the annual mean sea level in Hong Kong in 2100 is likely to increase by 0.37-0.82 m and 0.57-1.08 m respectively relative to the average of 1.45 m, which is above the chart datum. (Measured at the HKO) during 1995-2014). [12]

2.2 The Re-emergence of Hydrogen as an Aviation Future Fuel

The main emission from (Jet-A) combustion is fossil fuel is CO₂, but It also has non-CO₂ emissions (water vapour, soot, sulphur dioxide and nitrogen oxides (NO_x = NO + NO₂) which can also adversely affect earth's climate. International emissions account for approximately 65% of the total CO₂ emissions from international aviation, totalling approximately 1Gt of CO₂ in 2018. These have been steadily rising at a rate of around 2.5% per year over the past two decades. [13]. The residual effect of current CO₂ emissions will contribute to the Earth's warming for many millennia, however, the effects of soot, water vapour and NO_x emissions will have ceased to have an effect in a few decades. This is why the 'net zero' level CO₂ reduction in aviation is necessary to help achieve the emission scenario of 1.5°C. This would require fundamental shifts in current technologies, use of alternative fuels and a cultural change in behaviour or demand.

NO_x emissions form short-term ozone, cause cooling by destroying the methane, these effects increase the warning of the atmosphere, moreover pollutant emission like water vapour and soot trigger the formation of contrails and form cirrus clouds under certain conditions. These clouds can increase the ERF as a result of global aviation to as much as 57% relative to the current ERF, however, observations under the COVID pandemic have brought forth evidence that this ERF may be smaller than previously thought.

One kilogram of JET-A combustion gives, 3.16 kg CO₂, and after safety, the primary objective of engine and airframe manufacturers is to lower the DOC, which are mainly due to fuel burn. [13]

In the long-ranged twin aisled aircraft categories, there have been new aircraft designs (Like the Boeing-787-9 and the Airbus A350-900) with improvements in their lift-drag ratio, fuel burn reduction has been achieved through better aerodynamic efficiency, lighter aircraft, and more efficient propulsion system. Improving only aircraft technology has a limiting scope in reducing CO₂ emissions with the air traffic growth projections. (Klower et al. 2021) suggest that to meet this higher demand without increasing the levels of CO₂ the use of alternative

fuels such as liquid hydrogen and bio synthetic (SAF) will become essential. Cumpsty et al. (2019), suggest that the maximum rate of fuel burn reduction with the new BWB designed aircraft would be no greater than about 1.3%, which is short of ICAO's target of 2%. These fuels would need to be certified by ASTM (American Section of the International Association for Testing Materials) to the same standard as Jet-A with a focus on safety issues. [13]

Low carbon hydrogen would be a diverse replacement to the aviation kerosene in use today, since it can be consumed in a fuel cell or burned in a boiler, turbine, or a jet engine to produce heat or electricity. Low carbon and green hydrogen will be essential in achieving net zero by 2050. [14]

2.2.1 The State of Current Hydrogen Fuel Technologies

There are various ways of producing hydrogen; the percentage of carbon in the produced hydrogen is dependent upon the energy inputs and technology. The three main methods of hydrogen production are called: grey, blue, and green hydrogen.

Grey Hydrogen

Steam reforming converts natural gas or coal under heat into H₂ and CO₂, with about 10t of CO₂ being released into the atmosphere as GHG for each tonne of hydrogen produced. H₂ extracted from methane creates about 285g of CO₂ per kWh, while coal gasification emits 675g of CO₂ per kWh of hydrogen power.

Blue Hydrogen

This is produced with a similar process to grey hydrogen, but carbon capture and storage (CCS) is added to prevent the CO₂ from being released.

Green Hydrogen

This type of hydrogen is generated by the electrolysis of water using only renewables, CO₂-free electricity sources. While the process is already viable, the speed of its adoption will depend on the cost of electrolyzers, supply chain logistics, and regulatory policies. [17]

Today, around 70 million tonnes of hydrogen are produced using natural gas and coal which is equivalent to 6% of global natural gas usage. In China, coal is used, to produce 23% of global hydrogen, 107Mt of coal is used in the process, this is 2% of global coal usage, with electricity and oil contributing to the rest of H₂ production. [15]. This results in a total CO₂ formation of approximately 830 Mt CO₂ per year, which is equivalent to CO₂ emissions of Indonesia and the United Kingdom combined.

There are three methods for producing hydrogen via reforming: steam reforming (SMR), where water is used as an oxidant and produces hydrogen, then there is partial oxidation, here oxygen in the air is used as an oxidant, or a combination of both water and oxygen can be used in Auto Thermal Reforming (ATR).

Natural gas is mostly used in SMR to obtain hydrogen, some of it is produced from liquified petroleum gas and naphtha, again partial oxidation is part of the process to extract hydrogen from coal and fuel oil as well. A gas containing carbon monoxide and hydrogen is produced (called synthesis gas), which is then converted to hydrogen and CO₂ is produced as a by-product.

Gasification and electrolysis are the other methods where coal and biomass can be converted to synthesis gas, electrolysis is the splitting of the water molecule into hydrogen and oxygen.

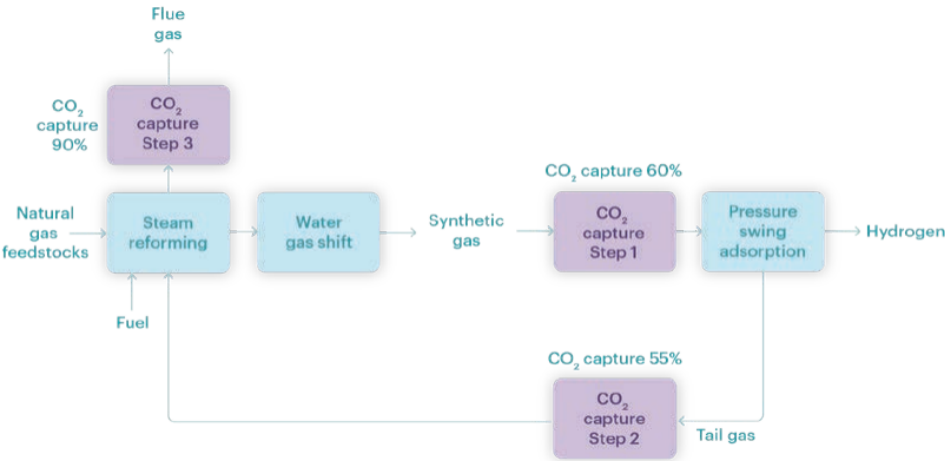
Hydrogen from natural gas

SMR using natural gas produces two streams a diluted one and a concentrated one, these contain different amounts of CO₂. Approximately 30-40% of natural gas is burned and used as fuel and the rest as feedstock for the process. (Including water).

Deploying CCUS technology with SMR plants can effectively decrease carbon emissions of up to 90%, when CCUS is applied to both the process and energy streams. When CO₂ is extracted from high-pressure synthesis gas stream, carbon emissions are reduced up to 60% (Figure 10).

The CO₂ can also be absorbed from the diluted flue gas. This can reduce the emissions further to 90% or more. Costs go up from USD 53 per tonne of CO₂ to USD 80 per t/ CO₂ in merchant plants and a further increment in the range USD (90-115) per t/ CO₂ in combined ammonia/urea and methanol plants.

Figure 8. Production process of hydrogen from gas with CCUS

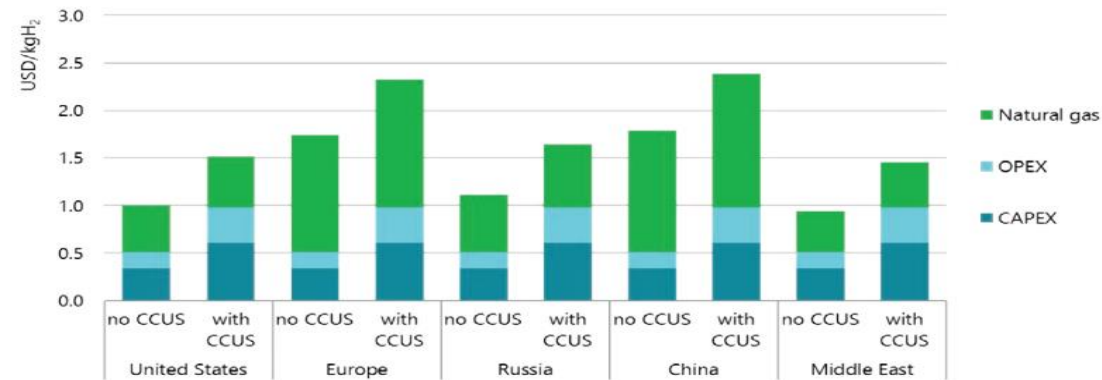


Source: IEAGHG (2017a), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS".

Figure 10 Schematic of hydrogen production process from gas with CCUS [15]

ATR allow the capture of carbon at a lower cost than SMR since it produces a more concentrated stream and involves higher recovery rates than SMR. Fuel costs are the greatest in all regions and costs range from 45%-75%. (Figure 11).

Figure 9. Hydrogen production costs using natural gas in different regions, 2018



Notes: kgH₂ = kilogram of hydrogen; OPEX = operational expenditure. CAPEX in 2018: SMR without CCUS = USD 500–900 per kilowatt hydrogen (kW_{H₂}), SMR with CCUS = USD 900–1 600/kW_{H₂}, with ranges due to regional differences. Gas price = USD 3–11 per million British thermal units (MBtu) depending on the region. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019. All rights reserved.

Figure 11 Costs of producing hydrogen from natural gas in different regions, 2018 [15]

China has a production cost of USD 2.4/kg H₂ (with CCUS), while the US cost of hydrogen with SMR and CCUS of USD 1.4-1.5/kg H₂.

Hydrogen production using water and electricity.

Water electrolysis is the division of water into its constituent elements of hydrogen and oxygen. Currently, only 0.1% of hydrogen is produced globally using this method for uses in high purity demands such as electronics and polysilicon markets. As the costs for renewable electricity are becoming more affordable and in particular in solar PV and wind, countries are investing a lot more in electrolyser plants to generate green hydrogen. The efficiency of the electrolyser system is currently between 60% and 81% depending on which technology is favoured and what is the required volume of hydrogen.

Electrolysis requires de-ionised water as well as electricity (from renewable sources like solar and wind). Approximately 9 litres of water are required to produce 1kg of H₂, 8 kg of oxygen is generated as a by-product, this can be used for the health care and for industrial purposes.

Freshwater availability can be an issue in water-stressed areas. Using seawater as a feedstock could become an alternative in coastal areas like Hong Kong, however, electrolysing seawater directly currently leads to corrosive electrode damage and build-up of impurities on membrane as well as to the production of chlorine. Currently, research is being conducted on how to make it easier to use seawater electrolysis and studies have shown that the use of manganese oxide for the anode and the addition of tungsten can further promote oxygen production; and reduce chlorine generation to 0.4%.

According to (Tractebel, 2018; Caldera et al, 2018) direct seawater electrolysis using the process of reverse osmosis and desalinating the seawater would require an electricity demand of 3-4 kilowatt hours (kWh) per m³ of water and will costs around 0.7-2.5 USD per m³ of water.

Three main electrolyser technologies are in use today these are: Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane (PEMEC) electrolysis, and solid oxide electrolysis Cells (SOECs).

Alkaline Electrolysis

AEC currently has the lowest CAPEX; hence, this electrolyser technology is the most widely used and has a life of 90000 hours. This process uses potassium hydroxide as the electrolyte and doesn't require the use of precious metals like PEMEC. AECs use reduced voltage as they are operated around 80°C and a pressure of 35 bar.

Although PEMEC has a higher efficiency than AEC, but it works using solid polymer electrolyte and hence, operates at a higher pressure and voltage than AEC, it also uses precious metals like platinum and iridium for catalysts also requiring a greater water purity. Research is being conducted to produce Dimensionally Stable (DS) composite membranes that don't swell when wet and can therefore last longer. [16]

SOEC also uses a ceramic electrolyte and operates at a higher temperature near 750°C. The higher temperature reduces the bond strength of water and hence a lower electricity input is needed. SOECs need a heat source to produce steam but they do have a higher efficiency. Solar thermal or geothermal heating systems or waste heat from the Fischer Tropsch synthesis as well as nuclear power plants could provide the heat source for high temperature electrolysis.

Figure 12 below summarises the three different types of electrolysis.

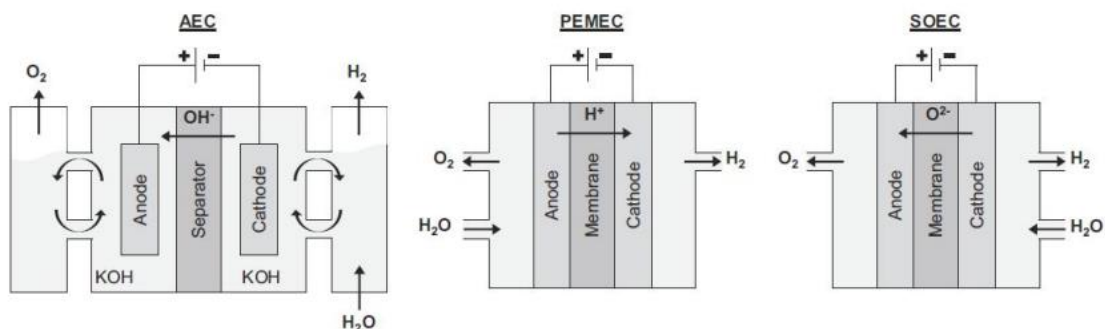


Figure 12 Alkaline Electrolysis Cell (AEC), Proton Exchange Membrane Electrolysis Cell (PEMEC) and Solid Oxide Electrolysis Cell diagrams (SOEC) [16]

Emerging technologies for hydrogen production

Methane splitting uses a three-phase alternating current plasma to produce hydrogen and carbon, there are no CO₂ emissions. Although not as efficient due to heat energy losses from the plasma, it does require 3-5 times less electricity than electrolysis for equivalent volumes of hydrogen produced. The solid carbon could be used in the rubber, tyres, printing, and plastics industries. [15]

Hydrogen from coal

Producing hydrogen using coal gasification has been used to make ammonia for fertilisers (especially in China), however, it produces CO₂ emissions of approximately 19t CO₂/ tH₂, which is double of that emitted by the use of natural gas.

CCUS technology is the most cost-effective process of producing cleaner hydrogen in China but currently the CO₂ intensity per kg is still twice as that of producing one kg of hydrogen. (kgCO₂/kgH₂) (Figure 13)

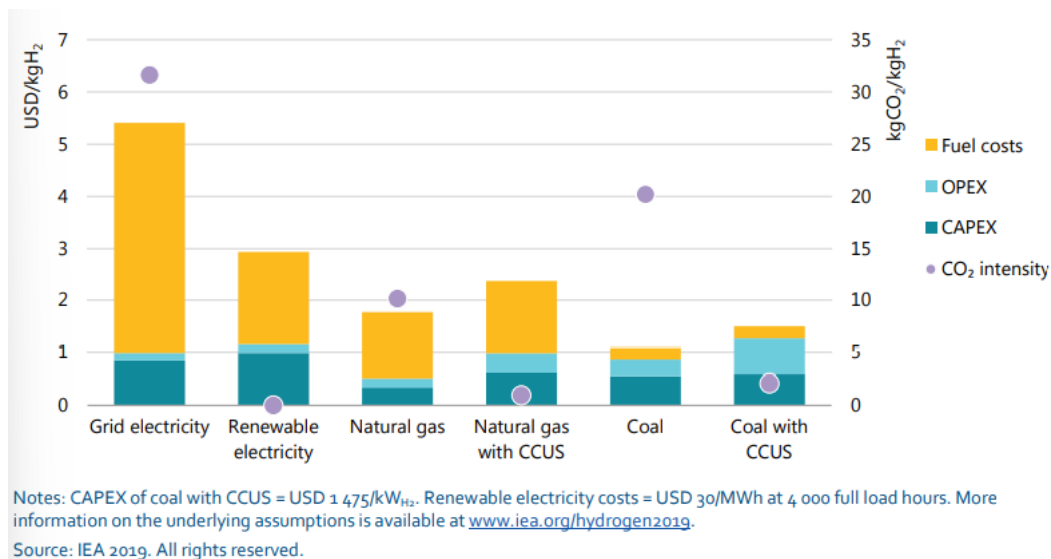


Figure 13 Hydrogen production costs in China today [15]

Hydrogen from biomass

Hydrogen is produced from organic matter anaerobically using microorganisms. The bacteria generate biogas after digestion and fermentation; biogas is a mixture of acids, alcohols, and gases. Hydrogen can also be generated using

thermochemical gasification of biomass which works like coal gasification to convert biomass into a mixture of carbon monoxide, CO₂, hydrogen, and methane. These gaseous mixtures are processed to extract hydrogen but imparts higher costs as well as demand on resources with the use of biomass than solar-to-wind based technologies.

Comparison between alternative hydrogen production pathways

With the exception of hydrogen production from coal fuel costs are the common factor in hydrogen production cost (Figure 14). This cost is highly dependent on gas and electricity costs. Hydrogen generation by electrolysis is also sensitive to CAPEX costs especially if the plants are working at part or full load hours.

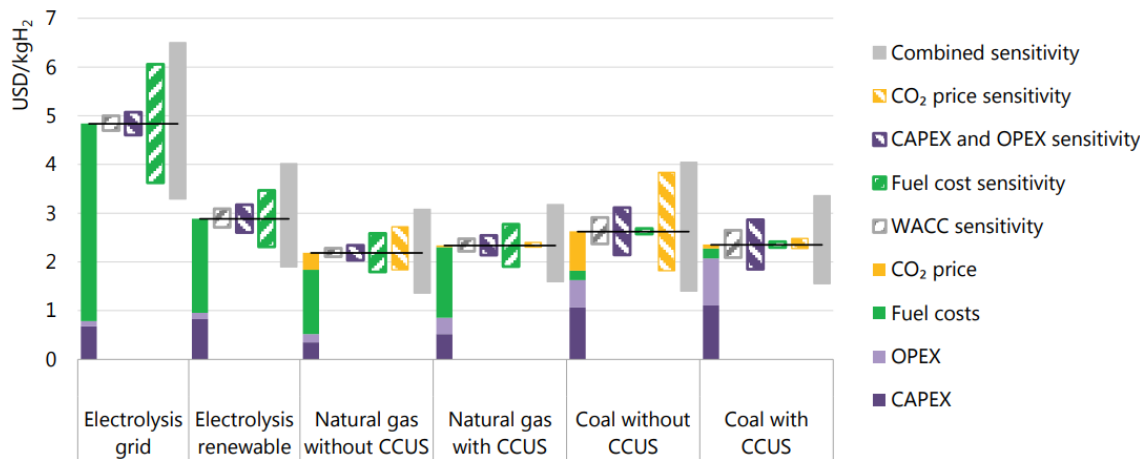


Figure 14 Costs for producing hydrogen using different technologies. 2030 [15]

Hydrogen production cost using natural gas is near USD 1.5-3/kgH₂, and if the hydrogen is produced from renewable sourced electricity (solar PV or onshore wind), it is near USD 2.5-6/kgH₂.

China's hydrogen production from renewable energy sources will reduce to around USD1.5k/gH₂ by 2030, and regions like Hong Kong with good renewable potential can benefit from transitioning towards green hydrogen. (Figure 15). [15]

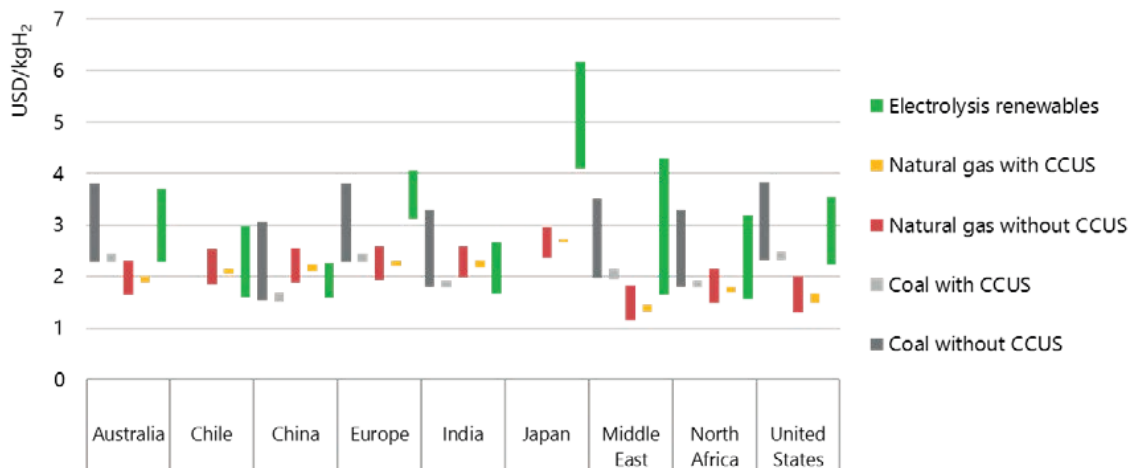


Figure 15 Costs of generating hydrogen in different parts of the world. [15]

2.2.2 Time for Green Liquid H₂ in Aviation

Since aviation produces CO₂ and non-CO₂ effects and engine and airframe manufacturers have been improving fuel efficiency with high OPRs, consequently elevating the temperature and pressure to the combustion chamber inlet. This has also had a knock-on effect of an increase in NO_x formation in the combustor. There has been a trade-off between low thermal NO_x combustor design at the expense of extra fuel efficiency.

Experimental aircraft using LH₂ were flown in the 1950's (Brewer 1991), more recently smaller aircraft have also been flown using hydrogen fuel cells. Hydrogen has three-four times the mass density as compared to Jet-A but contains approximately a quarter of energy density per unit volume than kerosene. (Mckinsey 2020)). This results in aircraft design with thicker wings, or the hydrogen fuel has to take up space in the fuselage. [17]. The 'Clean Sky' study (Mckinsey 2020) recommends that BWB designs will be required for longer ranges..[13]

Bicer and Dincer (2017) found that on the proviso that hydrogen is produced from low carbon or renewable sources, LH₂ powered aircraft compared well to their kerosene fuelled equivalents on a life cycle basis. Ramos Pereira et al. (2014) concluded that although there are many infrastructural barriers to the use of liquid

hydrogen in aviation but the environmental advantages of such a fuel use would be considerable.

Green LH₂ offers wider flammability limits as a fuel and can hence be combusted at a leaner FAR in the combustion chamber, this can lower the maximum temperature and with improved mixing and shorter ignition and residence times can significantly reduce NO_x emissions. This will, however, require a combustor re-design. Pollutant emissions like sulphur, soot, smoke, and aromatics are also eliminated, however, it will continue to contribute to contrail formation. [17]

2.2.3 Asia-Pacific Initiatives

In Hong Kong, the main international carrier, Cathay Pacific, has planned in achieving the net-zero carbon emissions target by 2050. The airline will be increasing the use of (SAFs). [19]

Japan has committed to the reduction of its greenhouse gas emissions by 46% for 2030 and reach net zero by 2050. Japan's strategies range from lifestyle and behavioural changes to floating offshore wind bases, making hydrogen with fossil fuels and nuclear energy.[20]

Australia has also committed to net-zero and has invested 20 billion dollars in low emission technologies such as cleaner hydrogen, CCUS and energy storage. Australia has set a solar electricity generation target of 15 dollars (10 USD) per megawatt hour. [21]

2.2.4 Challenges and Solutions of H₂ in Aviation

In 2018, Boeing flew a commercial airliner on 100% biofuel. Although biofuel is a SAF but its agricultural processes, collection and conversion into liquid fuel is carbon intensive as well as competing farming land area becomes a limiting factor.

Hydrogen propulsion is another option for aircraft flight but to have carbon-neutrality, the hydrogen must be produced either with renewable energy or with natural gas integrated with (CCS). [22]

Hydrogen has been demonstrated to work as an aviation fuel by Boeing with the first aircraft to fly on hydrogen power in 2008 (A Hydrogen fuel-celled single person plane) and then in 2012, a LH₂ powered (UAV). However, more research is needed to ascertain if the aircraft's structure and fuel tanks can be designed and built to fly as safely as the current airplanes in operation. Zero Avia has very recently, flown a hydrogen powered experimental aircraft and has a target of manufacturing (10-20) a passenger aircraft using hydrogen fuel cell propulsion system.

Apart from the challenges of a greater fuel weight, whether it be in liquid or gaseous form, there is the additional complexity of designing and making a lightweight vacuum-insulated tank that keeps the fuel around 20K.(See A-2.2.4). If a gaseous tank is being used then the greater pressure requirement of 250-350 bar will add even more weight. (Figure 17)

Although liquified hydrogen has 2.8 times the energy density as compared to kerosene (MJ/kg), it only offers a combined fuel and tank weight fraction (gravimetric efficiency) of 18% with recent storage designs. Kerosene on the other hand has a gravimetric efficiency of 78 percent, which is about 1.6 times greater, so for liquid hydrogen to be competitive with Jet-A the gravimetric efficiency must be at least 28%.

The aircraft fuel cells can be fuelled with LH₂, hydrocarbons, or ammonia. SOFCs offer a good option as they operate at high temperatures (around 800°C) compared to PEMs (100°C), this can be useful at high altitudes as lower air density reduces the heat removal potential and SOFCs with their greater temperature differential relative to the ambient air can facilitate heat rejection much better than PEMs., but the downside is that they weigh more, however for longer duration flights their higher efficiency can compensate for their additional weight. [22].

There would also be a greater surface area design requirement on a hydrogen fuelled aircraft which will increase aerodynamic drag.. This can be reduced by carefully modifying other parts of the aircraft. One possible solution is the BWB design. Fuel cells will also have lesser oxygen availability at high cruising

altitudes and the air would need to be compressed by using available propulsion power.

Gas turbines of today could combust hydrogen as a fuel with relatively few modifications; producing no CO₂ or soot but it will generate NO_x and water vapour as pollutants. Water vapour remains for longer at higher altitudes and will condense and precipitate as rain.

A LH₂ propelled aircraft will be required to meet equivalent standards of safety and integrity as those fuelled with Jet-A. There are many challenges with the technology that would need to be overcome, like inertness of the fuel tank, electrostatics during the fuelling process and the structural integrity of the tank. After which the next step would be to assess the performance of the aircraft and its efficiency. [22].

2.2.5 Siemen's PEM Industrial Electrolyser

The Siemens Energy electrolysis solution for making green hydrogen from renewables at an industrial scale is based on the PEM concept. It offers high efficiency at high power density to yield high-quality gas even at partial load, with low maintenance requirements and good reliability, and without chemical by products or impurities. It helps operators achieve scaling effects through a modular design that allows for large-scale industrial electrolysis with low CAPEX and low production costs. It has a power consumption of 17.5MW, an efficiency rate of 75% and an output between 100 and 2,000 kg per hour (335 kg/h per full module array). (Figure 16)

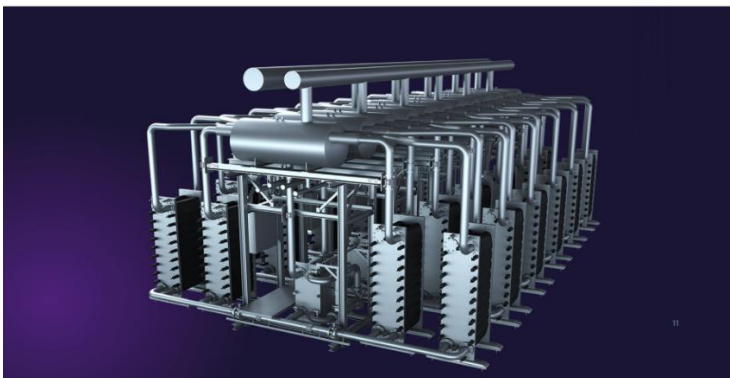


Figure 16 Modern PEM electrolyser for large-scale applications

The UAE (United Arab Emirates) currently sources about 2% of its electricity from renewables. In Dubai the (DEWA) and Siemens Energy are cooperating to generate a green hydrogen solar energy park using the Sylzer 200 electrolyser, (based on the PEM technology). The solar park has a site area of 127km² with a production capacity of 5000 MW planned by 2030, it will save a carbon emissions savings of 6.5 million tonnes per annum.

2.2.6 Storage

Hydrogen needs to be compressed for storage at high pressure in a gaseous state and liquified at lower temperatures (Figure-A2.2.4), these challenges have efficiency and cost implications. Hydrogen compressed at 700 bars has a density of 42 kg/m³ as compared to LH₂ which has a density of 70.8 kg/m³ with 120 MJ/kg LHV, which results in 8.5 GJ/m³. On the other hand, kerosene has 33.6 GJ/m³ with a density of 0.785 kg/m³ and 42.8 MJ/kg. [16] (Figure 17).

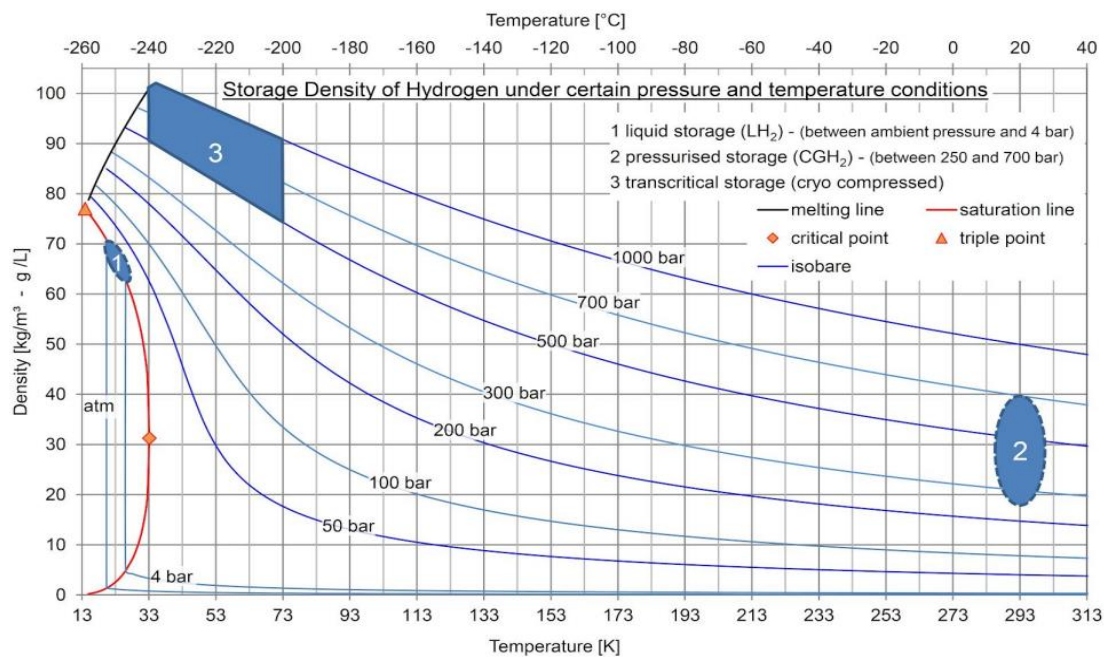


Figure 17 Hydrogen densities for storage at different temperatures and pressures [16]

LH₂ must be stored in separate tanks. As a consequence, this impacts the aircraft design requiring thinner wings and greater wing loading than conventional aircraft. The Airbus long range hydrogen powered aircraft is a BWB design. (See B-2.2.6)

Cylindrical tanks have a larger surface area than spherical ones, which will increase the material weight significantly. Additionally, during aircraft manoeuvres, a larger single tank would need baffles or partitions to control the liquid hydrogen from sloshing. Storage in a number of tanks is the most favourable combination of low weight and safe fuel storage while minimising LH₂ boil-off.

2.2.7 Boil-Off

Evaporation of liquid H₂ is a significant challenge for long-range international flights. The tank has to be insulated so the boil-off rate is kept under a manageable percentage e.g., 0.05% per hour. This can be achieved using vacuum insulated tanks, minimal point-contact supports and gas/liquid transfer coils and reduce the rate of heat transfer (Figure 18). However, this type of spherical storage tank isn't inscribable with civil aircraft fuselages architectures, furthermore, the best tank size and architecture will depend on the mission and should be evaluated in each case.[16]

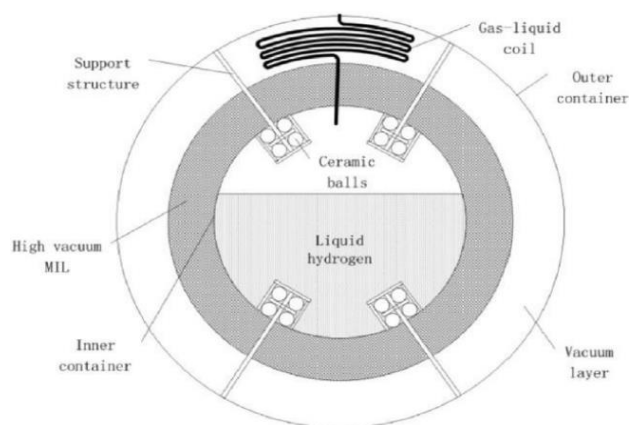


Figure 18 A spherical tank design with an evaporation per hour of 0.05%.[16]

The boil-off rates can vary with tank geometry but remain fairly steady and below fuel consumption rate even at idle/taxi thrust settings. Preliminary studies conducted by (Huerte, Pilidis, 2021, Singh.R, 2012.) has shown that LH₂ can be efficiently stored aboard the aircraft in tanks with gravimetric efficiencies between 0.77-0.7. Further optimisation of the tank may be possible with investigating

materials, dormancy time, venting pressure, tank ullage and number of tanks required for the aircraft under consideration. [23]

2.2.8 Factors Affecting Optimal Storage Tank Design

Integrating very large tanks inside the aircraft and keeping the weight as light as possible is a challenge for LH₂ storage, especially for long-haul international flights. Heat transfers increase the fuel temperature and hence the boil-off rate, while fuel extraction during operation reduces the temperature. Consequently, the remaining liquid fraction absorbs the heat and vapourises to occupy the space left by the extraction. During the tank design process, a balance between these two phenomena has to be achieved for a flight operation scenario. A larger surface area to volume ratio tank would provide a greater heat leakage and hence, may be suitable for aircraft with shorter duration missions, requiring higher mass flow rates.[24]

For long haul flights the design can either be based on a maximum tank temperature and pressure resulting in a thicker tank or a greater insulation thickness which will mean a heavier tank. On the other hand, if the design parameter is heat leakage then a decrease in surface area to volume ratio is required, this increases the tank diameter which in turn will elevate the hoop stresses and again thicker tank walls will result. A hydrogen tank with a gravimetric efficiency of 0.66 will be half the weight of a kerosene tank with the same inherent energy [24]. Optimum tank design has the maximum inscribable diameter for a particular aircraft.

When the maximum allowable tank gas pressure is reached (dormancy time), due to boil-off by the vaporisation of the liquid hydrogen into the empty tank space, at that point venting becomes necessary. For civil passenger airlines, the cruise fuel flow rate will reduce the tank pressure, and this must be controlled carefully by heat addition to avoid the pressure falling below the ambient value.

Vacuum insulated tanks offer a good solution for the initial stages of hydrogen usage as they can be divided into smaller ones with a smaller length to diameter

ratio, they also offer a longer dormancy time and venting may not be permitted at the airports. [24]

2.2.9 Mechanical properties and failure mechanisms of metallic materials under cryogenic hydrogen environments

LH₂ tanks are currently manufactured from austenitic steels 304 and 316, super alloy A286 (iron-based) or stainless steel and aluminium alloys 6061 and 7060. (Figure 23) and table (B-2.1).

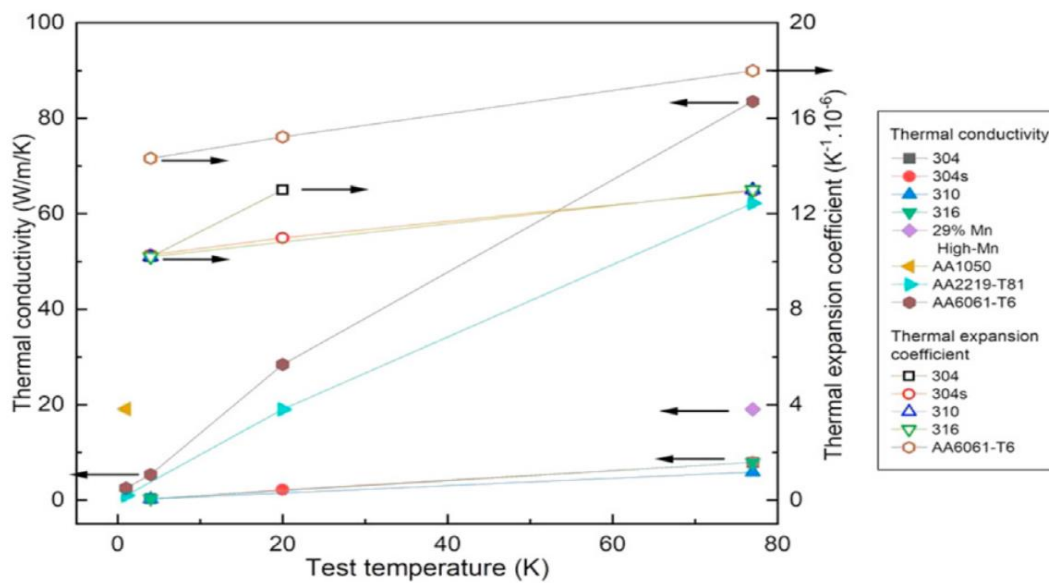


Figure 19 Thermal expansion and conductivity coefficients of austenitic steels and aluminium alloys at cryogenic temperatures. [25]

Austenitic steels have lower thermal and expansion coefficients than aluminium alloys and hence, austenitic stainless-steel tanks have better thermally stability.

2.2.10 Cryogenic temperature and hydrogen embrittlement

The failure mechanisms of cryogenic and hydrogen embrittlement are largely dependent on the chemistry and atomic structure of materials.

Embrittlement due to cryogenic temperatures

The ductile to brittle transition of metallic materials is dependent on the chemical composition at cryogenic temperatures. Cryogenic temperatures induce cleavage-like intergranular cracks and brittle transgranular fractures at cryogenic

temperatures. This induces cleavage-like intergranular fracture and brittle transgranular fracture at cryogenic temperatures.. Grades of austenitic stainless steels 316 and 316L with a greater composition of Ni are good at maintaining ductility and toughness.[25]

Embrittlement due to hydrogen

The fracture toughness and/or ductility of metallic materials can be degraded due to the presence of atomic hydrogen, which is called hydrogen embrittlement. Hydrogen environment embrittlement, hydrogen reaction embrittlement and internal hydrogen embrittlement can occur. (Figure 20) illustrates the relationship between the hydrogen embrittlement influencing factors.

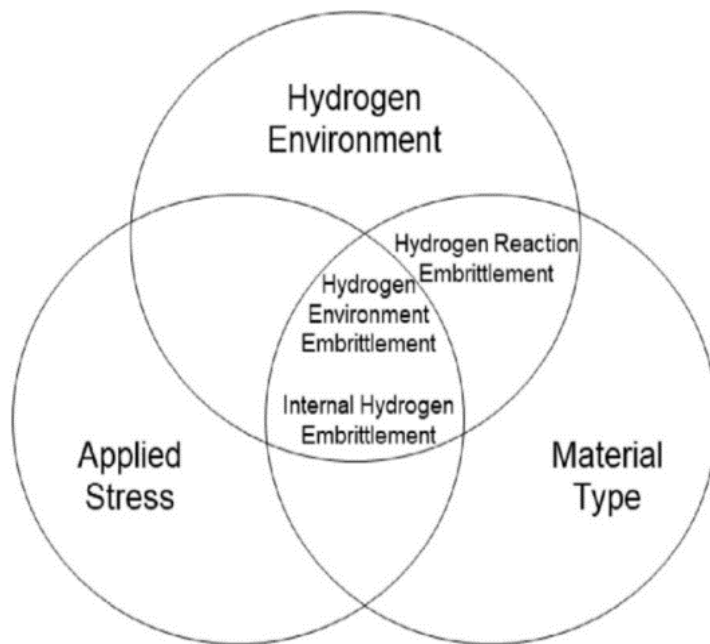


Figure 20 Factors affecting hydrogen embrittlement mechanisms. [25]

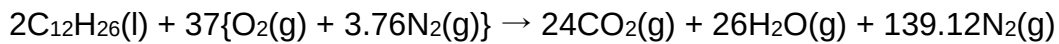
Stainless steel of the type 316 austenitic stainless steel is also resilient against hydrogen embrittlement and retains 70% of its elongation in air as seen under a hydrogen environment.

(Figures A-2.3a and 2.3b) show the Electron Microscope surface scans of the transgranular cracks and dimple rupture in austenitic stainless steel of type 316 in 10 bar hydrogen at 200K. [25]

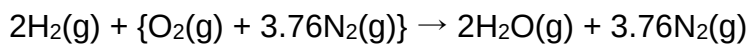
2.2.11 Combustion

Although conventional jet engine combustors can run on hydrogen fuel, they are not designed for hydrogen and consequently affect the performance adversely. This due to variances in the fuel-air-ratio for the kerosene and hydrogen.

Kerosene:



Hydrogen:



Hydrogen can flashback and also produces much higher flame temperatures which can generate higher NO_x emissions.[26]

The combustion of hydrogen is more complex and not only the (FAR) has to be adjusted for but also the combustor geometry has to be re-evaluated. Conventional combustor geometry is inadequate in mixing the hydrogen fuel and air effectively. Hydrogen combustion produces large diffusive flames allowing the formation of stoichiometric ratios around the flames and hence, inducing higher NO_x emissions. But hydrogen also burns with greater stability than kerosene at leaner equivalence ratios, and the attainment of stoichiometric conditions (Figure 20) can be mitigated against due to this useful property. (Figure 19), This would also be accompanied by increasing the mixing to eliminate local hotspots.[24]

Thermal NO_x is produced via the three main reactions as described by the Zel'dovich mechanism. The third reaction as proposed by Lavoie, Haywood, and Keck, where the atomic nitrogen reacts with the hydroxyl radical makes a significant contribution to thermal NO_x production.

1. $N_2 + O \rightleftharpoons NO + N$
2. $N + O_2 \rightleftharpoons NO + O$
3. $N + OH \cdot \rightleftharpoons NO + H \cdot$

For effective hydrogen combustion all parameters must be evaluated during combustor re-design including high flame speeds, cryogenic temperature, flame stability, residence time, combustion efficiency and acoustics.

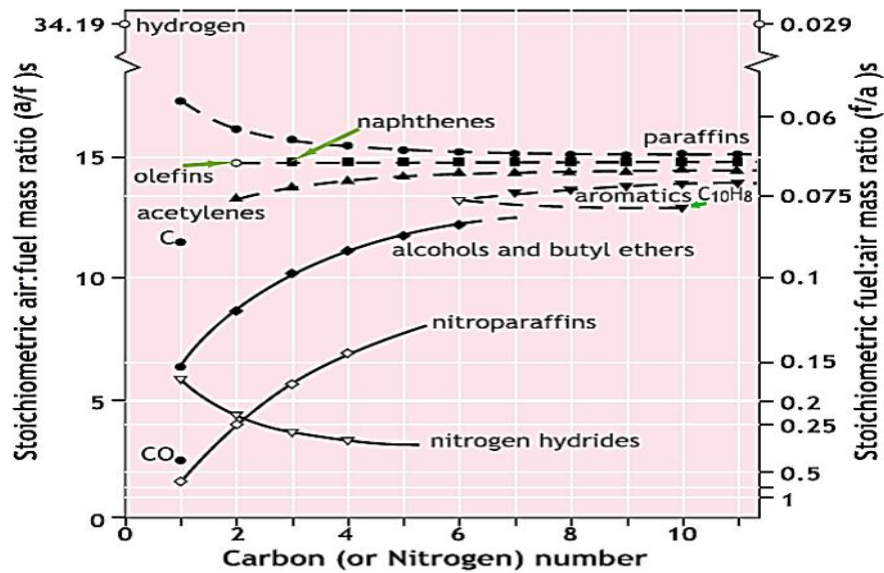


Figure 21 Stoichiometric air: fuel mass ratios for hydrocarbon and substitute fuels.[26]

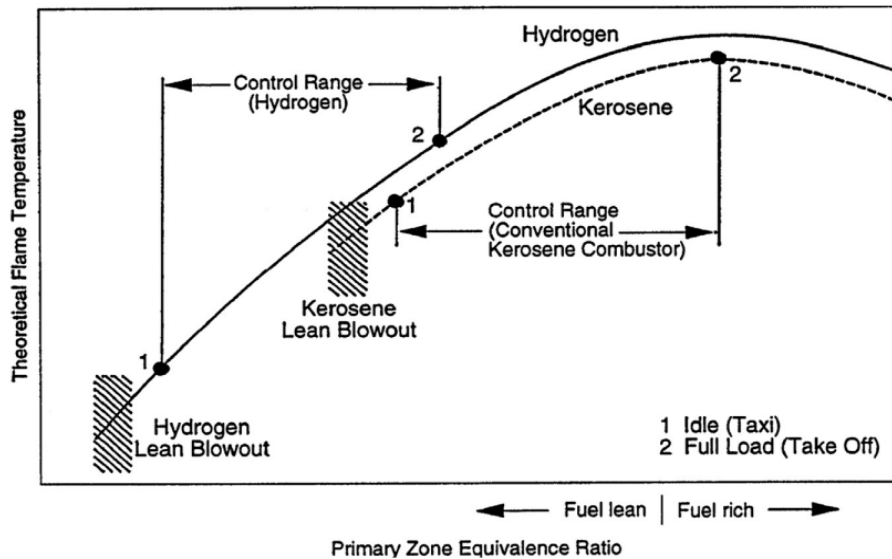


Figure 22 Temperature characteristics hydrogen and kerosene. [24]

Lean Direct Injection (LDI) and micro-mix combustion methods are the two most viable currently, that can improve local mixing of flows and lower the equivalence ratios and avoid the formation of hotspots and eventual higher NO_x emissions.[24]

2.2.12 Safety

Cryogenic hydrogen has low ignition energy and a higher volatility, it also has a lower flame emissivity or a higher lower flammability, hence, liquid hydrogen is more dangerous in confined spaces and less damaging in open air. This presents the ideal premise of placing the tanks outside the passenger cabin. Overpressure may lead to leak of the tank or component, which represents a combustion hazard. A high ignition energy source in partial confinement can turn deflagration into detonation.

Material failure due to excessive pressure and leaks as well as hydrogen permeation and embrittlement and heat leakage due to conduction, convection and radiation can lead to storage tank failure.

Since the adiabatic expansion energy of LH_2 is 6 to 15 times lower than GH_2 , hence, a lesser amount of stored energy will be given out in a short period of time. This means that LH_2 methods can allow a potential higher standard of safety in case of sudden pressure tank failure during refuelling. [25]

2.2.13 Transportation

There are some challenges associated with storing LH_2 aboard ships for transportation, these mainly arise from hydrogen molecules getting absorbed into the tank material and becoming atomic hydrogen which can then move across the lattice structure and cause mechanical deformation (environmental embrittlement). There is also cryogenic embrittlement due to low temperature. [25]

Hydrogen can also be transported from a central storage facility to the aircraft via trucks. Shorter transport distances would be appropriate as many trips would be required to take the cryogenic hydrogen as it has a third of the volumetric energy density than that of kerosene, although this would be more cost-effective than a pipeline distribution network the cost would be higher than that of kerosene transportation due to the increased cost of the cryogenic tank and multiple/larger fuel trucks.[25]

2.2.14 Hong Kong's Maritime Routes

Hong Kong's maritime shipping lanes are well established and interlinked to the road transportation network. This would make it easier to transport hydrogen from the production sites to HKIA. (Figure 23 and 24). [26,27]



Figure 23 Hong Kong's shipping channels and marine transportation logistical infrastructure. [26]

HySTRA have recently (2019) launched the first liquid hydrogen carrying ship in Japan (Figure-A2.2.13). It has a capacity of transporting 75 tonnes of LH₂. It has a single tank with a capacity of 1250 m³ of liquid hydrogen. The tank is constructed with an evacuated MLI (multilayer insulation). [70]



3 Hong Kong's Renewable Energy Production Potential

3.1.1 Wind

Analysis of the wind power potential was modelled and assessed in Hong Kong using LiDAR technology. The power yields for an offshore wind farm were calculated using the WAsP2 program were confirmed. Results showed that the offshore wind power potential in Hong Kong was 14,449 GWh, which is equivalent to 32.20% of electricity usage in 2017. (Figure 25). [29]

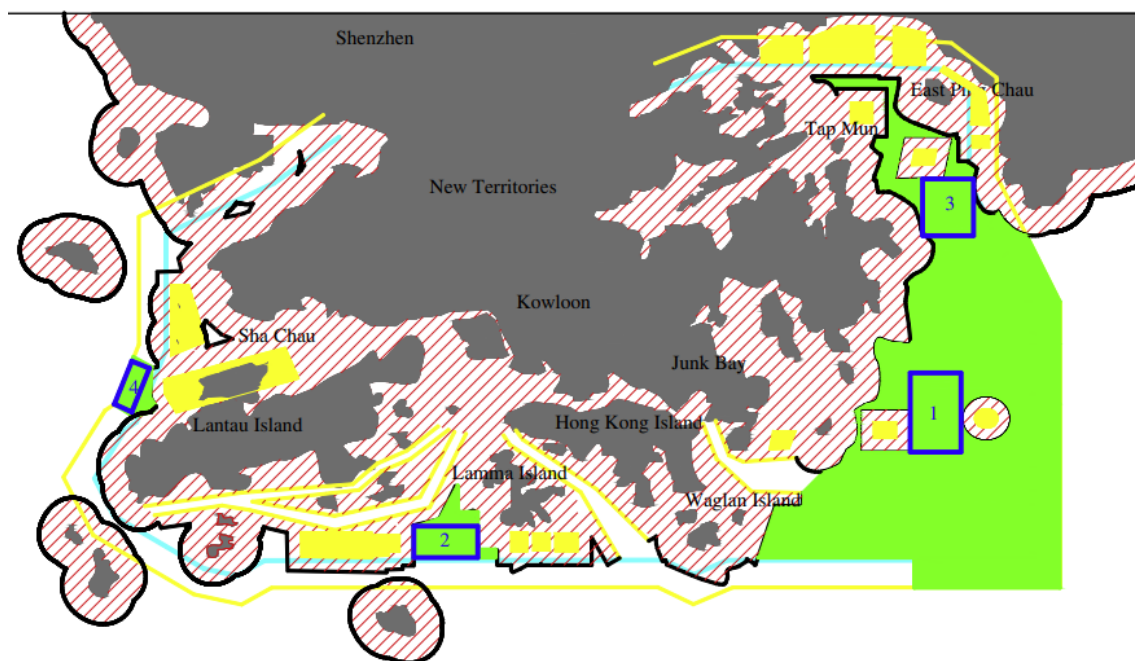


Figure 25 Four potential OSWF locations modelled for Hong Kong.[30]

The theoretical offshore wind farm in (Figure 25), numbered No 2. was chosen for an assessment into Hong Kong's offshore wind power potential. A maximised number of 25 wind turbines (at 5MW each) were simulated in the wind farm architecture. The results yielded an annual power of 5.78×10^8 kWh, at a cost of energy of 1.55 HKD/ kWh. According to this the total annual offshore (including sites at 1,3 & 4) wind power potential in Hong Kong was calculated to be 14,449 GWh, this is 58.6% of the total transport energy consumption. (Figure A-2). Furthermore, after the consideration of wind farms in rural areas the estimated

potential in Hong Kong was 2630 GWh/yr., given that the total area of a higher wind resource potential in Hong Kong is about 393 Km².

A study was conducted where wind flow over high-rise buildings was investigated. This research showed that over 300,000 buildings in Hong Kong with a height of 65m and above had the potential of producing wind power. The available power was estimated to be between 2 and 3TWh/yr. [31]

The Hong Kong, End-use Data 2019 indicated that the total RE (Renewable Energy) was 2,442 TJ with a weighting of 0.9% (Table-B.2) and the RE weighting in electricity consumption was only 0.3%.

3.1.2 Solar

In Hong Kong solar energy has been identified as an appropriate renewable energy resource for wide-scale applications. PV and SWH technologies are attractive options. The annual global radiation in Hong Kong ranged from 4392 MJ/m² in 1978 to 5408 MJ/m² in 2022 with a mean value of 4820 MJ/m².

The annual mean daily total global solar radiation in 2019 varied from 10.6 MJ/m²/day in February to 16.0 MJ/m²/day in July. This data suggests that the global radiation is appropriate to facilitate the use of wide-scale solar application.[33].

The research proposes to apply PV systems in industrial, commercial, and residential sectors, since these were the major electricity end-users, demanding 67% and 27% of the total electricity consumption.[34]

After considering wide-scale applications of PV (including BIPV) and (SWH) systems in Hong Kong, the annual useful energy output is calculated to be 46,270TJ, this is equivalent to about 30% of entire electricity consumption for buildings in Hong Kong for the year 2019. This would reduce the annual greenhouse gases, SO₂, NO_x and RSP by 10,960, 7.2, 10.8 and 0.4kt respectively.[35]

3.1.3 Biomass

Biomass is CO₂ neutral in a complete life cycle, it is also readily available and easy to use. Biomass can be used to produce hydrogen using either thermochemical conversion or by biological hydrogen production. The former includes pyrolysis and gasification, and the latter can either utilise direct or indirect biophotolysis. Other accompanying processes are water gas shift reaction, photo fermentation and dark fermentation.

Thermochemical pyrolysis involves the heating of the biomass (usually liquid oil, gas compounds or charcoal) to temperatures in the range 650K-800K and under a pressure of 0.1-0.5MPa. In gasification, the biomass is partially oxidised by heating it at 1000K and the product gasses are steam reformed to generate hydrogen following a water gas-shift reaction.[32]

3.1.4 Current Hydrogen Production in Hong Kong

Renewable energy is a very promising technological option for Hong Kong in producing green hydrogen, although wind power and solar PV and BIPV panels wouldn't satisfy the entire energy consumption of Hong Kong but can potentially reduce the carbon emissions significantly.[32].

It has been found out in a study in China conducted for a coastal city that with the rapid advancement in solar and wind power technologies, there is an improved production potential for hydrogen. Wind power costs per kWh are lower than those of solar power. Energy required for producing 1kg of hydrogen reduced from 55.6 kWh/kg in 2017 to 44.5 kwh/kg. [39]

The potential of hydrogen production from other clean power sources such as hydro-electric power and nuclear power can also be considered by the policymakers as the development and maturity of technologies for hydrogen production like nuclear thermochemical water splitting cycles, solar thermochemical water splitting cycles and photoelectrochemical cells gets improved.[32].

4 Current Green Hydrogen Hub Initiatives for Aviation

4.1 The Hamburg Green Hydrogen Hub

As of 2025, the former Moorburg coal-fired power plant in the port of Hamburg will be used to generate hydrogen from green electricity. A capacity of 100 megawatts is planned from the outset and is to be increased as demand grows. The main customers for the green hydrogen will be the industries based around the port, alongside mobility providers.[40]

4.2 Hydrogen Infra-Structure Design for Moorburg and UAE

The Moorburg site is ideal for this project: it offers short distances to the port and a direct connection to the existing and planned infrastructures such as the gas grid on the user side. On the supply side, it is also connected to both the national 380,000-volt transmission grid and the 110,000-volt grid of the city of Hamburg. In addition, overseas vessels can dock directly at the site and use the quay and port facility as an import terminal. The existing 45 km gas network will be suitable for hydrogen by 2025 and expanded to 50 kilometres and then to 60km by 2030.[41]

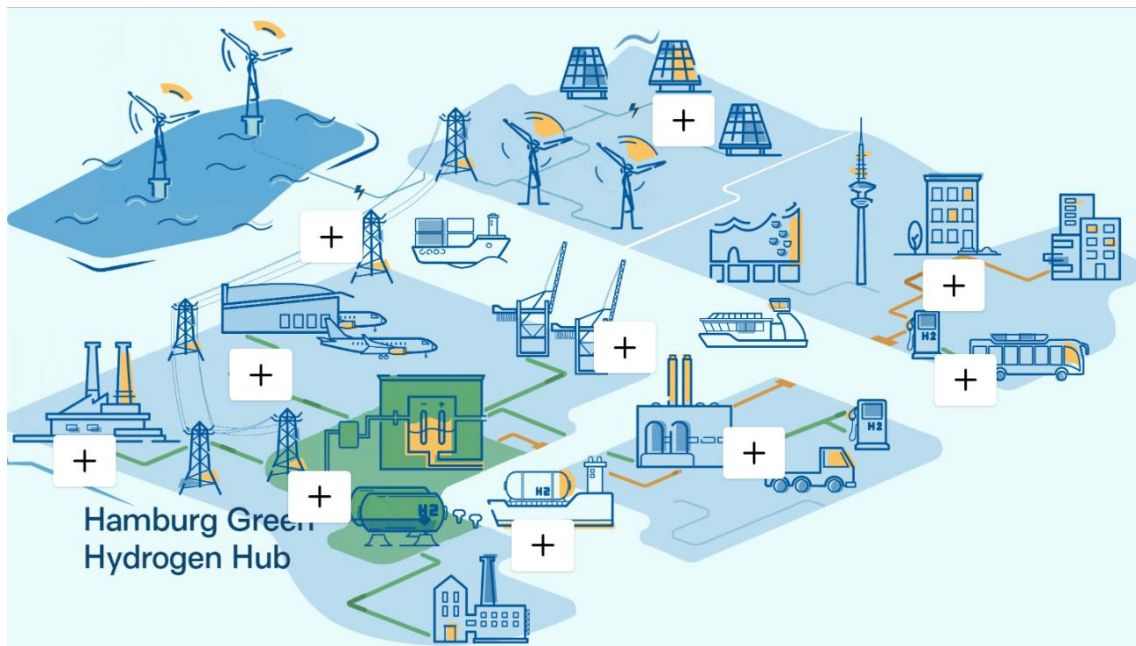


Figure 26 A Green Hydrogen Hub for Moorburg. [41]

5 Methodologies

5.1 Turbomatch Engine Modelling Methodology

1. A three-shaft turbofan engine (based on the Trent-XWB-97) with separate nozzles was modelled in Turbomatch (Kindly see Figure 1 below), HP and IP turbine cooling bleeds were incorporated into the model.
2. An iterative process was used to determine the correct mass flows, COTs, TETs, compressor pressure ratio's, Overall-pressure ratio, compressor and turbine efficiencies, surge margins, turbine cooling bleed flows. (Please see tables 5&6)
3. Simulations were conducted for DP (Cruise) and ODP (Take-Off) conditions, for determining the ESFC for each engine, specific thrust, nozzle areas, mass flows and jet velocities of the core nozzles, for comparisons between the kerosene and hydrogen engines. The three different engines had the same BPR, OPR and intake mass flow, where one was run on kerosene and the other two combusted hydrogen one with a fixed COT and the other with a constant NT were simulated for design point and off-design point conditions. (Please see Figure 40 and Tables 6 &7)
4. An intercooler was added to the baseline model (Please see Figure 2 below) between the IPC and the HPC. The primary purpose of it was to obtain a total temperature at its exit. This will evaporate the cryogenic hydrogen to acceptable pre- combustion temperatures for both DP and ODP flight conditions.

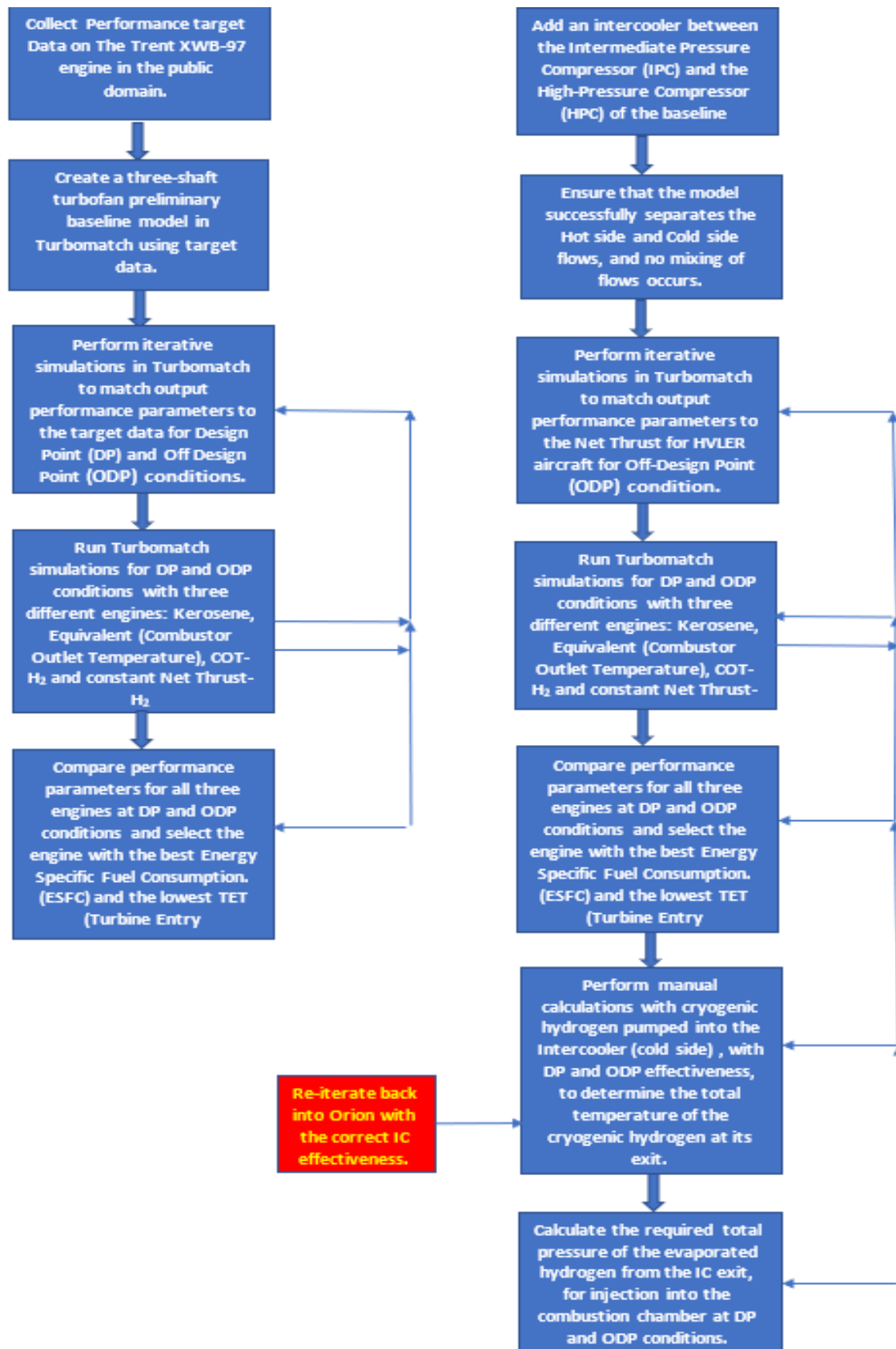


Figure 27 Turbomatch engine modelling methodology. [55-62]

5.2 Orion Aircraft Performance Modelling Methodology

The Orion aircraft performance code is an in-house Cranfield University MATLAB program which uses the Turbomatch engine simulation input file, and an aircraft model program, all incorporated in the Orion input file to calculate aircraft and performance parameters and the installed engine performance outputs. The baseline and intercooled Net Thrust Engine Orion input files are shown in, (E-7.1).[66]

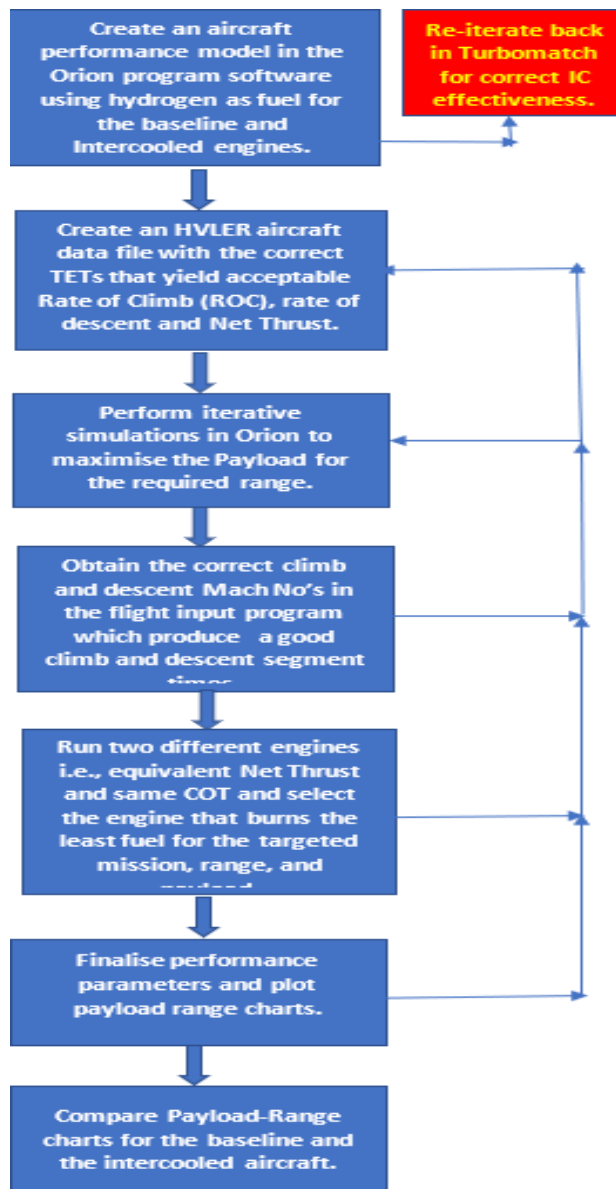


Figure 28 Orion Aircraft Performance Model Methodology.

5.3 Green Hydrogen Production Methodology

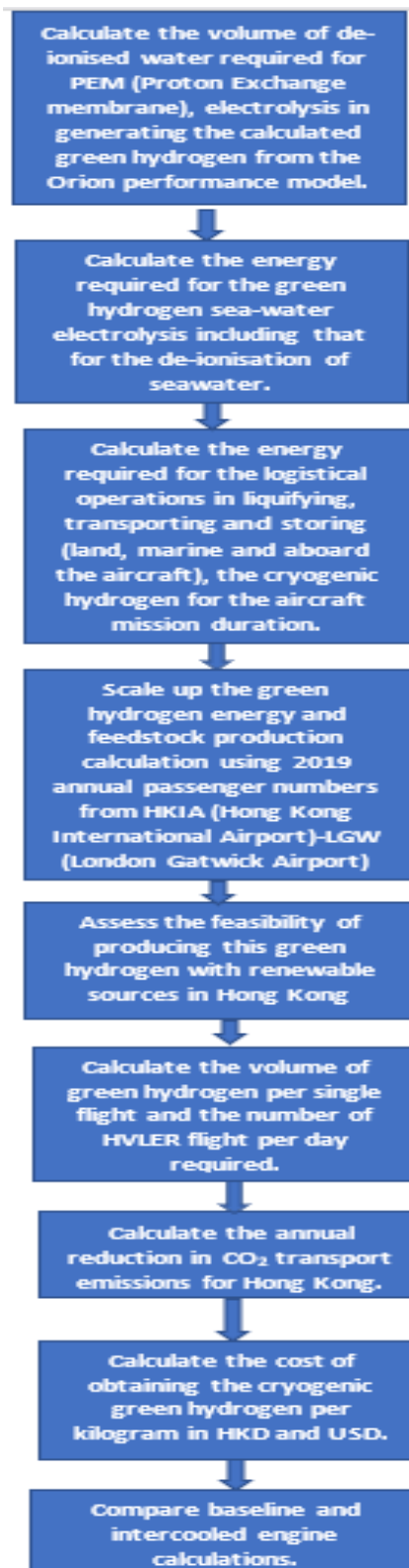


Figure 29 Green Hydrogen production feedstock, energy, cost, and carbon footprint methodology.

6 Aircraft Engine Modifications for Hydrogen Usage

6.1 Rationale For Baseline Engine Selection

This thesis uses the HVLER Cranfield University derivative design hydrogen aircraft proposed by (Huete. J Nalianda. D and Pilidis. P) as part of the first innovation wave as detailed in [30]. The aircraft performance software Orion, which is a bespoke program developed by Cranfield University was used to model the HVLER baseline and intercooled aircraft running on kerosene and hydrogen fuels respectively.

The HVLER aircraft integrates the airframe of a A380 with the wings of an A350-1000, long range twin-engine aircraft with the Trent XWB turbofans.[28]

The Hong Kong's national carrier Cathay Pacific operates 43 A350 aircraft and HKIA can accommodate both A380 and A350 aircraft on its runways.



Figure 30 HVLER Hydrogen aircraft concept. [30]

6.2 The Trent-XWB-97

The Trent XWB-97 engine has been designed exclusively to power the Airbus A350-1000 aircraft. It is a high bypass ratio of 9.6:1 and an OPR of 50:1, an axial flow turbofan engine, it has a three-shaft layout with a 3.00 m fan and IP and HP spools with 8 and 6 stages respectively. The engine has three turbines which drive the compressors with a 6-stage LPT, a 2-stage IPT and a single stage HPT. It has an annular combustor.[45]

The engine length is 5.812m with a Dry Weight of 7,550 kg with a Thrust-to-weight ratio of 5.82. It has a Net Maximum Continuous thrust of 431.5 kN and a cruise TSFC of 13.5 g/kN.s.



Figure 31 Airbus A-350 aircraft with Trent XWB engines.[46]



Figure 32 A380 Aircraft airframe.[46]



Figure 33 The Trent-XWB-97 Engine. [43]

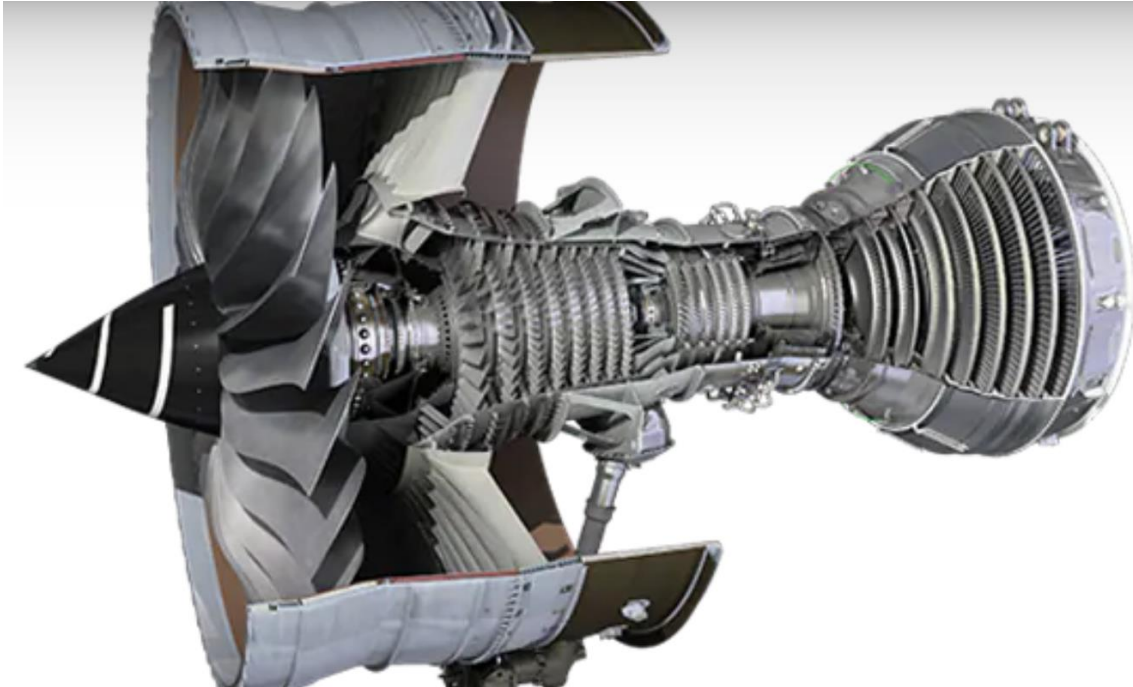


Figure 34 Trent-XWB-97. [42]

6.3 Intercooler Engine Technologies for Jet Engines

6.3.1 The Intercooled Cycle

The function of the intercooler is to remove thermal energy from the first compressor and thus reducing the temperature of the air entering the second compressor, this lowers the work required by the second compressor, consequently, increasing net thrust while keeping the same turbine work requirement. (Figure 32).

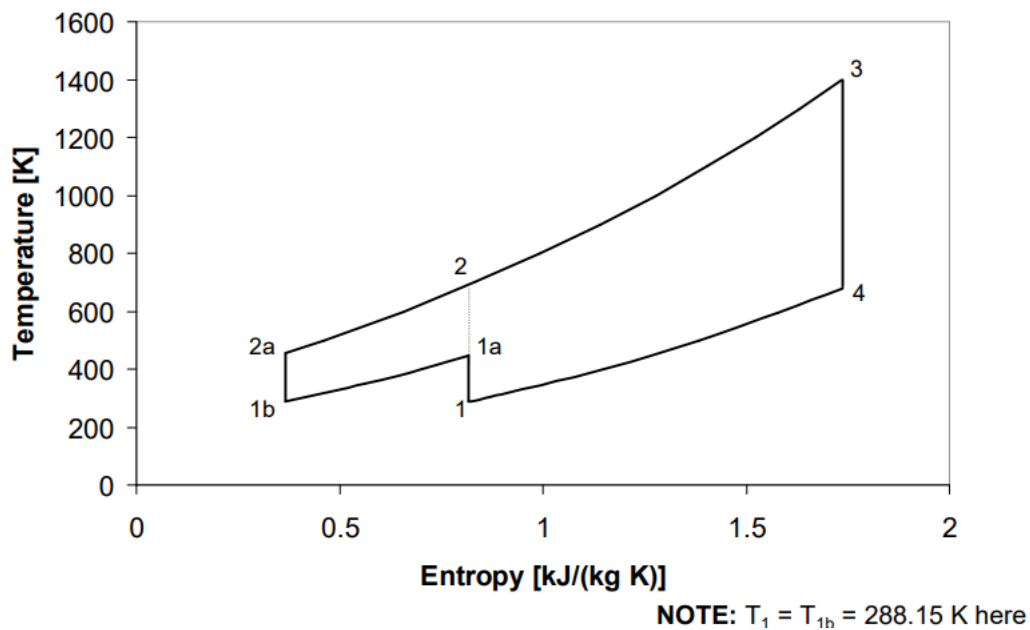


Figure 35 The Ideal Brayton cycle with an intercooler. [53]

Therefore, intercooling will increase the specific work or net thrust of the cycle. The downside of intercooling is that the air entering to the combustor will be cooler, thus extra heat addition via an increase fuel flow will be required. The greater work/net thrust obtained from the cycle will be less than the extra heat addition, and hence, fuel consumption will go up. (Figure 33). [53]

GAS TURBINE CYCLES - INTERCOOLING

Image courtesy of Rolls-Royce

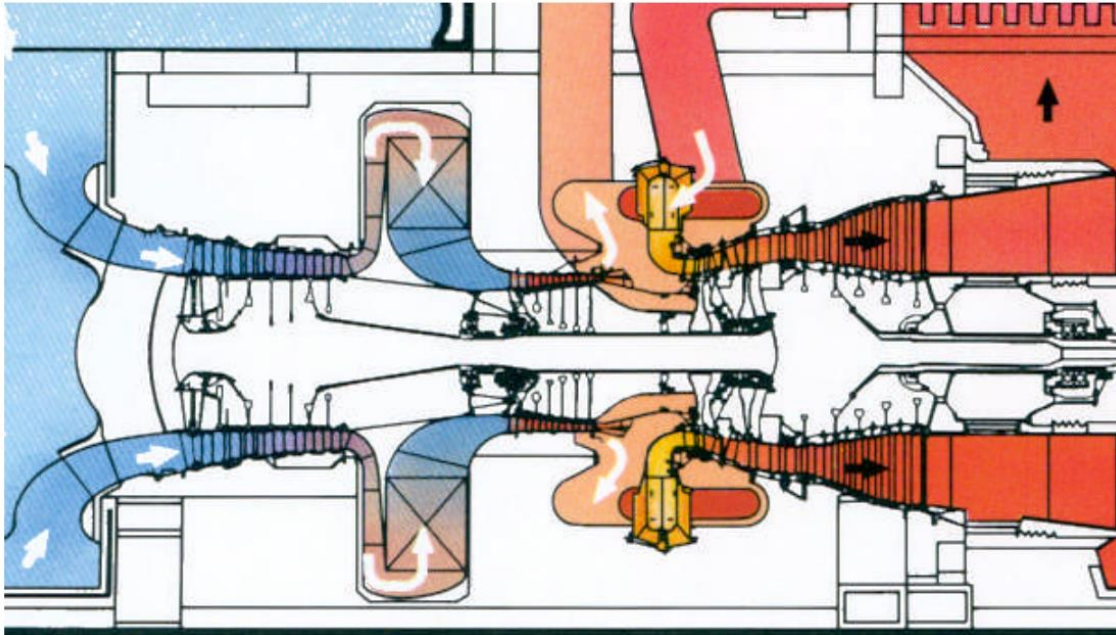


Figure 36 An Intercooled gas turbine. [53]

The improvement in gas turbine technology has meant an increased OPR and TET. This has made intercooling of great interest as an alternative technology option in elevating the OPR and TET by the cooling of the HPC delivery air. T-S diagrams are shown below. (Figures 34a and 34b)

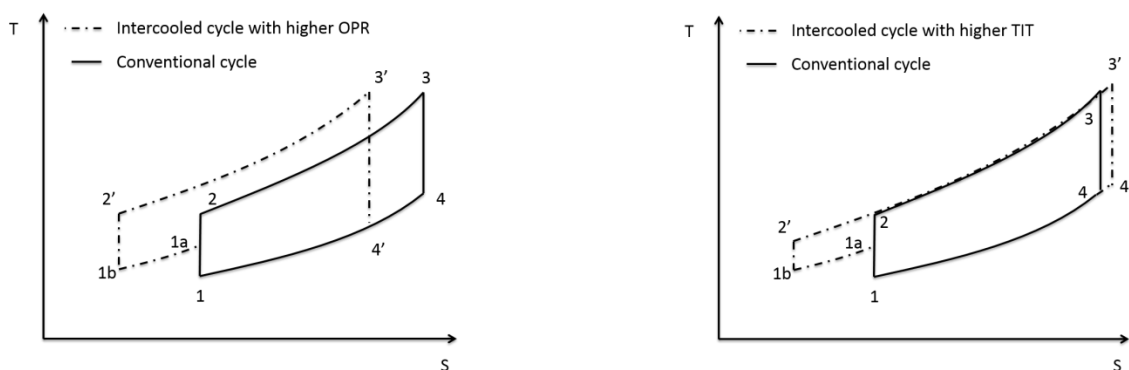


Figure 37a and Figure 34 b Intercooled cycles with higher OPR and TET. [47]

This makes intercooling a prime candidate for a greater energy efficiency as well as the potential for lower NO_x emissions.[47]

The following advantages could be harnessed with the use of intercooling:

- (a) A cooler HPC delivery air can lead to higher OPR and lower TET.
- (b) A low specific thrust would reduce the engine core and hence provide the opportunity for a higher BPR.
- (c) A potential to reduce NO_x emissions with lower flame temperatures.

It is recommended to aim for a compact intercooler design since a larger intercooler will add to nacelle drag with an increase in the engine diameter, impart greater pressure losses through the intercooler, impact the length of the shafts and effectively add to the weight of the engine. These design drawbacks have the potential of negating the positive benefits on the use of an intercooler.

The position of the intercooler between two compressors provides the most thermodynamic benefits and is preferred due to less complexity required in its installation.[47]. Intercooler use during the flight envelope especially for ODP and DP conditions as well as during climb operation is also a key in minimising the fuel burn, since these require varying intercooling demands for an intercooled aeroengine.[52]

6.3.2 Heat Exchangers in Aero-engines

Aero-engines require compact heat-exchangers, FTHEs are recommended for aero-application use. These can internally consist of tubes and /or fins, which could be elliptical or circular, or flat shaped, fins could be flat, rippled, or discontinuous. Since aero-engine flows require high pressure, circular fins are an excellent choice for the intercooler. Flat fins provide a balanced choice as although ripple fins are capable of higher heat transfer rates, they have greater pressure losses than flat-finned intercoolers.[49]

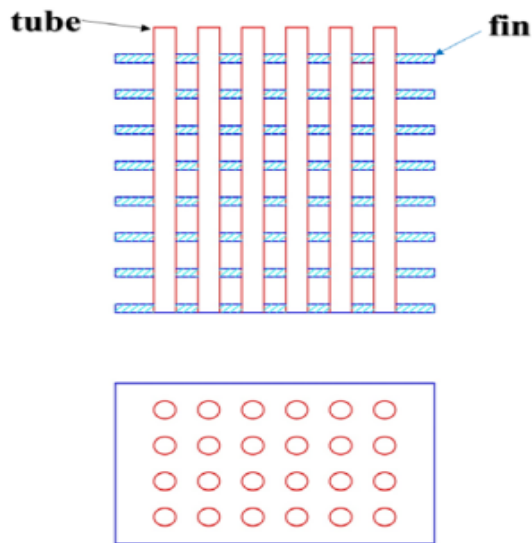


Figure 38 Fin tube heat exchangers

The intercooler has one cold-side and a hot-side, for an aero-engine, cooler airflow from the outer engine duct flows through the cold-section and the hot air flows from the post-compressor air into the hot-section of the intercooler. The thermal heat transfer occurs as both flows go through their respective sides. The medium can be air-air or cryogenic hydrogen-air. (Figure 36). Heat is transferred from the hot side to the cold side until steady state conditions are achieved.

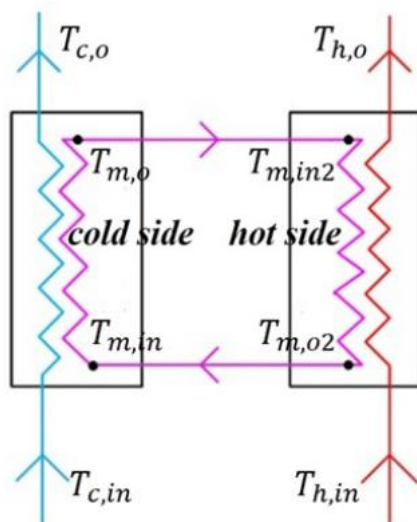


Figure 39 Heat exchange system. [49]

Although the design of the intercooler is not part of the objective for this thesis, only a simple aspect of the calculation on the performance is performed in the calculation of the outlet temperature from the cold side of the intercooler. Pressure losses and heat effectiveness were taken from literature and not modelled.

Equations (6.1)(6.2)(6.3)(6.4) were used to calculate the intercooler, hot side and cold side outlet temperatures post design point and off design point Turbomatch performance simulation output results. [49]

$$C_c = WC_p \quad (6.1)$$

$$T_{m,m} = \frac{T_{m,in} + T_{m,o}}{2} \quad (6.2)$$

$$q = \epsilon(T_{m,in} - T_{c,in})C_{min} \quad (6.3)$$

$$T_{c,o} = T_{c,in} + \frac{q}{C_c}, T_{m,o} = T_{m,in} - \frac{q}{C_m} \quad (6.4)$$

$$\epsilon = \frac{q}{q_{max}} \quad (6.5)$$

6.4 Recommended Intercooler for the Trent-XWB

An intercooler was simulated for both the Jet A fuel and the liquid hydrogen fuelled engines. The objectives for integrating the intercooler between the IPC and HPC were as follows:

1. Research shows this position of the intercooler gives the most performance benefits in Net Thrust and ESFC.
2. To vapourise the LH₂ flowing from the storage tank by injecting it into the cold side of the intercooler.
3. To raise the temperature of the vapourised hydrogen sufficiently enough that it wouldn't be too detrimental to the combustor performance for both design point and off-design point conditions.
4. To increase the net thrust of the engine required for the HVLER aircraft take-off condition. Without further increasing TET.

5. A lower COT as well as potential for a lower combustion chamber flame temperature possibly resulting in lower NO_x emissions.
6. The lower TET achieved would require less cooling air to the NGV and HPT, hence a longer blade life, also and this cooling air can be diverted to augment thrust.

Literature studies have shown intercooler weight estimation and sizing for comparable engine to the Trent-XWB. Figure 37 shows the engine and nacelle dimensions.

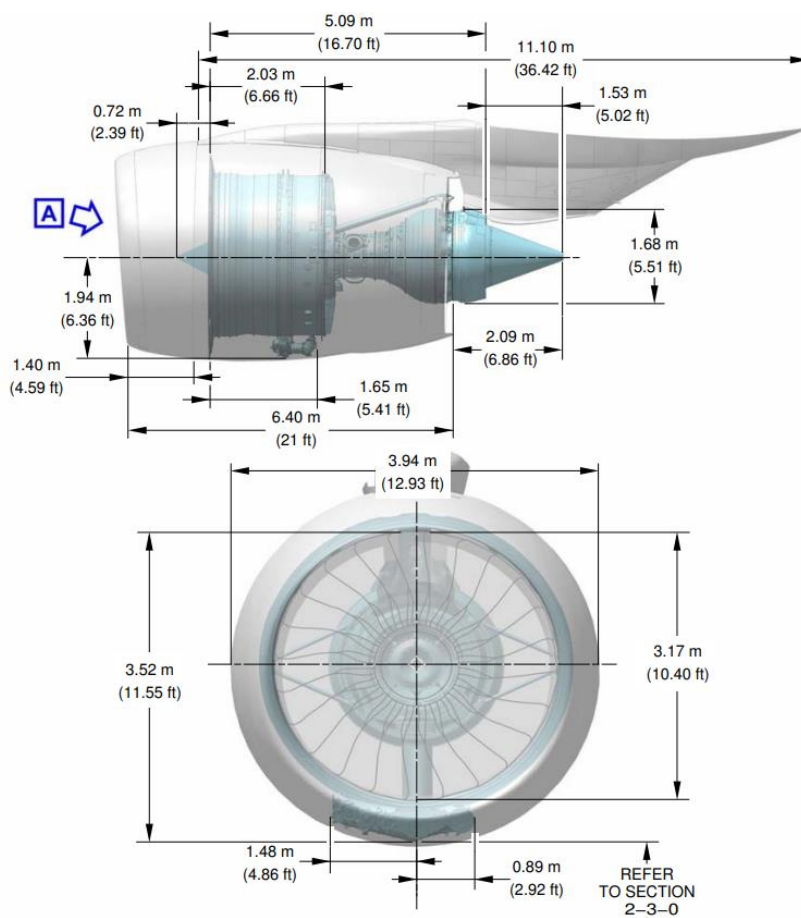


Figure 40 Trent-XWB Engine and Nacelle dimensions. [54]

A very few studies have been conducted on the weight estimation of a three-spool high bypass turbofan engine intercooler, although the estimation of the intercooler weight is not a focus of this work, according to the literature a value 400 Kg will be assumed and the associated accessories of pumps, valves and

pping will also be assumed amassing a total added weight to the engine of 500kg. [49]

Performance assumptions were made based on design data and experimental results in literature, with the intercooler effectiveness and pressure drop for the cold and hot sides. [52]

Intercooler effectiveness is defined as the inlet and outlet temperature differential divided by the difference between the overall maximum and minimum temperatures entering and leaving the intercooler. There are trade-offs in design methodologies between choosing higher effectiveness on one hand and selecting higher cost, weight, nacelle drag and pressure losses on the other hand.

Air pressure drops vary for ODP and DP conditions. Heat effectiveness greater than 0.5 requires a pressure drop between 4-14%, while for a greater effectiveness of 0.6-0.8 this ranges between 6-15%

Annular inter-connecting ducts (ICD) can be used to connect the intermediate-pressure compressor to the high-pressure compressor. (Figure 38)

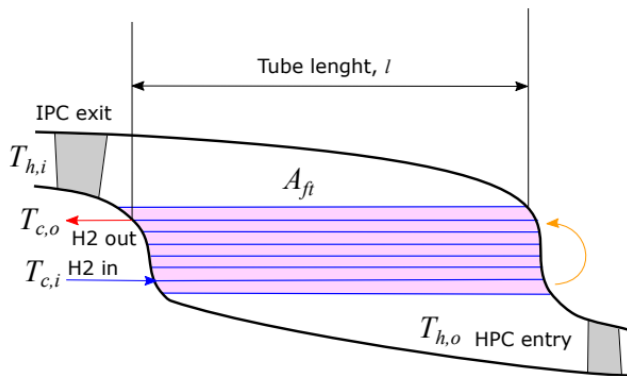


Figure 41 A cross-sectional view of the interconnecting duct for a compact hydrogen heat exchanger.[50]

To meet the temperature limits of ASME B31.12 (Standard on Hydrogen Piping and Pipelines), austenitic (300 series) stainless steels are recommended for piping in gaseous and liquid hydrogen services. Type 316/316L is the most stable grade with relatively high resistance to hydrogen embrittlement when exposed to high-pressure hydrogen.[50]

6.4.1 Intercooler performance assumptions

Parameter	Design Point (Cruise)	Off-Design Point (Take-Off)
Effectiveness	0.6	0.755
Hot-side pressure loss	6.5%	6.5%
Cold-side pressure loss	6.0%	10.0%

Table 1 Intercooler performance assumptions. [52]

6.4.2 Fuel Distribution System

The main task of the fuel systems for Jet-A or the cryogenic fuelled aircraft is to deliver the fuel either kerosene or H_2 with the appropriate pressure and temperature to the combustion chamber with the required fuel flow for the operating condition.

(Figure 39), below shows such a system, vapourised H_2 will be injected into the combustion chamber after pressurisation by the fuel pumps to a pressure that is 5% higher than the combustion chamber total pressure.[51]

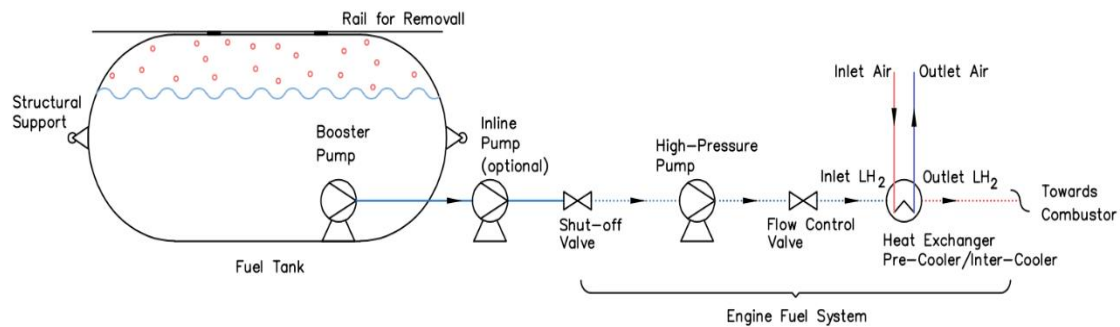


Figure 42 A diagram illustrating the fuel distribution system for cryogenic hydrogen.[51]

To conform to the weight constraints of the HVLER aircraft a recuperator and pre-cooler were not modelled for our particular thesis.

7 Engine Performance Simulations and Assumptions.

The Trent-XWB engine data was obtained from the documents in the public domain, these numbers were used as a starting point e.g., the TSFC for Design Point (Cruise), the OPR, BPR, altitude of 10668 m at a Mach No. of 0.8. (Tables 1 & 2).

The three-shaft baseline engine architecture was setup using the Turbomatch 3.0 (GUI) with an intake, three compressors, a combustor and three turbines with one separated hot nozzle and one cold nozzle. (See Figure 43). These were represented as bricks in the software and were given station numbers and initial values were added to each brick before running the code. (See Table 4)

Initially, the Kerosene engine was modelled using the Turbomatch 3.0 (GUI) software for the Off-Design Point condition (Take-Off). The compressor Pressure Ratios were first fixed to achieve an OPR of 50:1. The Fan PR and compressor and turbine efficiencies were also iterated for and kept at realistic values. (Tables 3 & 4).

The Net Thrust was reduced using the High-Pressure Turbine cooling flow from the HPC and was adjusted by setting the cooling flow at a value of 20.1 %.

The TET value stated in [55] for Take-Off condition for Kerosene was used as a starting point. Iterations were performed as a multivariable parametric analysis and the Net Thrust was attained with adjustments in TET and intake mass flow. There were engine bleeds for cabin air-conditioning, nacelle and wing anti-icing bleeds for the Take-Off and Cruise according to [55], these were not included in the model to keep it simple as later the intercooler was to be added.

Baseline Engine Performance Parameters at SLS ISA Conditions

Parameter	7 th Iteration Engine Data	Target Engine Data
Net Thrust (kN) – Take-Off	431.5	431.5
TSFC (g/kN/s) – Cruise	13.5	13.5
TET (K)	1920.4	1900
Mass flow (kg/s) – Take-Off	1500	>1436
Fan pressure ratio (FPR)	1.44	-
IPC Ratio (Intermediate Pressure Compressor)	5.90	-
HPC Ratio (High Pressure Compressor)	5.90	-
OPR (Overall Pressure Ratio)	50.:1	50:1
Bypass ratio (BPR)	9.6:1	9.6:1

Table 2 Baseline engine iteration data vs. published data. [55].

Baseline engine Input Simulation Parameters

Parameter	Design Point (Cruise Conditions)	Off-Design (Take-Off Conditions)
Altitude (m)	10668	0.0
Mach number	0.80	0.0
Mass flow (kg/s)	368.7	1500
Fan pressure ratio (FPR)	1.44	1.44
IPC Ratio (Intermediate Pressure Compressor)	5.9	5.9
HPC Ratio (High Pressure Compressor)	5.9	5.9
OPR (Overall Pressure Ratio)	50:1	50.12:1
Bypass ratio (BPR)	9.6:1	9.6:1

Table 3 Baseline engine input simulation parameters. [55]

Brickname	Station numbering	Isentropic efficiency	Mass of air bleed (%) - ODP/DP	Pressure loss (%)
Intake	1,2	-		
Fan (LPC)	2,3	0.91		
Bypass Splitter	3,20,4	-		
Duct	20,21	-		1.5
Convergent Nozzle	21,22	-		
Compressor (IPC)	4,5	0.90		
Splitter	5,25,6	-	1.5	
Compressor (HPC)	6,7	0.90		
Splitter	7,26,8	-	20.1/15.0	
Combustor	8,9	0.99		4.0
Mixees	9,10,26	-		
Turbine (HPT)	10,11	0.92		
Mixees	11,12,25	-		
Turbine (IPT)	12,13	0.92		
Turbine (LPT)	13,14	0.93		
Convergent Nozzle	14,15	-		

Table 4 Turbomatch simulation modelled parameters for Jet A. [55]

7.1 Hydrogen Engine Performance Simulations

7.1.1 The Off-Design Point Condition

The Off-Design Point condition was taken as Take-Off in the Turbomatch simulation model (Figure 43). Once the input and output parameters were established through a parametric investigation, simulations were performed for the Off-Design Point with Jet A and Hydrogen fuels. A further two engines were run but with hydrogen fuel; one with a constant COT and another with constant engine NT (C-6.2.1). The mass flow, OPR and BPR were controlled so a fair comparison between the three engines can be made. (Table 7)

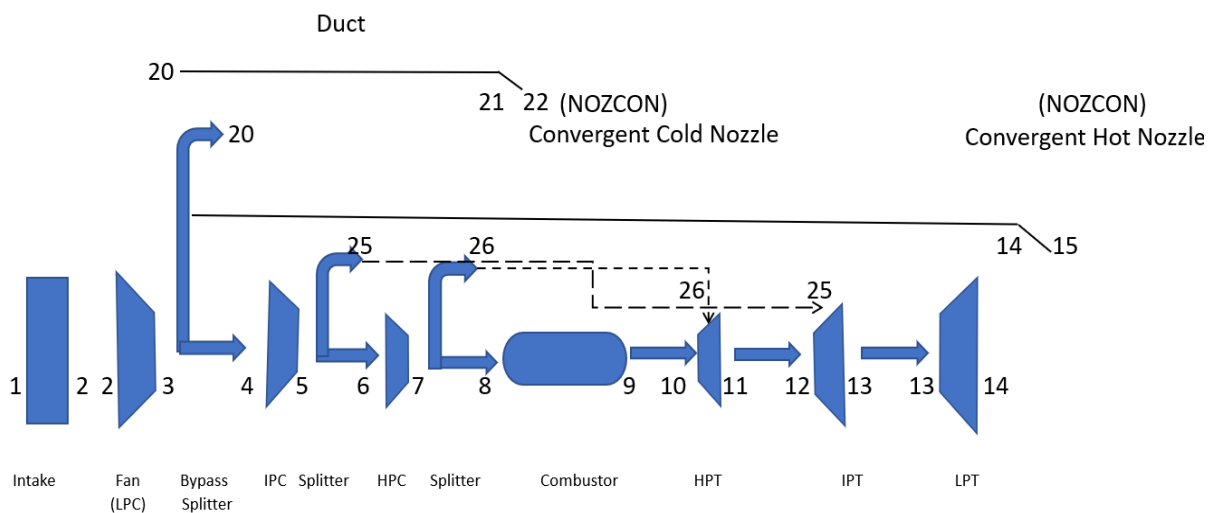


Figure 43 Baseline Turbomatch engine model. [55]

7.1.2 The Design Point Condition

The Design-Point condition was taken to be as cruise. The baseline Turbomatch model was used to perform parametric iterations and achieve the baseline Trent-XWB performance parameters. (C6.2.2), again a further two more hydrogen fuelled engines with constant COT and a constant Net Thrust were simulated with the mass flow rate being controlled. (Table 6)

7.2 Engine Performance Simulations with The Intercooled Engine

The baseline engine was modelled with an air-air intercooler between the IPC and the HPC for the ODP condition. Several iterations were performed to determine the optimal bypass flow percentage into the hot side of the intercooler, the cold and hot side intercooler effectiveness and pressure losses. These parameters were further fed into the Orion aircraft performance model and simulations were run iteratively until an optimal feedback loop (Between the Turbomatch model, the cold side outlet intercooler temperature, and the aircraft performance parameters) was created producing the desired aircraft performance parameters. Consequently, 15% bypass flow was chosen for the hot side of the heat exchanger with an effectiveness of 0.755, and the cold side of the intercooler with an effectiveness of 0.6. Pressure losses for the hot and cold sides of the intercooler were taken from literature and computations made until an acceptable cold side outlet temperature was obtained. This would be sufficient to vapourise the cryogenic hydrogen in a manual calculation to the value recommended in literature. See (Table 1) and (D-6.3.5).

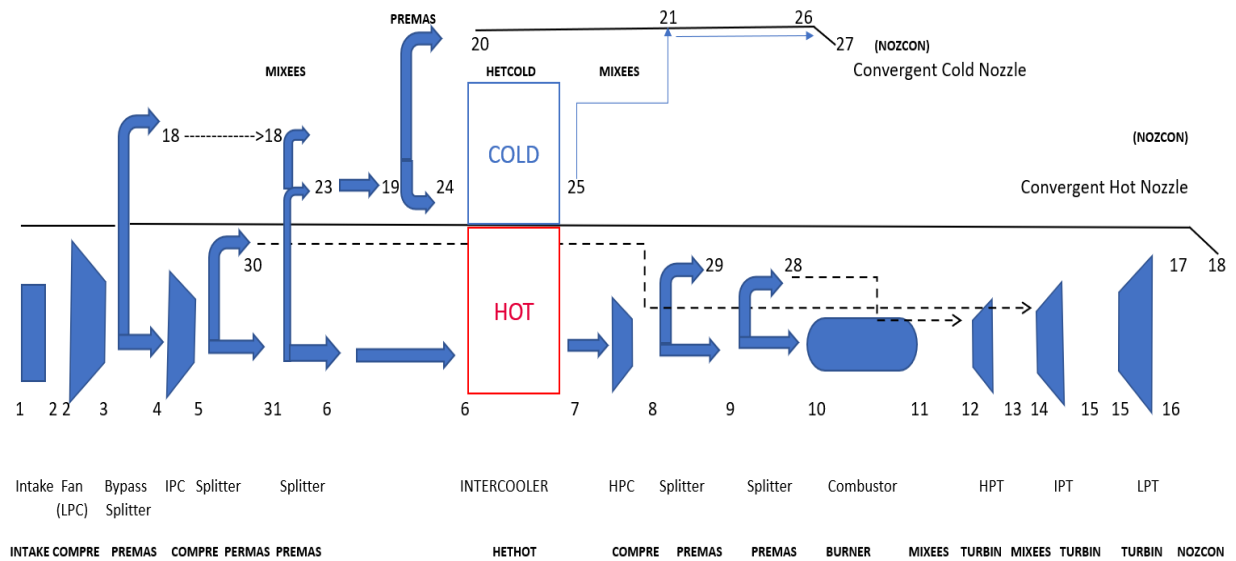


Figure 44 Baseline with intercooled engine Turbomatch model. [64][65].

7.2.1 Rationale for the Intercooler Position

The air-air intercooler is placed between the IPC and the HPC. This is intended to provide information post Turbomatch simulation that can be used to perform calculations with air on the cold side of the intercooler being replaced by cryogenic hydrogen. This data is used in a manual computation to derive the increase in the fuel temperature before its injection into the combustion chamber and to also reduce the HPC work by cooling the compressed mass flow entering the HPC. The calculation further informed the pressure computation for the hydrogen fuel high pressure pump required to inject the evaporated gaseous hydrogen into the combustion chamber. (See Figure 42).

7.2.2 The Off-Design Point Condition

The intercooler engine was run with the same methodology as the baseline engine, a kerosene engine, a hydrogen engine with constant COT and another hydrogen engine with constant Net Thrust. The mass flow and all other parameters including the intercooler effectiveness and pressure losses were kept the same so a fair operating point comparison can be made. The higher Net Thrust requirement of the HVLER aircraft engine (448kN) was obtained by manipulating the COT in the Turbomatch program simulation. (C-6.3.2) and (Table 7)

7.2.3 The Design Point Condition

The intercooled engine was run with the same intercooler parameters and operating point conditions as the Design point baseline engine, and the same three engines were simulated as before. (C-6..3.3). (Table 8).

7.2.4 Performance Comparison Methodology

A parametric analysis was performed using the results in (Tables 5-8), The main parameters of interest post Turbomatch simulations were Energy Specific Fuel Consumption (ESFC), COT, TET, Net Thrust, Core Nozzle Area, and Core Exit Jet Velocity. The change in mass flow affected the nozzle areas of the baseline and intercooled engines, it was ensured by manipulating the COT and mass flow that these are equal so a fair comparison can be established between the two operating conditions.

7.2.5 Pre-Combustion H₂ Temperature at DP and at ODP Conditions.

One of the objectives of the intercooler was to use it as a heat exchanger and vapourise the cryogenic hydrogen coming from the tank (See Figure 42) to a temperature which would bring performance benefits when injected into the combustion chamber. (Figures 45 and 46) shows a block diagram of the temperature and pressure conditions. (D-6.3.5) shows the detailed calculation.

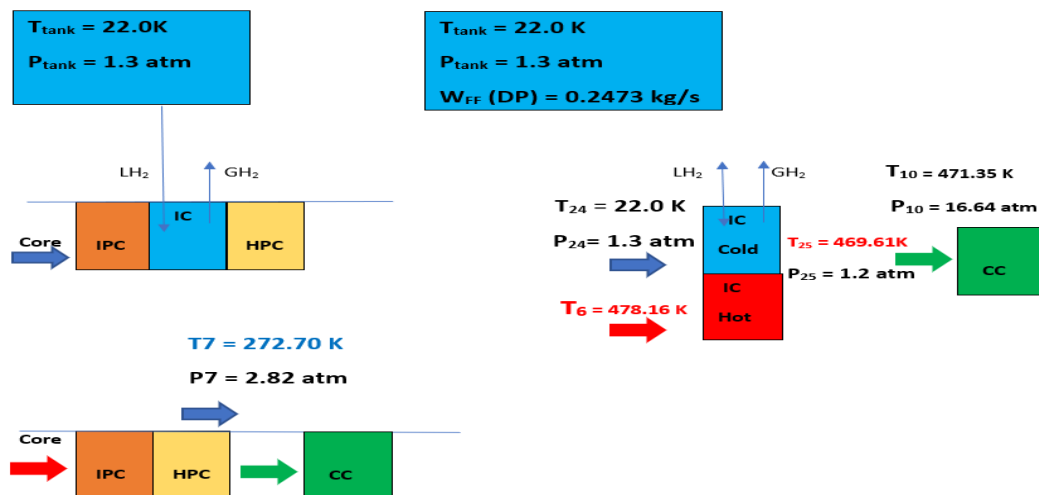
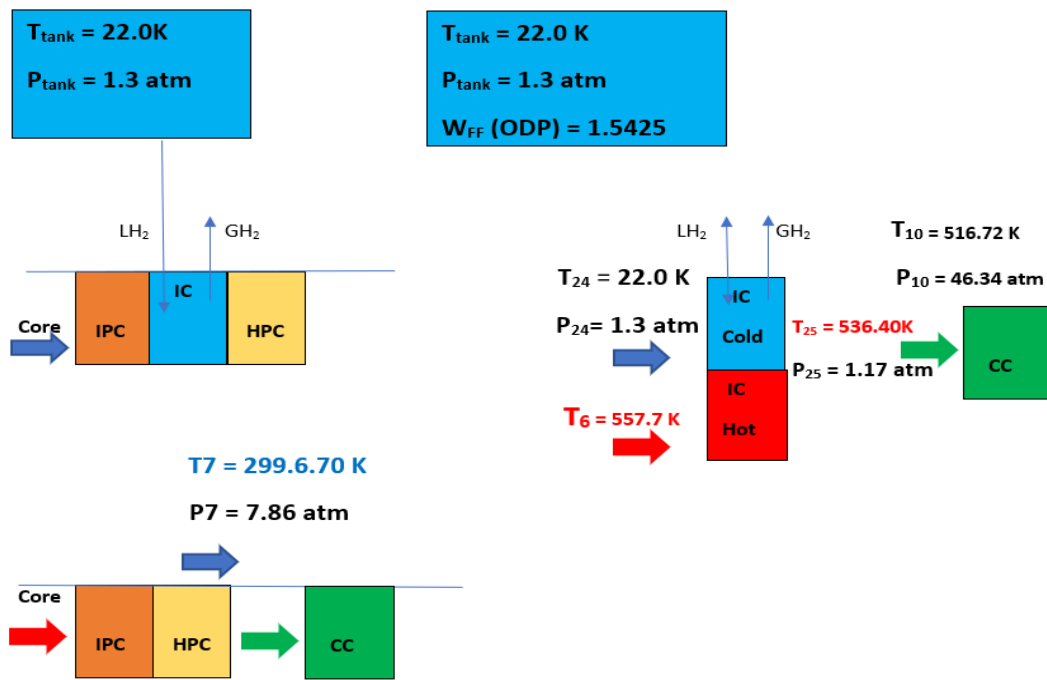


Figure 45 Intercooled (DP) Net Thrust engine, gaseous hydrogen, exit temperature and pressure. [63][49]



Intercooled (ODP) equivalent net thrust engine, gaseous hydrogen, exit temperature and pressure.

Figure 46 Intercooled (ODP) Net Thrust engine, gaseous hydrogen, exit temperature and pressure. [63][49]

8 Design Modifications of Current Commercial Aircraft for Hydrogen Fuel (The HVLER Cranfield Concept)

The HVLER is a hydrogen aircraft concept that integrates the airframe of a 600-tonne double decker airliner (inspired by the Airbus 380), with the wing and engines of a long-range twin-engine airliner (inspired by the Airbus A350-1000 with its two Trent XWB turbofans).[27]

An aircraft performance model using the HVLER Cranfield concept airplane, was established with the integration of the verified Turbomatch engine, for both the baseline and the intercooled engine as well as the kerosene engine (For equivalent CO₂ calculation). This was done in the Orion aircraft performance code by: using the correct TETs for each mission segment, Mach Nos for climb and descent, payload, Take-off weight and range. Several iterations were performed until acceptable rate of climb, climb and descent times and net thrust was obtained for the intended payload and range. (Please see Tables 6 & 7 below).

A payload-range chart was also obtained for the most ESFC efficient engine from both the baseline and intercooled engines. (Please see Figures 3 & 4 below)

For the objective flight mission profile of Taxi-Take-off-Climb-Cruise-Descent landing and Taxi, the total hydrogen fuel burn in tonnes was calculated using the Orion aircraft performance model for the equivalent COT and Net Thrust engines. The engine providing the least fuel burn aboard the HVLER aircraft was selected for renewable energy, feedstock, flights per week and total green hydrogen requirement and cost calculations. (Please see Tables 8 & 9 below)

8.1 HVLER Aircraft Performance Simulations (HKIA-LGW)

The aircraft was modelled for Jet A and Hydrogen fuels with baseline and intercooled engines, again as per previous methodology, three engines were investigated, i.e., Jet A, Constant COT, and an equivalent Net Thrust engine.

In the aircraft data input file, the TETs for all flight segments in the mission profile were adjusted iteratively. The flight input file was also changed simultaneously with the payload, climb Mach no, and descent Mach no. Several iterations were

conducted until the correct Rate of Climb (ROC), Lift to Drag Ratio (L/D), Net Thrust, Block fuel burn, SFC, Total mission time, Climb Time, Descent, Time, and Flight ETRW were obtained. A typical flight mission profile is shown in (Figure 45).[62]

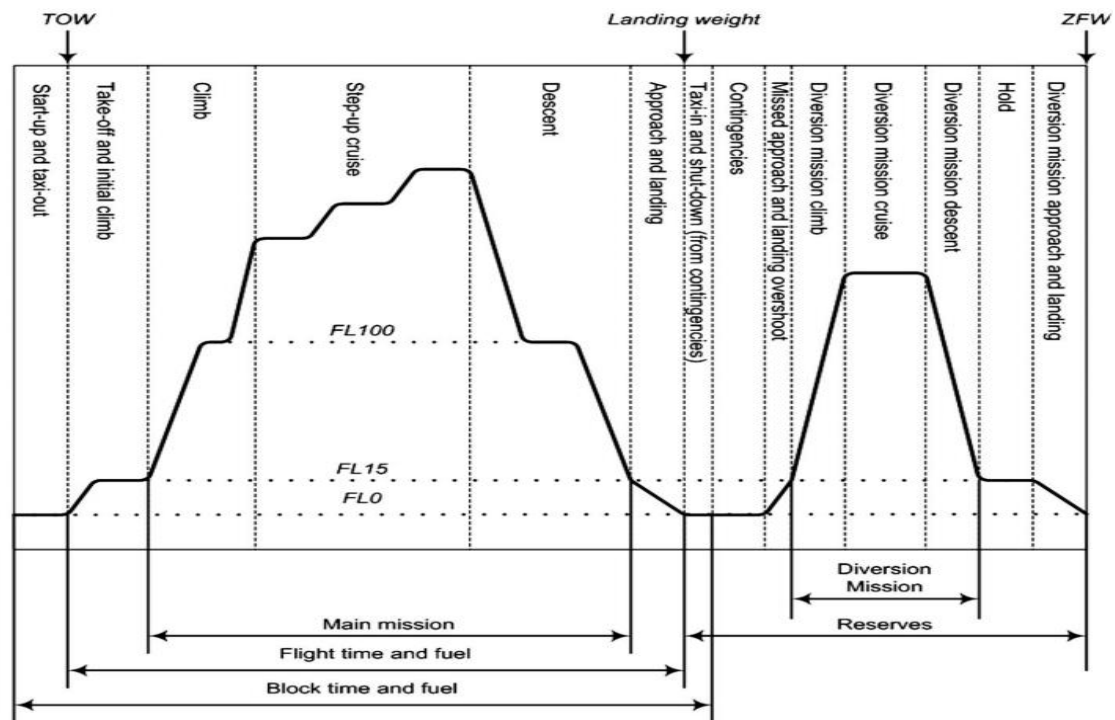


Figure 47 A typical flight mission.[48]

8.2 Green Hydrogen Production and Supply Chain: Energy, feedstock, cost, CO₂ emissions and required flights.

An addition of an electrolyser plant was envisaged as an infra-structure output of the wind farm energy for green hydrogen production. A green hydrogen supply chain perspective was adopted to liquify, store and transport the required hydrogen to the HKIA airport. Calculations of feedstock and the total energy required was based on this strategy of a local supply chain decarbonisation.

Research on Hong Kong's current energy usage and renewable energy (wind energy and solar energy) infra-structure, and modelled energy yield predictions was performed.

The mass of the green hydrogen requirement provided by the aircraft mission performance output was used as a starting point for energy and de-ionised water feedstock calculations. A LH₂ logistical supply chain energy calculation was performed which started from electrolysis to liquification and incorporated elements of storage, transportation, fuel transfer and the cryogenic storage of LH₂ aboard the aircraft. The total energy considerations were then used to calculate the cost of 1kg of green cryogenic hydrogen and the total flights per day that will satisfy the passenger numbers.

9 Results and Analysis

Comparing the DP performance of the baseline kerosene and hydrogen engines to the engines fitted with an intercooler, for the H_2 equivalent COT and H_2 equivalent F_N respectively (Tables 7 and 8 below), the fuel flow reduction of almost two thirds is shown for both engines, In the H_2 equivalent COT engine the net thrust increases by 4.1% for the baseline case and 3.1% for the IC case, this is also shown by the increased specific thrust in both the baseline and the intercooled architectures. This is expected due to the much higher calorific value of hydrogen. There is an increase in ESFC of 4.1% if COT is kept constant, however, with the fixed F_N engine there is a decrease in ESFC of 1.71%, this pattern is repeated with the intercooled case with corresponding ESFC values lowered to 3.9% and 1.3% (decrease), this is even though the core nozzle mass flow decreases, the core nozzles velocity increases, and its area is reduced in both baseline and intercooled cases. For the H_2 equivalent COT engine fitted with an intercooler, the core mass flow is reduced by 1.9%, with a nozzle velocity increase of 5.7 % and a nozzle area reduction of 13.1%. In the H_2 equivalent F_N engine with a net thrust of 431.5 kN for the baseline case and an F_N of 448kN for the intercooled engine which was matched to the required HVLER aircraft engine F_N requirement. This also resulted in a decrease in COT of 28K for the baseline and 32.6K for the intercooled engine as well lower TET. Although, the reduced fuel flow also lowers the exhaust mass flow (by 1.6% and 1.9%) and hence reduces the thrust, this mass flow, through the turbine results in a higher total temperature drop and a greater total pressure drop across it, but it still provides the same amount of power to drive the compressor. The temperature and pressure drop across the turbine exit affect the pressure thrust adversely with the decrease in nozzle exit velocities reducing the momentum thrust. At the same time, the reduction in thrust due to a decrease in the mass flow is compensated by the increase in the net thrust (4.1% & 3.1%). This is because the combustion products contain no CO_2 , but a larger proportion of the exhaust gases is made up of H_2O . Water has a C_p value much higher than CO_2 and hence, this affects the performance favourably augmenting the net thrust. For a fixed power output, the total

temperature decreased by (1.64%) and total pressure dropped by (0.6%) across the turbine in the Intercooled engine. In the equivalent thrust engine as compared to the baseline kerosene intercooled, engine. A larger nozzle expansion ratio (2.5%) yielded a larger exhaust velocity (0.85%) in the intercooled engine at DP, thus increasing the momentum thrust.

The equivalent FN baseline engine showed a reduction in the core nozzle area of 2.8% with a decrease in core exhaust mass flow of 1.6% and an increase in core exhaust velocity of 1.1%. This pattern is repeated in the intercooled scenario with values of 3.77%, 1.9% and 1.64% respectively.

9.1 Baseline Vs. Intercooled Turbomatch Engine Performance

Baseline ODP	Ker.	H ₂ eq. COT	Δ [%]	H ₂ eq. F _N	Δ [%]
W ₁ [kg/s]	1500	1500	-	1500	-
W _F [kg/s]	3.5365	1.3219	-62.6	1.2209	-65.5
F _N [kN]	431.5	440.96	2.2	431.5	-
COT [K]	1920.4	1920.4	-	1856.7	-3.3
TET [K]	1742.3	1749.35	0.40		-2.7
SFC [g/kN/s]	8.0	3.00	-62.5	2.83	-64.6
ESFC [J/N/s]	345.4	359.7	4.1	339.5	-1.71
SPT [N*s/kg]	287.7	293.98	2.2	287.7	0.0
A _{CORENOZ} [m ²]	0.4077	0.3547	-13.0	0.3964	-2.8
W _{OUTCORE} [kg/s]	145.0	142.8	-1.5	142.7	-1.6
V _{OUTCORE} [m/s]	553.2	579.9	4.8	559.2	1.1

Table 5 Baseline Turbomatch engines at Off-Design Point.

Baseline+IC ODP	Ker.	H ₂ eq. COT	Δ [%]	H ₂ eq. F _N	Δ [%]
W ₁ [kg/s]	1500	1500	-	1500	-
W _F [kg/s]	4.3500	1.6539	-62.0	1.5425	-64.5
F _N [kN]	448.0	456.2	1.83	448.0	-
COT [K]	1828.2	1828.2	-	1758.0	-4.0
TET [K]	1602.3	1612.8	0.66		-3.1
SFC [g/KN/s]	9.7	3.6	-62.9	3.44	-64.5
ESFC [J/N/s]	418.5	435.0	3.9	413.1	-1.3
SPT [N*s/kg]	298.7	304.1	1.81	298.7	-
A _{CORENOZ} [m ²]	0.2974	0.2583	-13.1	0.2862	-3.77
W _{OUTCORE} [kg/s]	144.5	141.8	-1.9	141.7	-1.9
V _{OUTCORE} [m/s]	554.4	586.1	5.7	563.5	1.64

Table 6 Intercooled baseline engines at Off-Design Point.

Baseline DP	Ker.	H ₂ eq. COT	Δ [%]	H ₂ eq. F _N	Δ [%]
W ₁ [kg/s]	368.7	368.7	-	368.7	-
W _F [kg/s]	0.5324	0.1986	-62.7	0.1887	-64.6
F _N [kN]	39.3	40.9	4.1	39.3	-
COT [K]	1440	1440	-	1412.0	-1.94
TET [K]	1352.9	1354.7	0.13		-1.69
SFC [g/KN/s]	13.5	4.9	-63.7	4.8	-64.4
ESFC [J/N/s]	583.9	583.4	-0.1	576.0	-1.35
SPT [N*s/kg]	106.6	110.8	3.9	106.6	0.0
A _{CORENOZ} [m ²]	0.4077	0.366	-10.2	0.4005	-1.76
W _{OUTCORE} [kg/s]	35.3	35.0	-0.85	35.0	-0.85
V _{OUTCORE} [m/s]	446.9	461.0	3.2	449.4	0.56

Table 7 Baseline Turbomatch engines at Design Point.

Baseline+IC DP	Ker.	H ₂ eq. COT	Δ [%]	H ₂ eq. F _N	Δ [%]
W ₁ [kg/s]	368.7	368.7	-	368.7	-
W _F [kg/s]	0.6964	0.2586	-62.9	0.2473	-64.5
F _N [kN]	44.5	45.9	3.1	44.5	-
COT [K]	1342.2	1342.2	-	1309.65	-2.4
TET [K]	1226.3	1229.2	0.24		-2.1
SFC [g/kN/s]	15.6	5.6	-64.1	5.55	-64.4
ESFC [J/N/s]	674.5	676.1	0.24	666.9	-1.13
SPT [N*s/kg]	120.7	124.4	3.0	120.7	0.0
A _{CORENOZ} [m ²]	0.2974	0.2640	-11.2	0.2900	-2.5
W _{OUTCORE} [kg/s]	35.1	34.7	-1.1	34.67	-1.2
V _{OUTCORE} [m/s]	444.8	462.0	3.87	448.6	0.85

Table 8 Intercooled baseline engines at Design Point.

9.2 Baseline vs Intercooled HVLER Aircraft Performance

The aircraft performance model results confirmed that the equivalent Net Thrust engine achieves the required range and payload with the least green hydrogen been used as compared to the constant COT engine and hence this particular hydrogen engine was selected to be integrated with the HVLER aircraft for the designed mission from HKIA to LGW. (**Table 9&10 & Figures 48 & 49** below).

Comparing the aircraft performance parameters at Take-Off, Initial Cruise and End of Cruise segments of the flight mission, the intake mass flow has increased by 3.84% for the baseline engine at Take-Off and for the same segment by 8.5% for the intercooled integrated engine. The Top of Climb and Initial Cruise OPR is elevated to 55.4 and 53.2 for the Top of Climb and Initial Cruise segments but under 50 for the End of Cruise case. The latter two being above the engine design value for the TrentXWB-97. The TOC and Initial Cruise are under 50 for the Intercooler case, only the Take-Off and top of climb is above the maximum engine OPR, the TOC being much higher with a value of 61.5. The HP spool rotational speeds decrease with the intercooled engine at the Initial Cruise and End of Cruise segments but increase for Take-Off and at the Top of Climb. The hot and

cold exhaust temperatures have both been reduced with the intercooler energy extraction as well as the TET as compared to the baseline engine. The ROC is increased by a factor of 1.4 with the intercooled engine and consequently the Climb Time is halved with a factor of 0.53. The intercooler adds 7.1 tonnes of fuel to the baseline mission. There is also an accompanying payload reduction of 4.7 tonnes.

The lower HP rotor speeds are because of the reduction in compression work due to the intercooled engine, The Top of Climb is the critical point where the OPR increases significantly due to the extra fuel weight that has to be carried to operate the intercooler, however, this can be optimised by another iteration with a more accurate Turbomatch model incorporating bleed mass flow offsets thus giving a precise mass flow value with which the COT can be further increased thus lowering the demand on the HPC and reducing the OPR closer to the design value of 50.

The Lift-to-Drag ratio for both aircraft scenarios for the TOC, Initial Cruise and End of Cruise are 18.01, 18.03 and 17.87 which are within acceptable limits for this aircraft. The Rate of Climb for the baseline and the intercooled cases are 1741 ft/min and 2439 ft/min respectively which are reasonable and within range.

Parameter(s)	Take-Off	Top of Climb	Initial Cruise	End of Cruise
Mach No.	0.218	0.750	0.80	0.80
Altitude [m]	0	9629.5	10668	10668
OPR	47.8	55.4	53.2	49.4
HPRPM [%}	1.004	0.969	0.950	0.931
W_1 [kg/s]	1560.2	697.8	630.5	616.36
W_{core} [kg/s]	162.5	72.7	65.7	64.2
Fuel flow (kg/s)	1.261	0.540	0.456	0.408
NT [kN]	345.4	99.52	82.3	75.9
SPT [Ns/kg]	221.4	155.8	130.5	123.1
ESFC [J/N/s]	438.1	651.1	664.9	645.1
TET [K]	1868.3	1761.3	1706.5	1651.1
Exhaust _{Cold} T [K]	904.9	840.6	809.6	778.8
Exhaust _{Hot} T [K]	1868	1761	1706	1651
ROC [ft/min]	1741	513	0	0
L/D Ratio	11.34	18.01	18.03	17.87
<i>Climb time [min]</i>	27.97			
<i>Flight time [hrs]</i>	11.83			
<i>Block Fuel [kg]</i>	36267			
<i>Payload [kg]</i>	31866			
<i>Range (nm)</i>	5211			
<i>ETRW [MJ/km]</i>	1.443			

Table 9 Aircraft performance data for hydrogen fuelled constant Net Thrust baseline engine.[66]

Parameter(s)	Take-Off	Top of Climb	Initial Cruise	End of Cruise
Mach No.	0.218	0.750	0.80	0.80
Altitude [m]	0	9629.5	10668	10668
OPR	52.4	61.5	47.4	43.9
HPRPM [%]	1.038	0.998	0.919	0.899
W_1 [kg/s]	1639.1	725.4	612.4	598.0
W_{core} [kg/s]	170.7	75.6	63.8	62.3
Fuel flow (kg/s)	1.912	0.811	0.505	0.451
NT [kN]	417.2	128.92	83.4	75.3
SPT [Ns/kg]	254.5	177.7	136.1	125.9
ESFC [J/N/s]	550.0	754.9	726.6	718.7
TET [K]	1868.3	1749.6	1523.4	1465.5
Exhaust _{cold} T [K]	548.4	503.1	432.9	415.3
Exhaust _{hot} T [K]	1468	1368	1182	1135
ROC [ft/min]	2439	1452	0	0
L/D Ratio	11.34	18.01	18.03	17.85
<i>Climb time [min]</i>	14.72			
<i>Flight time [hrs]</i>	11.97			
<i>Block Fuel [kg]</i>	43349			
<i>Payload [kg]</i>	27184			
<i>Range (nm)</i>	5211			
<i>ETRW [MJ/km]</i>	1.892			

Table 10 Aircraft performance data for hydrogen fuelled constant Net Thrust Intercooled engine.[66]

9.2.1 Payload Range Diagram for The Baseline Engine

The HVLER equipped with the baseline engine is able to carry a maximum payload of 35.88 tonnes until it reaches a range of 4634 nautical miles. At the required range of 5211nm the payload reduces to 31.9 tonnes as a greater volume of fuel is carried i.e., 38.7 tonnes. (See E-7.2). This scenario carries the design payload of 232 passengers and cargo achieving the range of 5211nm from HKIA to LGW. A further increase in range will decrease the payload at a constant rate and in the final segment the maximum range is achieved with a steeper decrease in payload per nautical mile in what is known as the Ferry range, which essentially carries zero payload and just the fuel.

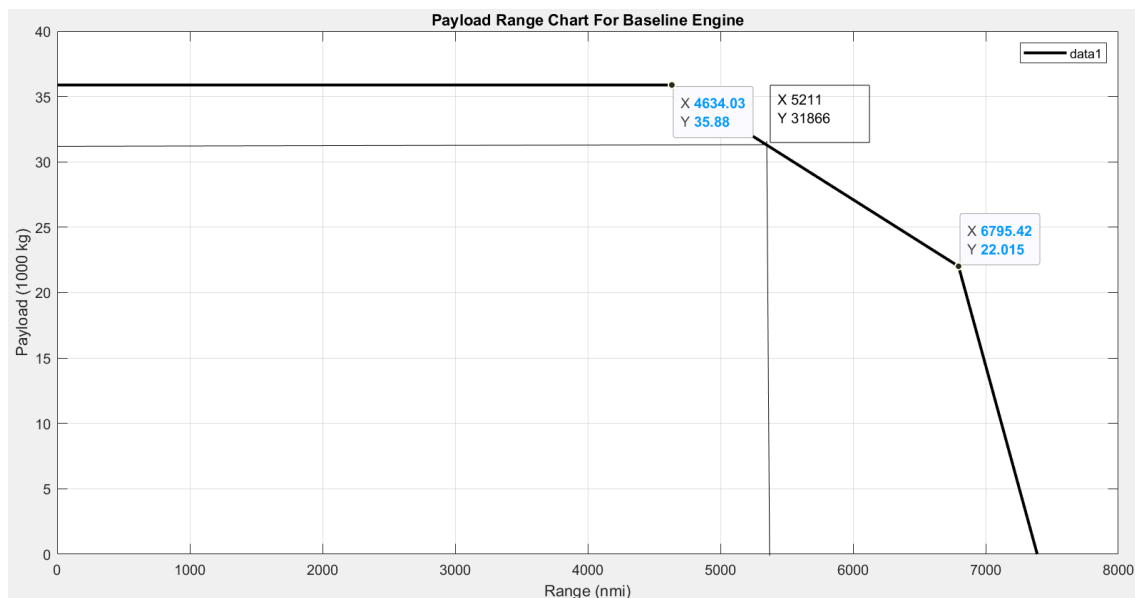


Figure 48 Payload-Range chart for the baseline engine aircraft.[66]

9.2.2 Payload Range Diagram for The Intercooled Engine

The HVLER equipped with the intercooled engine is able to carry a maximum payload of 35.88 tonnes until it reaches a range of 4064 nautical miles. This is a reduction of (12.3 %). At the required range of 5211 nm the payload reduces to 27.2 tonnes, this decreases by (14.7%) as compared to the baseline aircraft case. as a greater volume of fuel is needed i.e., 40.6 tonnes. (See E-7.2.1). This scenario reduces the design payload of 232 passengers by (5.2%), however, still

achieving the range of 5211nm from HKIA to LGW. A further increase in range reduces the payload at even a greater rate and in the final segment the maximum range is achieved with even a steeper decrease in payload per nautical mile as compared to the baseline, resulting in a shorter Ferry range.

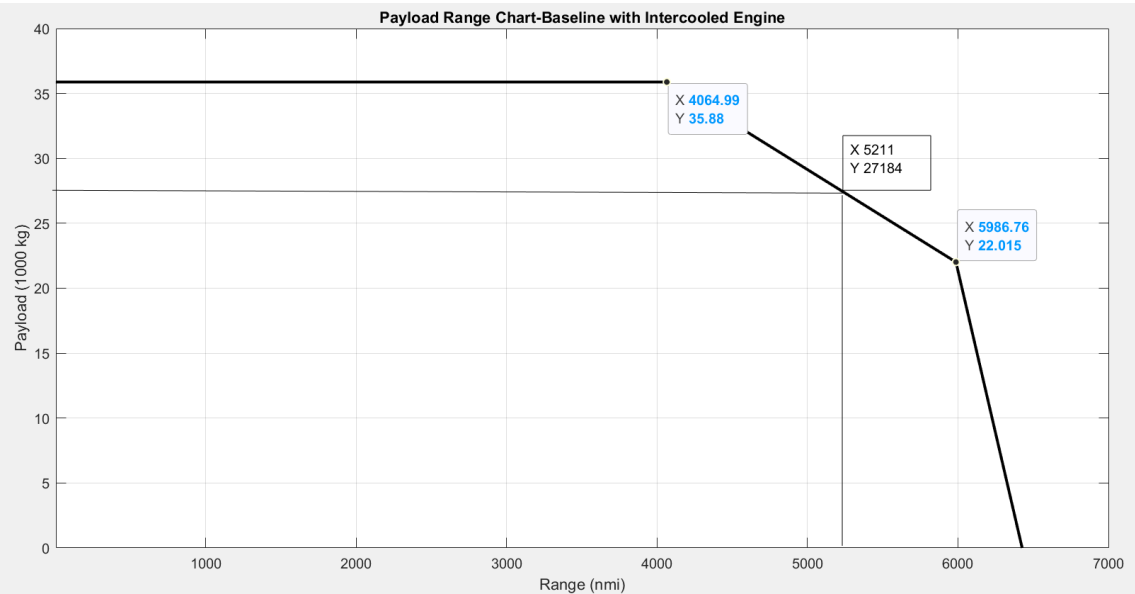


Figure 49 Payload-Range chart for the intercooled engine aircraft. [66]

9.3 Green Hydrogen Infra-structure, Feedstock, energy, cost production- A Green Supply Chain perspective.

The Siemens Silzer 300 electrolysis module was used as a Green Hydrogen producing powerplant for the following calculations. [73]. This electrolyser has six module arrays and each array generating 335 kg of gaseous hydrogen, a full load generates around 2000 kg of hydrogen per hour.

A Green Hydrogen HVLER flight mission and logistical supply chain energy calculation was conducted. (Table-B 8.41 and Table-B 8.42). [67-71]

9.3.1 Infra-structure Requirement

According to the calculation in (Table-B 8.41 and Table-B 8.42), The total energy requirement for the flight mission and associated logistical supply chain operations is estimated to be 12.6 GWh and 14GWh for the baseline aircraft and the intercooled aircraft fuel requirements respectively.

(Table 11) shows that the LH₂ requirement for the baseline and Intercooled integrated HVLER aircraft are 38.7 and 43.4 metric tonnes respectively. This equates to a maximum volume of 614.4 m³ which is below the 700 m³ tank limit of the HVLER. Adding the energy demands of the logistical supply chain and the de-ionisation of the water increases the LH₂ to 66.1 and 74.1 metric tonnes.

Energy required per day would be 12.56GWh and 14.08GWH for operating the baseline aircraft and the intercooled aircraft respectively.

The maximum de-ionised water requirement for the electrolyse was calculated to be 740.9m³ and the energy needed for this process was 2.96GWh.

Considering the passengers per year from HKIA-LGW the total number of flights per week required are 14 for the baseline case and 15 for the intercooled scenario.

The total reduction in the CO₂ emissions footprint for Hong Kong including the flight, infra-structure and the supply chain would be 1.22 Mega tonnes for the baseline case and 1.35 Mega tonnes for the intercooled aircraft. This is equivalent to a reduction of 12.8% in the Civil Aviation Carbon Footprint for Hong Kong. The

cost of producing the cryogenic hydrogen including its production, storage transportation and transfer/storage abroad the aircraft is calculated to be USD 4.96.

Using the daily total energy requirement (Two flights and supply chain logistics) of 14.08GWh [B-8.42], gives 256 tonnes of liquid hydrogen. Operating the electrolyser for a 16-hour daily operation with all six arrays yields a power demand of 128MW and at least seven electrolyser module installations. There would be a deionised water requirement of 741 cubic metres for the electrolyzers. (Table 11).

Requirements	Baseline Aircraft	Intercooled Aircraft
Single Mission LH ₂ [mt]	38.7	43.4
Single Mission LH ₂ [m ³]	546.6	612.4
Logistics Total LH ₂ [mt]	66.1	74.1
Energy [GWh] / Day	12.56	14.08
De-ionised Water [m ³]	661.2	740.9
Double Mission LH ₂ [kg]	132.2	148.2
Weekly Flights	13.8	15.1
CO ₂ Footprint Flight [Mt]	0.52	0.59
CO ₂ Infra-Structure [kt]	0.14	0.15
CO ₂ Supply Chain [Mt]	1.22	1.35
% CO ₂ Emissions/Year	3.0	3.35
% CO ₂ Transport/ Year	16.7	18.5
% Civil Aviation/Year	11.6	12.8
<i>Cost LH₂ /kg (USD)</i>	<i>4.96</i>	
<i>Pax/Year (HKIA-LGW)</i>	<i>166735</i>	

Table 11 Green Hydrogen production Energy, Feedstock, cost, CO₂ emissions and Required Flights for Hong Kong. [67-71]

9.4 Hong Kong- A Green Hydrogen Hub Possibility

The data for windfarm modelling, solar energy calculations of BIPV and Non-BIPV systems for Hong Kong, Coal Power stations, road, maritime transportation, and logistical infra-structure were accurately mapped on a google map. [30-36]. The latitudes and longitudes were inputted on a Google Map of Hong Kong and the modelled wind farms in literature were located accurately. [30]. BIPV systems were placed in urban areas and the non-BIPV components were dispersed on the remaining Islands and rural area of Hong Kong.



Figure 50 Mapping of renewable energy data and transport and energy networks.

Key:



Wind Farm



Building Integrated Photovoltaic (BIPV) systems.



Coal Fired Power Station



Hong Kong International Airport (HKIA)



Non -BIPV Systems (Solar arrays)

10 Conclusions

10.1 Limitations and Benefits of the HVLER Intercooled Concept.

The COT and TET are lower for both the baseline and intercooled engines running on H_2 fuel, meaning that the same turbine cooling technology can be used. The specific thrust increases by (11.7%) for the intercooled engine at DP. The ESFC decreases by (1.35%) for the baseline equivalent thrust engine at DP, using the IC, this decreases slightly to 1.13%.

The ESFC for ODP decreases by 1.7% for the equivalent thrust engine and increases by 4.1% for ODP for the constant COT engine. (Tables 5 & 6). For the intercooled engine at ODP the constant COT increases to 3.9%, but the equivalent net thrust engine still shows a decrease of 1.3%.

Fitting the intercooler will result in minimal changes to the baseline engine geometry as specific thrust increases by 13.2% for DP and 3.8% for ODP, the core nozzle area reduces by 3.8%, and the core mass flow lowers by 1.9%.

Evaporating the hydrogen by heating it prior to injection into the combustion chamber may achieve performance benefits. The intercooler calculations using compact heat exchanger theory yields pre-injection hydrogen temperatures of 295.7K for DP and a temperature of 536.4K for the ODP condition. The total pressures required to pump the gaseous hydrogen into the combustion chamber will be 14.3 atm and 43.6 atm at DP and ODP respectively. (D-6.35)

The increase in the OPR with the HVLER intercooled concept at the Top of Climb, can be attributed to the extra weight but it is also due to the intercooling as it does increase the OPR and core specific thrust which is the case with the intercooled engine fitted aircraft. The net thrust for the baseline and the intercooled engines is in the range (82-83kN) at Initial Cruise, this is close to the cruise net thrust value of (81kN) of the HVLER.

This increase in mass flow, ST and OPR could mean that the BPR may need to increase (to 11.0) as well as the FPR (to 1.6) and hence the addition of extra nacelle weight, drag and a taller/heavier fan. On the other hand, an extra HP

compressor stage might need to be added to achieve the increase in OPR with the intercooled engine. At DP, the higher HPR blade speeds at the Top of Climb scenario may require a mechanical design assessment of the HP compressor since it is close to the 100% ESA five-minute continuous thrust certified value [55], the HP turbine loading, and the hot nozzle area requirement would also require re-evaluations.

There is a decrease in engine thermal efficiency with the intercooler engine and SFC relative to the stated design value for JET-A, however, there is an improved ESFC with hydrogen. Usually, the effects of the intercooler on the degrading of the thermal efficiency are counteracted by a recuperator, and the exhaust temperatures for both the baseline and intercooled engines show a good case for recovering some energy, but in this investigation, this wasn't possible due to the severe weight limitations with the HVLER, even with the intercooler alone there is a loss of 12 passengers of the HVLER flight mission.

The intercooler effectiveness can be systematically adjusted during flight to reduce the cold side pressure loss of the intercooler and to get the optimum cycle performance. There are good pre-combustion gaseous hydrogen temperatures reached with the intercooler and lower TET, meaning cooling flow can be routed for thrust augmentation as well as provide a longer blade life. Lower HP spool speeds would also place a lesser load on the bearings with the intercooled case.

The reduction in COT and TET although suggests a lower combustion temperature, however, this exploration didn't look into the maximum combustion temperature and the location of possible hotspots due to incomplete mixing in the primary zone of the combustor. Generally, a combustor will need to be redesigned to facilitate lower NO_x emissions by reducing hotspots in the combustion zone.

The total green hydrogen for a one- way flight from LGW-HKIA is (43.4 tonnes), and the total energy requirement for the cryogenic fuel in the aircraft storage tanks is 7.04 GWh. (Table 9)

The resulting volume of hydrogen required aboard the aircraft for a single flight is 612.4 m³ this is within the specifications of the HVLER hydrogen aircraft with the storage tank capacity of 700m³ [86].

This would require setting up seven Siemens large-scale PEM electrolyzers each with a power consumption of 17.5MW and a production of approximately 16 tonnes of green hydrogen per hour. (Assuming a 16-hour operation daily. This can be sourced from one 200MW wind farm in [87]&[24].

According to [33], the two offshore wind farms at locations 2 and 4 (Figure 25) have been modelled to produce 100MW and 200MW power yields respectively. Theoretically, initially the wind farm north of the HKIA can be built to provide the power needed to produce the required hydrogen, it is estimated in [67] that an input investment cost of USD 16/MWh per 100MW capacity (550 million USD) would be required to get this operational for a 200MW offshore wind farm.

This proposed offshore wind farm has a central location which is accessible to marine transportation and is nearby the road transportation networks and can serve as a central hub for hydrogen production and storage for the provision of green hydrogen to HKIA. (Figures 23,24 & 25).

The HVLER aircraft if fully adopted for the proposed single mission from HKIA-LGW would reduce the Hong Kong Civil Aviation carbon footprint by 12.8 %, the annual transport CO₂ emissions by 18.5% and the total CO₂ emissions for Hong Kong by 3.35%.

The current estimated potential for off-shore wind power in Hong Kong is 14,449GWh annually, hence, the total (whole supply chain) green hydrogen production for LGW-UK is 35.6 percent of the yearly potential off-shore wind potential energy percentage. [30] [32]. This doesn't consider the full solar potential as well as the onshore wind power potential of Hong Kong.

10.2 Environmental Benefits to Hong Kong

The findings will provide a financial incentive (in the form of retaining the current engine and aircraft) and an encouragement to researchers in to further exploring the use of intercoolers in jet engines for the heating of cryogenic green hydrogen. It will also provide peer-reviewed literature to the aviation industries around the world and governments who have committed to achieving net-zero emission by 2050. This would contribute towards a more informed decision-making discussion about transitioning towards a carbon-neutral hydrogen based-economy and in reducing the carbon footprint induced by the combustion of kerosene and other fossil fuel-based aviation fuels. In the context of Hong Kong with a 50 % reliance on coal as an energy source and the evident trends of rising average monthly temperatures and a broader climate modelled regional temperature rise of 1.5⁰C by 2040, it is imperative that the Hong Kong government starts seriously investing in a sizeable renewable energy infra-structure for it to enable the use of H₂ with a view of initiating with civil aviation as it has the greatest carbon footprint ,and a green hydrogen supply chain to support this transformation. Just switching to green hydrogen for the HKIA-UK annual flights will reduce Hong Kong's carbon footprint by a value of 1.35 million tonnes of CO₂. This is 12.8% of total carbon Civil Aviation footprint of Hong Kong and 18.5% of the total transportation carbon footprint. The green hydrogen revolution will require a sizeable investment with this project alone amassing at least 500 million USD of investment and a return of 4.96 USD per kilogram of liquid hydrogen.

The economy will also benefit with job creation in the renewable energy sector and H₂ aviation transportation and logistics, a coherent national carbon-neutral strategy and LH₂ aviation safety, storage and transportation regulations will also take learn from neighbouring Asian-Pacific nations like Australia and Japan and European nations.

10.3 Hong Kong A Future Green Hydrogen Hub

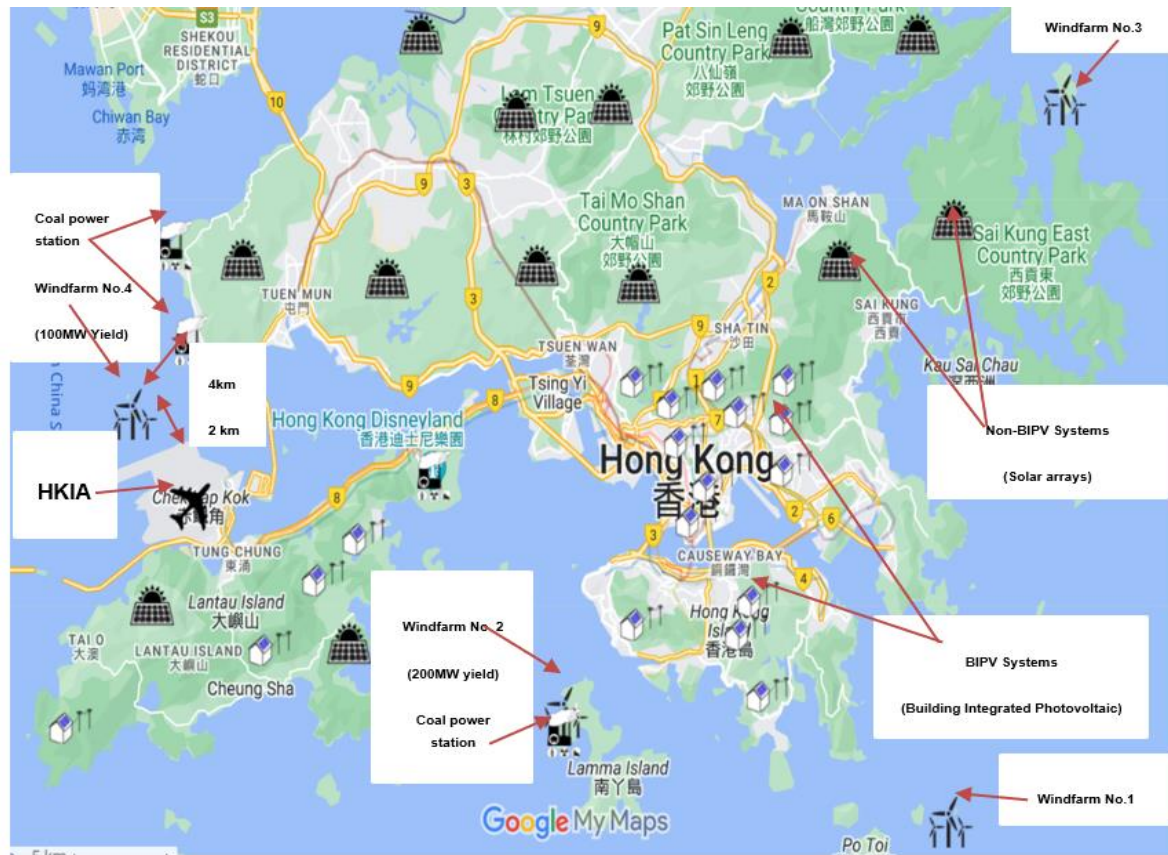


Figure 51 A Potential Green Hydrogen Ecosystem for Hong Kong.

Hong Kong being the world's fourth largest shipping cargo terminal has a well-developed shipping lane as well as cargo handling and logistical architecture in place. The maritime and road transport connectivity can be used to transport the hydrogen. It is recommended that due to the close proximity (to HKIA) of the proposed offshore windfarm No.4 with a 100MW capacity be the starting point of renewable energy infra-structure development. The coal fired power station north of it (Black Point Power Station) which is planned to be de-commissioned for 2025 be converted into a hydrogen generating electrolyser plant, liquification, storage and transportation facility. (Figure 49). There would need to be procurement or modification of existing vessels for the purpose of cryogenic hydrogen transportation with storage tanks that can safely carry the liquid hydrogen from the proposed electrolysis plant to the airport. This would require changes to existing maritime regulations for the carrying of hydrogen aboard ships.

The second phase for renewable energy transformation would be windfarm No.4 again with very close proximity to a power station that can again be converted into a liquid hydrogen plant. There is already a well-established road network connecting it to the Hong Kong Island and then to HKIA. Specialised cryogenic hydrogen carrying trucks/tankers would need to be acquired so the total daily demand can be met.

The third and fourth phases will see the wide use of solar arrays in rural areas and then the application of BIPV technology to urban areas with high rise buildings.

Currently, in China the cost of renewable electricity would become a good competitor with natural gas and CCUS. Coal with CCUS although the cheapest comes with the highest carbon intensity. The OPEX costs are still higher than renewables, but renewables have lower CAPEX costs. CAPEX and OPEX sensitivities are higher for renewable energy, but it has no CO₂ costs associated with it. (Figures 13,14 & 15), Advancing electrolyser technologies will create a balance between these two energy sources, as costs will drop by 2030 [39] and with surrounding Asia-Pacific nations taking the lead in green hydrogen production Hong Kong will see the need to follow suite.

11 Recommendations and Further Work

The Turbomatch can be modified to allow the injection of cryogenic hydrogen into the cold side of the intercooler and calculate the outlet conditions, furthermore, the performance effect on the relatively cooler fuel temperature being injected into the combustion chamber with a higher COT can be calculated.

The Trent-XWB has massflow offtakes for cabin and nacelle bleeds, these can be modelled into the program to get a more accurate value of the engine massflow at ODP and DP conditions. The intercooler weight estimation can be performed for the Trent-XWB by conducting a sizing exercise.

The turbine cooling air can be lowered to account for the hydrogen engine running at a much lower TET, this cooling air can be used to increase the net thrust.

The NO_x reduction would be crucial in a hydrogen fuelled aircraft and as such a re-designed combustor with micromix and DLI concepts would need to be investigated for the Trent-XWB and CFD analysis performed to ensure that the hot spots are within minimum NO_x production limits and away from the main combustion area.

The HVLER intercooled concept can be optimised for a lower TET as the ROC is much quicker than the baseline case.

A pipeline infrastructure to transport LH₂ from the electrolyser plant north of HKIA to the airport (Figure 51) can be investigated and the cost vs. benefits compared to marine (LH₂ ship) and road (LH₂ truck) transportation.

The cryogenic hydrogen can be fed through the stators; although this has been suggested in literature by Yutaka Ito and Takao Nagasaki (2012) [88], but a liquid hydrogen as a medium hasn't yet been tried; it will certainly be interesting to design, model and simulate (Using CFD analysis) a specialised heat exchanger consisting of rings of stator blades each stator blade acting as a cell in one particular stator ring. This will entail designing the internal structure of the stator as a heat transfer entity, with a cryogenic hydrogen channelling within and an accompanying distribution system to pump the gaseous hydrogen to the

combustion chamber. It is envisaged that this system would not need the extra weight required as that of an intercooler. It will also be possible to add a recuperator with the same methodology and improve the engine thermal efficiency. An aerodynamic analysis of the hole punched stator blade will also need to be conducted.

Engine performance calculations can then be performed again with the revised baseline engine and with this re-designed 'intercooled' engine incorporating the additional recuperator. This would also necessitate a new Turbomatch engine model and possibly additions to the code. The results can then be run on the Orion aircraft performance program and further insights attained.

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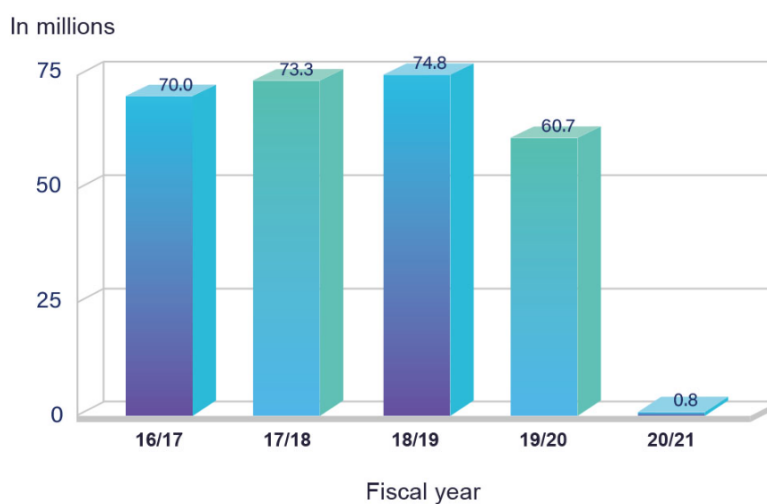
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APPENDICES

Appendix A

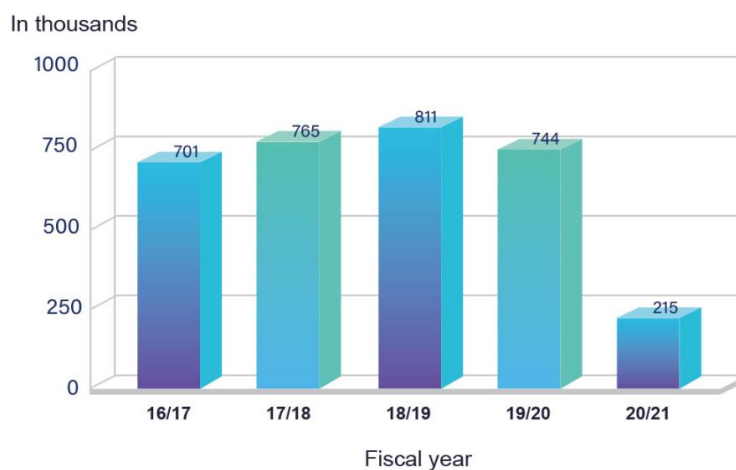
A.1 HKIA Five Year Passenger Traffic

Five-Year Passenger Traffic at Hong Kong International Airport



A.1.1 HKIA Five Year Flight Traffic

Five-Year Total Flights Handled by Air Traffic Management Division



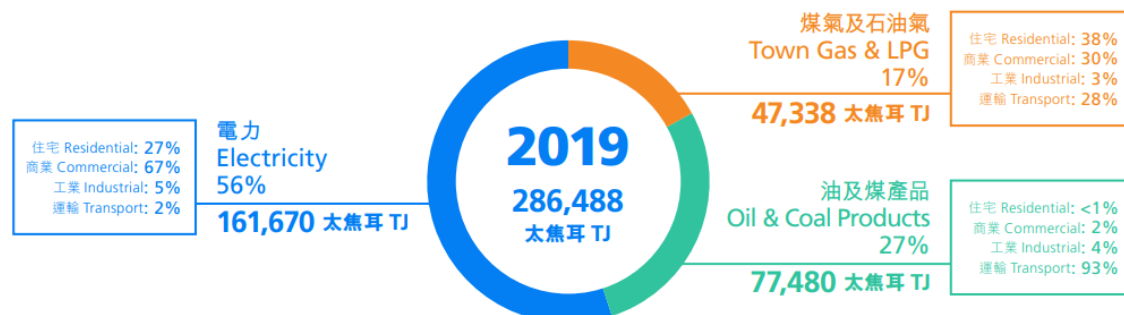
A.2 Total energy Consumption by Fuel and by Sector

圖表 Chart 7

所有能源消耗按燃料和類別劃分

Total Energy Consumption by Fuel & by Sector

參考表格 Refer Table 2, 8, 9, 10



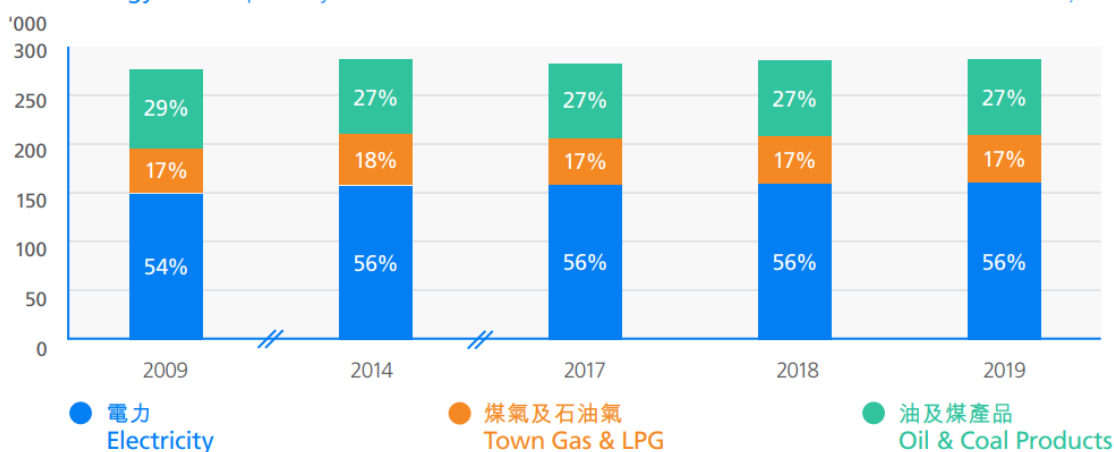
圖表 Chart 8

所有能源使用按燃料劃分

Total Energy Consumption by Fuel

參考表格 Refer Table 2

單位 Unit : 太焦耳 TeraJoule

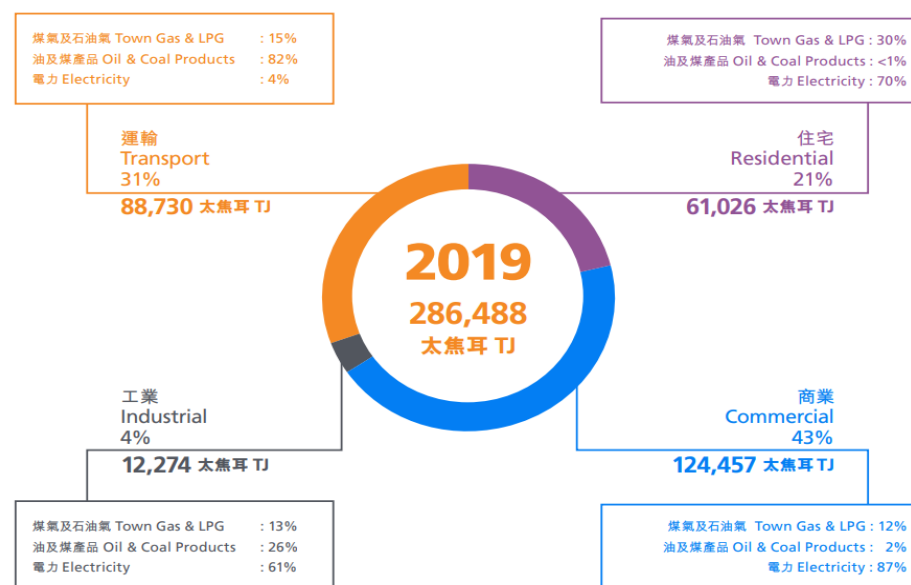


圖表 Chart 13

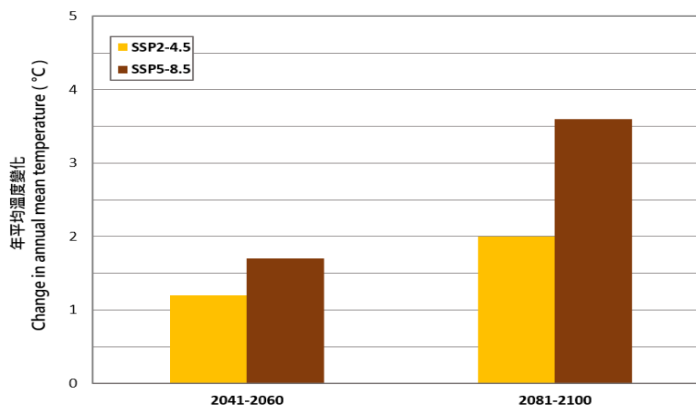
所有能源消耗按類別和燃料劃分

Total Energy Consumption by Sector & by Fuel

參考表格 Refer Table 3, 4, 5, 6, 7

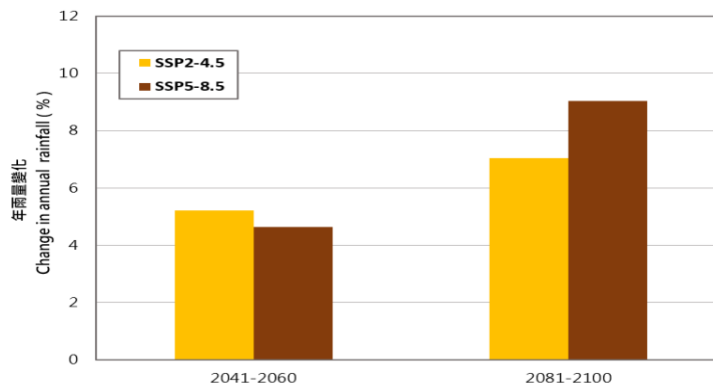


A.2.1 Projected change in the annual mean temperature of Hong Kong



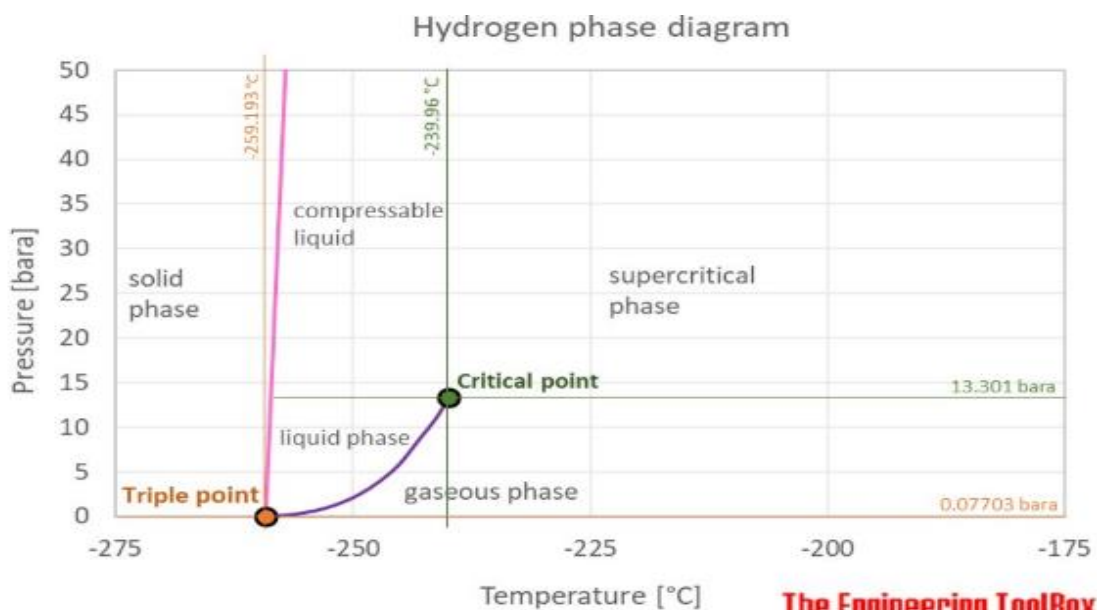
Projected change in annual mean temperature of Hong Kong relative to the average of 1995-2014 under the intermediate (SSP2-4.5) and very high (SSP5-8.5) greenhouse gas emissions scenarios. (Data source: IPCC AR6)

A.2.2 Projected change in the annual rainfall of Hong Kong



Projected change in annual rainfall of Hong Kong relative to the average of 1995-2014 under the intermediate (SSP2-4.5) and very high (SSP5-8.5) greenhouse gas emissions scenarios. (Data source: IPCC AR6)

A 2.2.4 Phase diagram of liquid hydrogen [75]



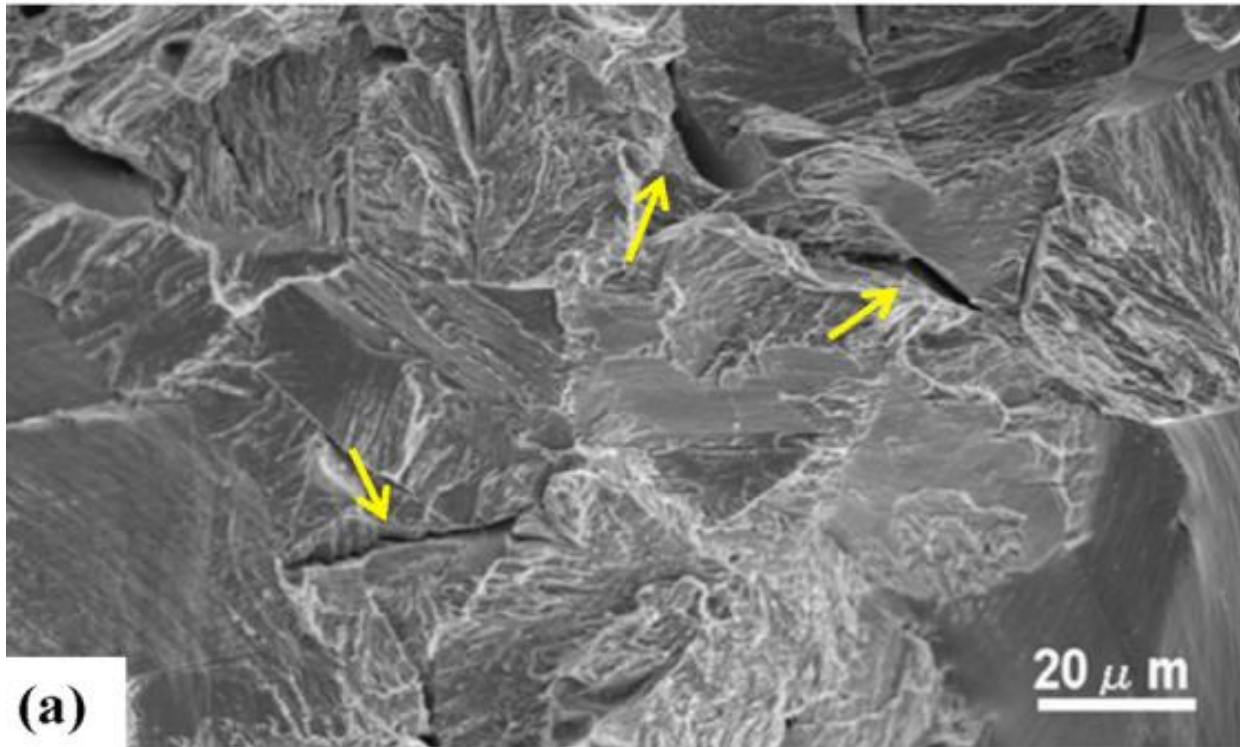
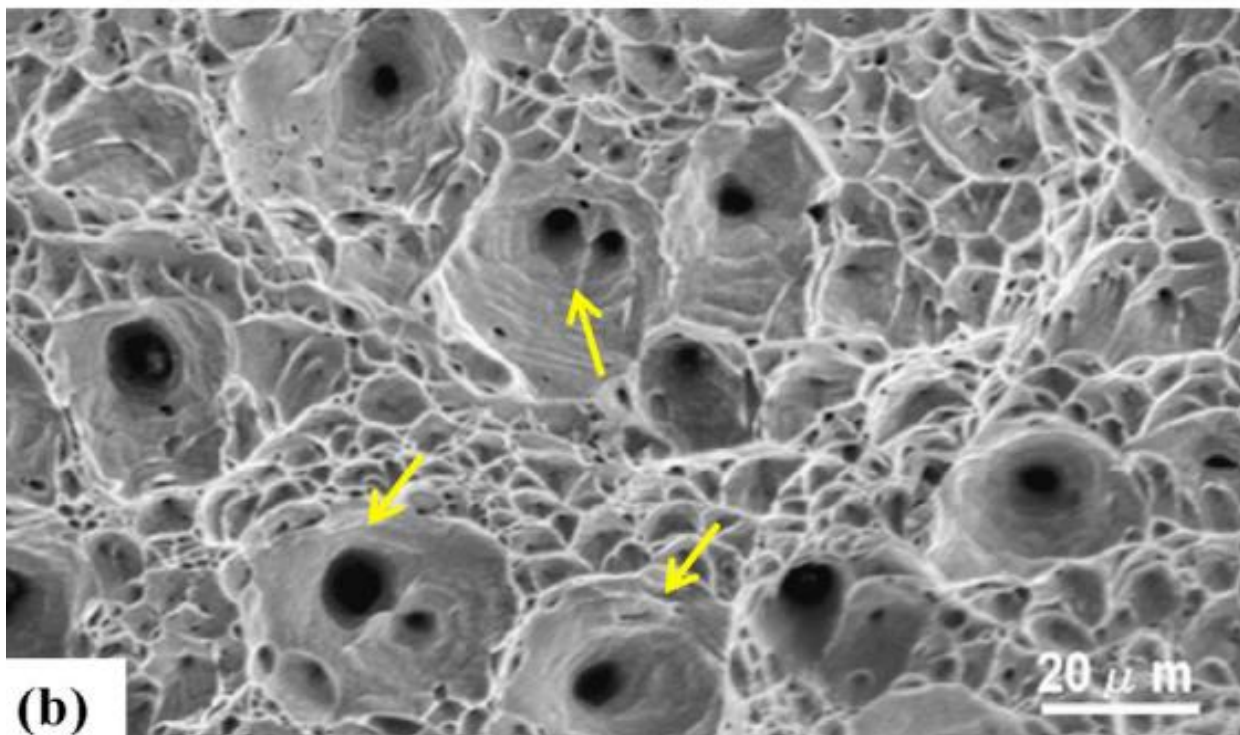
A2.2.4 BWB Hydrogen future aircraft [76]



A2.2.13 Liquid hydrogen transportation ship (HySTRA).[70]



A.2.3 SEM of fracture surfaces of (a) the type 316 (Ni_{eq} 26.45%) austenitic stainless steel with transgranular cracks and (b) the type 316 (Ni_{eq} 28.29) austenitic steel with dimple rupture (both were tested in 10 bar hydrogen at 200K). [25]



Appendix B

B.1 Hong Kong International Airport Flight and Passenger Data

(April 2016 – March 2021)

Fiscal Year	Aircraft Movement		Passenger *		Commercial Cargo	
	Movement	% Change (from last fiscal year)	Number	% Change (from last fiscal year)	Tonnes	% Change (from last fiscal year)
2016-2017	410 455	0.1%	70 047 862	1.1%	4 635 588	6.7%
2017-2018	423 436	3.2%	73 257 295	4.6%	4 981 942	7.5%
2018-2019	428 895	1.3%	74 822 142	2.1%	4 957 124	-0.5%
2019-2020	377 455	-12.0%	69 719 078	-18.8%	4 591 781	-7.4%
2020-2021	127 801	-66.1%	835 961	-98.6%	4 555 070	-0.8%

* Passengers include transfer, but exclude transit passengers.

B.1.1 Total Flights Through Hong Kong International Airport

Five-Year Total Flights Handled by Air Traffic Management Division

(April 2016 – March 2021)

Fiscal Year	Flights Handled*	% Change (from last fiscal year)
2016-2017	700 868	5%
2017-2018	764 824	9%
2018-2019	810 817	6%
2019-2020	744 197	-8.2%
2020-2021	214 921	-71.1%

* "Flights Handled" is the total number of aircraft handled by the Air Traffic Management Division of CAD in the year. It includes:

- (1) international and local aircraft movements at the Hong Kong International Airport;
- (2) flights transiting the Hong Kong Flight Information Region not landing Hong Kong;
- (3) flights landing and departing the Macao International Airport handled by the Air Traffic Management Division.

B.1.2 CO₂ emissions from passenger transport in 2019-top 10 departure countries (International and Domestic)

Rank	Departure country	CO ₂ [Mt]	% of total global CO ₂	RPKs [billions]	% of total global RPKs	CO ₂ intensity [g CO ₂ / RPK]
1	United States ^a	61.9	7.9	668	7.7	93
2	China ^b	34.5	4.4	397	4.6	87
3	United Kingdom ^c	30.3	3.9	353	4.1	86
4	United Arab Emirates	21.5	2.7	243	2.8	89
5	Germany	21.4	2.7	240	2.8	89
6	Spain	16.7	2.1	217	2.5	77
7	Japan	16.0	2.0	187	2.1	86
8	France ^d	15.9	2.0	183	2.1	87
9	Australia ^e	12.5	1.6	145	1.7	86
10	Canada	11.9	1.5	141	1.6	84

Rank	Departure country	CO ₂ [Mt]	% of total global CO ₂	RPKs [billions]	% of total global RPKs	CO ₂ intensity [g CO ₂ / RPK]
1	United States ^a	117	15	1,222	14	96
2	China ^b	68.4	8.7	770	8.8	89
3	India	12.1	1.5	140	1.6	86
4	Russian Federation	10.2	1.3	113	1.3	90
5	Japan	9.92	1.3	87.5	1.0	113
6	Brazil	9.49	1.2	96.4	1.1	98
7	Indonesia	8.08	1.0	81.7	0.9	99
8	Australia ^c	7.05	0.9	72.2	0.8	98
9	Canada	6.28	0.8	62.5	0.7	100
10	Mexico	5.51	0.7	57.5	0.7	96

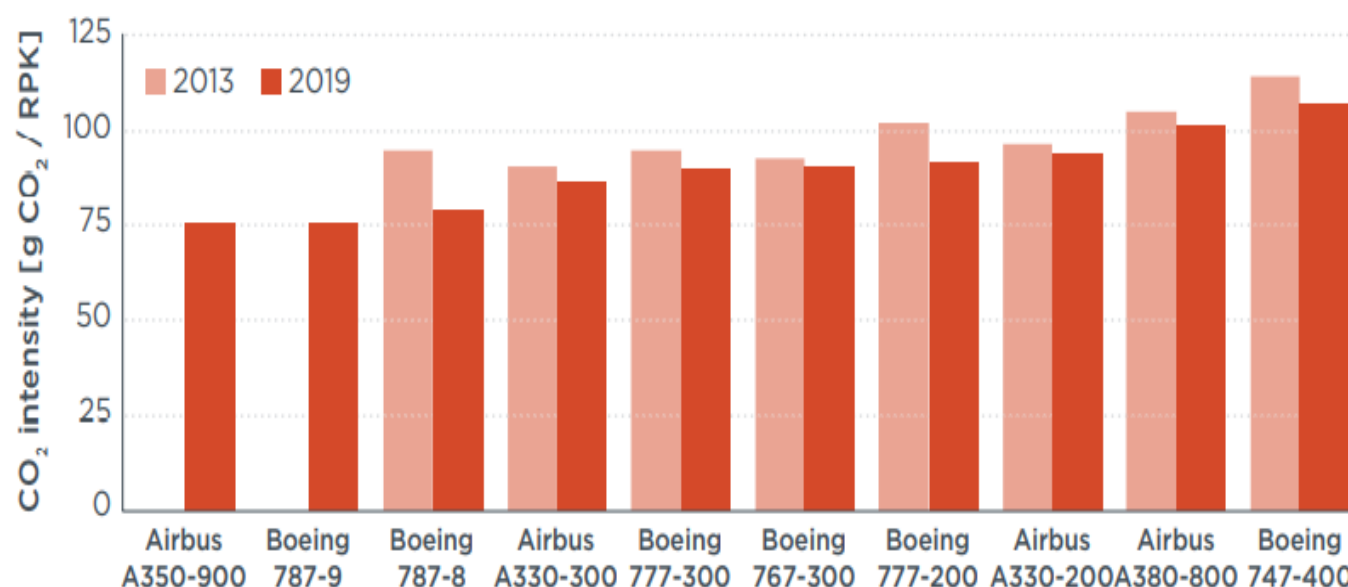
^a Includes American Samoa, Guam, Johnston Island, Kingman's Reef, Midway, Palmyra, Puerto Rico, Saipan (Mariana Islands), Wake Island, U.S. Virgin Islands

^b Includes Hong Kong SAR and Macau SAR

^c Includes Christmas Island, Coco Islands, Norfolk Island

B.1.3 Passenger CO₂ emissions from the top 10 widebody aircraft types, ranked by total emissions, in 2013, 2018 and 2019.

2019 rank	Widebody aircraft type	Avg seats per flight (2019)	CO ₂ emissions [Mt]			Change 2013-2019
			2013	2018	2019	
1	Boeing 777-300 / -300ER	353	46.2	78.6	77.0	+ 67%
2	Airbus A330-300	298	29.1	43.6	40.6	+ 39%
3	Airbus A380-800	500	16.2	33.8	34.3	+ 112%
4	Airbus A330-200	270	29.5	33.6	33.6	+ 14%
5	Boeing 777-200 / -200ER / -200LR	315	38.4	32.0	32.3	- 16%
6	Boeing 787-9	284	—	23.7	29.8	—
7	Boeing 787-8	257	2.86	18.8	19.3	+ 574%
8	Airbus A350-900	302	—	12.7	18.9	—
9	Boeing 767-300 / -300ER	246	27.4	17.3	15.9	- 42%
10	Boeing 747-400	366	30.9	12.5	11.6	-62%



B.2 Renewable Energy in Hong Kong by Type and by Fuel

香港可再生能源按類別劃分

Type of Renewable Energy in Hong Kong

單位 Unit：太焦耳 Terajoule

可再生能源類別 Type of Renewable Energy	可再生能源 Renewable Energy	所佔比例 Percentage
轉廢為能 Waste-to-energy	2,074	84.9%
風能及水能 Wind Energy & Hydropower	15	0.6%
太陽能 Solar Energy	74	3.0%
生物柴油 Bio-diesel	279	11.4%
總計 Total	2,442	100.0%

表格 Table 16

香港可再生能源按燃料劃分

Type of Renewable Energy in Hong Kong by Fuel

單位 Unit：太焦耳 Terajoule

燃料類別 Type of Fuel	燃料佔所有能源用途的比重 Weighting of Fuel in Energy End-use	可再生能源在所屬燃料類別的比重 Weighting of Renewable Energy in Respective Fuel Type
電力 Electricity	161,670 (56.4%)	424 (0.3%)
煤氣及石油氣 Town Gas & Liquefied Petroleum Gas	47,338 (16.5%)	1,739 (3.7%)
油及煤產品 Oil & Coal Products	77,480 (27.0%)	279 (0.4%)
總計 Total	286,488 (100.0%)	2,442 (0.9%)

B.2.1 Thermal conductivity and expansion of cryogenic materials

Table A1 – Thermal conductivity and expansion coefficient of austenitic steels and aluminium alloys at cryogenic temperatures [92–96].

Material type	Temperature [K]	Thermal conductivity [W/m/K]	Thermal expansion coefficient [K ⁻¹ ·10 ⁻⁶]
Austenitic stainless steels			
304	4	0.28	10.20
	77	7.90	13.00
304s (stabilised)	4	0.27	10.28
	20	2.17	10.99
	77	7.92	12.95
310	4	0.24	10.20
	77	5.90	13.00
316	4	0.28	10.20
	77	7.90	13.00
High-Mn (29% Mn)	77	19.00	N/A
Aluminium alloys			
1050	1	19.10	N/A
2219-T81	1	0.96	N/A
	20	19.00	N/A
	77	62.20	N/A
6061-T6	1	2.52	N/A
	4	5.35	14.32
	20	28.43	15.22
	77	83.53	18.00

8.4 Green Hydrogen Production and Supply Chain: Energy, Feedstock, Cost, CO2 Emissions and Required Flights.

8.41 Baseline Aircraft Engine Green Hydrogen Fuel Calculation. [67-71]

HVLER (Baseline) Mission Requirement HKIA-LGW				Feedstock Requirements		Energy	
Total Liquid Hydrogen Mission Requirement in Tonnes	546.56	LH2/Cubic metres		De-ionised Water (Litres per kilogram) of hydrogen	10.00	Feedstock	
38.686	546555.81	LH2/Litres		Daily (Single flight) mass of hydrogen required post electrolysis+Logistics (tonnes)	66.12	CO2	
Electrical energy required to generate one tonne of hydrogen				Total volume of required water (Litres)	661178.91	Hydrogen requirement	
55MWh				Total volume of de-ionised water in cubic metres	661.18	Cost in USD	
Power consumption to produce 2000 kg of hydrogen per hour per electrolyser.				Energy required to de-ionise one kilogram of water (kJ/kg)	14.40	Weekly Flights	
17.5MW				Energy required to de-ionise one metres cubed of water (kWh)/kg	4.00		
Energy required to generate the required hydrogen (MWh)	2127.73			Total energy required to de-ionise the required water for the mission (MWh)	2644.72		
				Total number of annual passengers to Hong Kong (2019)	166735.00		
Hydrogen Liquefaction				Total number of single flights required annually	718.69		
Energy Requirement for hydrogen liquefaction per kWh/kg	15.00			Total annual amount of annual hydrogen consumption for a single flight (tonnes)	24199.15		
Total energy required for the liquefaction process in (MWh)	580.29			Total liquid hydrogen requirement for a single flight (Cubic metres)	546.56		
				Total liquid hydrogen requirement per day (cubic metres)	1093.12		
Cryogenic Hydrogen Storage kw/kg	6.00			Total number of weekly single flights required from HKIA-LGW	13.82		
				Required annual flights CO ₂ emission from Hong Kong to London Gatwick. (Tonnes).	517004.57		
Total energy required for storage (MWh)	232.12			CO ₂ emission Hong Kong including supply chain infra-structure carbon offset. (Tonnes).	1215914.39		
				Percentage of the total annual CO ₂ emissions of Hong Kong (2019)	3.02		
Cryogenic Hydrogen Transportation kW/kg	9.00			Percentage of total annual transport emissions in Hong Kong (2019)	16.73		
Total energy required for transportation (MWh)	348.17			Percentage of total annual International Civil Aviation emissions for Hong Kong (2019)	11.58		
Cryogenic Liquid Hydrogen Transfer to aircraft kW/kg	3.00			CO ₂ penalty of setting up the wind farms (tonnes)	138.19		
Total energy required for fuel transfer (MWh)	116.06			CO ₂ saving with the use of a green hydrogen supply chain. (tonnes)	699048.00		
Aircraft Cryogenic Storage kW/kg	6.00						
Total energy required for storage (MWh)	232.12						
Liquid Hydrogen Required in Heating to Pre-Combustion Temperature (tonnes)	38.69			Direct Operating Cost per flight in USD (Kerosene)	112967.00		
				Direct Operating Cost per flight in USD (Hydrogen)	75025.00	1.085 USD/ kg (JetA)	Hong Kong
				Total green hydrogen cost in USD per day (Total hydrogen supply chain and flights)	571628.84	4.33 USD/kg (H2)	Europe
Total Energy required for a single HVLER flight (MWh)	3636.48	6.28	12.56	12562399.27			
		GWh	GWh/day	KWh/day			
		Ionisation	Two flights	Hydrogen requirement per day for all flights to UK (tonnes)	47517.96		
				Hydrogen needed for two flights per day to UK (tonnes)	132.24		
				Energy in kWh needed per kilogram of liquid hydrogen for one day (kWh/kg)	95.00		
				Cost in Hong Kong Dollars (HKD)	147.25		
				Cost in US Dollars (USD)	19.14		
				Cost in US Dollars (USD) per Kilogram of cryogenic hydrogen	4.96	USD/kg (H2)	Hong Kong

8.42 Intercooled Aircraft Engine Green Hydrogen Fuel Calculation. [67-71]

HVLER Mission (With Intercooler) Requirement HKIA-LGW				Feedstock Requirements		Energy	
		LH2/Cubic					
Total Liquid Hydrogen Mission Requirement in Tonnes	612.43	metres		De-ionised Water (Litres per kilogram) of hydrogen	10.00	Feedstock	
43.349	612434.67	LH2/Litres		Daily (Single flight) mass of hydrogen required post electrolysis+Logistics (tonnes)	74.09	CO2	
Electrical energy required to generate one tonne of hydrogen				Total volume of required water (Litres)	740873.82	Hydrogen requirement	
55MWh				Total volume of de-ionised water in cubic metres	740.87	Cost (USD)	
Power consumption to produce 2000 kg of hydrogen per hour per electrolyser.				Energy required to de-ionise one kilogram of water (kJ/kg)	14.40	Weekly Flights	
17.5MW				Energy required to de-ionise one metres cubed of water (kWh/kg)	4.00		
Energy required to generate the required hydrogen (MWh)	2384.20			Total energy required to de-ionise the required water for the mission (MWh)	2963.50		
				Total number of annual passengers to Hong Kong (2019)	166735.00		
Hydrogen Liquefaction				Total number of single flights required annually	786.49		
Energy Requirement for hydrogen liquefaction per kWh/kg	15.00			Total (annual) amount of hydrogen consumption for a single flight (tonnes)	27115.98		
Total energy required for the liquefaction process in (MWh)	650.24			Total liquid hydrogen requirement for a single flight (Cubic metres)	612.43		
				Total liquid hydrogen requirement per day (Cubic metres)	1224.86		
Cryogenic Hydrogen Storage kW/kg	6.00			Total number of weekly single flights required from HKIA-LGW	15.12		
				Required annual flights CO ₂ emission from Hong Kong to London Gatwick. (Tonnes).	587454.60		
Total energy required for storage (MWh)	260.09			CO ₂ emission Hong Kong including supply chain infrastructure carbon offset. (Tonnes).	1345550.75		
				Percentage of the total annual CO ₂ emissions of Hong Kong (2019)	3.35		
Cryogenic Hydrogen Transportation kW/kg	9.00			Percentage of total annual transport emissions in Hong Kong (2019)	18.51		
Total energy required for transportation (MWh)	390.14			Percentage of total annual International Civil Aviation emissions for Hong Kong (2019)	12.81		
Cryogenic Liquid Hydrogen Transfer to aircraft kW/kg	3.00			CO ₂ penalty of setting up the wind farms (tonnes)	154.84		
Total energy required for fuel transfer (MWh)	130.05			CO ₂ saving with the transportation and fuel transfer to aircraft using green hydrogen. (tonnes)	758251.00		
Aircraft Cryogenic Storage kW/kg	6.00						
Total energy required for storage (MWh)	260.09						
Liquid Hydrogen Required in Heating to Pre-Combustion Temperature (tonnes)	43.35			Direct Operating Cost per flight in USD (Kerosene)	158744.00		
				Direct Operating Cost per flight in USD (Hydrogen)	77091.00	1.085	USD/ kg (JetA) Hong Kong
				Total green hydrogen cost in USD per day (Total hydrogen supply chain and flights)	640529.87	4.33	USD/kg (H2) Europe
Total Energy required for a single HVLER flight. (MWh)	4074.81	7.04	14.08	14076602.55			
		GWh	GWh/day	KWh/day			
		Ionisation	Two flights	Hydrogen requirement per day for all flights to UK (tonnes)	58268.68		
				Hydrogen needed for two flights per day to UK (tonnes)	148.17		
				Energy in kWh needed per kilogram of liquid hydrogen for one day (kWh/kg)	95.00		
				Cost in Hong Kong Dollars (HKD)	147.25		
				Cost in US Dollars (USD)	19.14		
				Cost in US Dollars (USD) per Kilogram of cryogenic hydrogen	4.96	USD/kg (H2)	Hong Kong

Appendix C

C6.2 Baseline engine Off-Design Turbomatch input file for Hydrogen fuel with constant Net Thrust engines.

C6.2.1 Off-Design Point-Hydrogen

```
|
File created using TURBOMATCH 3.0 (GUI)

////
OD SI HY VA FP
-1
-1
INTAKE S1,2 D1-6 R7 W1,2
COMPRES2,3 D8-19 R20 V8 V9
PREMAS S3,20,4 D21-24 V21
DUCTER S20,21 D25-29 R30
NOZCON S21,22,1 D31-34 R35
COMPRES4,5 D36-47 R48 V36 V37
PREMAS S5,25,6 D49-52
COMPRES6,7 D53-64 R65 V53 V54
PREMAS S7,26,8 D66-69
BURNER S8,9 D70-79 R80
MIXEES S9,26,10
TURBIN S10,11 D81-96 V82
MIXEES S11,25,12
TURBIN S12,13 D97-112 V98
TURBIN S13,14 D113-128 V114
NOZCON S14,15,1 D129-132 R133
PERFOR S1,0,0 D134,135,136,137,35,7,80,133,0,0,0,0,0
CODEND

////
1 0.0 ! Altitude
2 0.0 ! T ISA deviation
3 0.0 ! Flight Mach n
4 -1.0 ! Pressure recovery
5 0.0 ! P ISA deviation
6 0.0 ! Relative humidity

8 0.8 ! Surge margin
9 0.8754 ! CN @DP - PCN @OD
10 1.44 ! PR @DP
11 0.91 ! Eta_is @DP
12 1 ! Error selector
13 4.0 ! Map number
14 1.0 ! Shaft number
15 1.0 ! SF PR
16 1.0 ! SF WRTP
17 1.0 ! SF Eta_is
18 -1 ! Volume (TR)
19 0 ! VSV rel to DP

21 0.90566 ! Lambda W (BPR / [BPR + 1])
22 0 ! Delta W (absolute flow to out_2)
23 1 ! Lambda P ([P_out_2 - deltaP] / P_in)
24 0 ! Delta P (absolute P change to out_2)

25 0 ! Intercooling/reheating switch
26 0.015 ! Pressure losses (deltaP/P_in)
27 1 ! Eta_comb
28 0 ! Limiting fuel flow
29 -1 ! Volume (TR)
```

```

31 -1.0      ! Floating area switch
32 1.0      ! SF Area
33 -1      ! Cone angle
34 -1      ! Inlet Mach n

36 0.87789  ! Surge margin
37 1.0      ! CN @DP - PCN @OD
38 5.9      ! PR @DP
39 0.9      ! Eta_is @DP
40 1        ! Error selector
41 5.0      ! Map number
42 2.0      ! Shaft number
43 1.0      ! SF PR
44 1.0      ! SF WRTP
45 1.0      ! SF Eta_is
46 -1      ! Volume (TR)
47 0        ! VSV rel to DP

49 0.015    ! Lambda W ([W_out_2ary - deltaW] / W_in)
50 0.0      ! Delta W (absolute flow to out_2)
51 1        ! Lambda P ([P_out_2ary - deltaP] / P_in)
52 0        ! Delta P (absolute P change to out_2)

53 0.817    ! Surge margin
54 1.0      ! CN @DP - PCN @OD
55 5.9      ! PR @DP
56 0.9      ! Eta_is @DP
57 1        ! Error selector
58 3.0      ! Map number
59 3.0      ! Shaft number
60 1.0      ! SF PR
61 1.0      ! SF WRTP
62 1.0      ! SF Eta_is
63 -1      ! Volume (TR)
64 0        ! VSV rel to DP

66 0.201    ! Lambda W ([W_out_2ary - deltaW] / W_in)
67 0.0      ! Delta W (absolute flow to out_2)
68 1        ! Lambda P ([P_out_2ary - deltaP] / P_in)
69 0        ! Delta P (absolute P change to out_2)

70 0.04     ! Pressure losses
71 0.99     ! Eta_comb
72 -1      ! Fuel flow
73 0.0      ! Water flow
74 288.0    ! Water T
75 0.0      ! Water phase (0=liquid, 1=vapour)
76 1.0      ! SF Eta_comb
77 -1      ! Volume (TR)
78 -1      ! Fuel T
79 -1      ! Fuel P coeff [P_fuel/P_cc]

```

```

81 0.0      ! Power out or P_out
82 0.7      ! Relative delH/T @DP
83 0.6      ! Relative CN @DP
84 0.92     ! Eta_is @DP
85 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
86 3.0      ! Shaft number (0=FPT)
87 5.0      ! Map number
88 -1.0     ! Power law index
89 1.0      ! SF WRTP
90 1.0      ! SF delH/T
91 1.0      ! SF Eta_is
92 -1       ! Spool rotational speed (TR)
93 -1       ! Spool moment of inertia (TR)
94 -1       ! Volume (TR)
95 -1.0     ! Turbine work split
96 0        ! NGV rel to DP

```

```

97 0.0      ! Power out or P_out
98 0.7      ! Relative delH/T @DP
99 0.6      ! Relative CN @DP
100 0.92     ! Eta_is @DP
101 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
102 2.0      ! Shaft number (0=FPT)
103 5.0      ! Map number
104 -1.0     ! Power law index
105 1.0      ! SF WRTP
106 1.0      ! SF delH/T
107 1.0      ! SF Eta_is
108 -1       ! Spool rotational speed (TR)
109 -1       ! Spool moment of inertia (TR)
110 -1       ! Volume (TR)
111 -1.0     ! Turbine work split
112 0        ! NGV rel to DP

```

```

113 0.0      ! Power out or P_out
114 0.8      ! Relative delH/T @DP
115 0.6      ! Relative CN @DP
116 0.93     ! Eta_is @DP
117 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
118 1.0      ! Shaft number (0=FPT)
119 5.0      ! Map number
120 -1.0     ! Power law index
121 1.0      ! SF WRTP
122 1.0      ! SF delH/T
123 1.0      ! SF Eta_is
124 -1       ! Spool rotational speed (TR)
125 -1       ! Spool moment of inertia (TR)
126 -1       ! Volume (TR)
127 -1.0     ! Turbine work split
128 0        ! NGV rel to DP

```

```

129 -1.0     ! Floating area switch
130 1.0      ! SF Area
131 -1       ! Cone angle
132 -1       ! Inlet Mach n

```

```

134 -1      ! Power out brick (power turbine) or -1
135 1        ! Propeller efficiency
136 0        ! Switch handle thrust/power
137 0        ! Thrust/power handle

```

```

-1
1 2 1500.0
9 6 1856.7
-1
-3

```

C6.2.2 Design Point – Hydrogen

File created using TURBOMATCH 3.0 (GUI)

```

////
DP SI HY VA FP
-1
-1
INTAKE S1,2 D1-6 R7
COMPRES2,3 D8-19 R20
PREMAS S3,20,4 D21-24
DUCTER S20,21 D25-29 R30
NOZCON S21,22,1 D31-34 R35
COMPRES4,5 D36-47 R48
PREMAS S5,25,6 D49-52
COMPRES6,7 D53-64 R65
PREMAS S7,26,8 D66-69
BURNER S8,9 D70-79 R80
MIXEES S9,26,10
TURBIN S10,11 D81-96
MIXEES S11,25,12
TURBIN S12,13 D97-112
TURBIN S13,14 D113-128
NOZCON S14,15,1 D129-132 R133
PERFOR S1,0,0 D134,135,136,137,35,7,80,133,0,0,0,0,0
CODEND

////
1 10668.0 ! Altitude
2 0.0 ! T ISA deviation
3 0.8 ! Flight Mach n|
4 -1.0 ! Pressure recovery
5 0.0 ! P ISA deviation
6 0.0 ! Relative humidity

8 0.8 ! Surge margin
9 0.8754 ! CN @DP - PCN @OD
10 1.44 ! PR @DP
11 0.91 ! Eta_is @DP
12 1 ! Error selector
13 4.0 ! Map number
14 1.0 ! Shaft number
15 1.0 ! SF PR
16 1.0 ! SF WRTP
17 1.0 ! SF Eta_is
18 -1 ! Volume (TR)
19 0 ! VSV rel to DP

21 0.90566 ! Lambda W (BPR / [BPR + 1])
22 0 ! Delta W (absolute flow to out_2)
23 1 ! Lambda P ([P_out_2 - deltaP] / P_in)
24 0 ! Delta P (absolute P change to out_2)

25 0 ! Intercooling/reheating switch
26 0.015 ! Pressure losses (deltaP/P_in)
27 1 ! Eta_comb
28 0 ! Limiting fuel flow
29 -1 ! Volume (TR)

```

```

31 -1.0      ! Floating area switch
32 1.0      ! SF Area
33 -1      ! Cone angle
34 -1      ! Inlet Mach n

36 0.87789  ! Surge margin
37 1.0      ! CN @DP - PCN @OD
38 5.9      ! PR @DP
39 0.9      ! Eta_is @DP
40 1        ! Error selector
41 5.0      ! Map number
42 2.0      ! Shaft number
43 1.0      ! SF PR
44 1.0      ! SF WRTP
45 1.0      ! SF Eta_is
46 -1      ! Volume (TR)
47 0        ! VSV rel to DP

49 0.015    ! Lambda W ([W_out_2ary - deltaW] / W_in)
50 0.0      ! Delta W (absolute flow to out_2)
51 1        ! Lambda P ([P_out_2ary - deltaP] / P_in)
52 0        ! Delta P (absolute P change to out_2)

53 0.817    ! Surge margin
54 1.0      ! CN @DP - PCN @OD
55 5.9      ! PR @DP
56 0.9      ! Eta_is @DP
57 1        ! Error selector
58 3.0      ! Map number
59 3.0      ! Shaft number
60 1.0      ! SF PR
61 1.0      ! SF WRTP
62 1.0      ! SF Eta_is
63 -1      ! Volume (TR)
64 0        ! VSV rel to DP

66 0.15     ! Lambda W ([W_out_2ary - deltaW] / W_in)
67 0.0      ! Delta W (absolute flow to out_2)
68 1        ! Lambda P ([P_out_2ary - deltaP] / P_in)
69 0        ! Delta P (absolute P change to out_2)

70 0.04     ! Pressure losses
71 0.99     ! Eta_comb
72 -1      ! Fuel flow
73 0.0      ! Water flow
74 288.0    ! Water T
75 0.0      ! Water phase (0=liquid, 1=vapour)
76 1.0      ! SF Eta_comb
77 -1      ! Volume (TR)
78 -1      ! Fuel T
79 -1      ! Fuel P coeff [P_fuel/P_cc]

```

```

81 0.0      ! Power out or P_out
82 0.7      ! Relative delH/T @DP
83 0.6      ! Relative CN @DP
84 0.92     ! Eta_is @DP
85 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
86 3.0      ! Shaft number (0=FPT)
87 5.0      ! Map number
88 -1.0     ! Power law index
89 1.0      ! SF WRTP
90 1.0      ! SF delH/T
91 1.0      ! SF Eta_is
92 -1       ! Spool rotational speed (TR)
93 -1       ! Spool moment of inertia (TR)
94 -1       ! Volume (TR)
95 -1.0     ! Turbine work split
96 0        ! NGV rel to DP

```

```

97 0.0      ! Power out or P_out
98 0.7      ! Relative delH/T @DP
99 0.6      ! Relative CN @DP
100 0.92    ! Eta_is @DP
101 -1.0    ! PCN @DP (-1=compressor turbine, 1=FPT)
102 2.0      ! Shaft number (0=FPT)
103 5.0      ! Map number
104 -1.0    ! Power law index
105 1.0      ! SF WRTP
106 1.0      ! SF delH/T
107 1.0      ! SF Eta_is
108 -1       ! Spool rotational speed (TR)
109 -1       ! Spool moment of inertia (TR)
110 -1       ! Volume (TR)
111 -1.0     ! Turbine work split
112 0        ! NGV rel to DP

```

```

113 0.0      ! Power out or P_out
114 0.8      ! Relative delH/T @DP
115 0.6      ! Relative CN @DP
116 0.93     ! Eta_is @DP
117 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
118 1.0      ! Shaft number (0=FPT)
119 5.0      ! Map number
120 -1.0     ! Power law index
121 1.0      ! SF WRTP
122 1.0      ! SF delH/T
123 1.0      ! SF Eta_is
124 -1       ! Spool rotational speed (TR)
125 -1       ! Spool moment of inertia (TR)
126 -1       ! Volume (TR)
127 -1.0     ! Turbine work split
128 0        ! NGV rel to DP

```

```

129 -1.0     ! Floating area switch
130 1.0      ! SF Area
131 -1       ! Cone angle
132 -1       ! Inlet Mach n

```

```

134 -1       ! Power out brick (power turbine) or -1
135 1         ! Propeller efficiency
136 0         ! Switch handle thrust/power
137 0         ! Thrust/power handle

```

```

-1
1   2   368.7
9   6   1437.0
-1
-3

```

C6.3 Intercooled engine Off-Design Turbomatch input file for Hydrogen fuel with constant Net Thrust engines.

C6.3.2 Off-Design Point-Hydrogen

File created using TURBOMATCH 3.0 (GUI)

////

OD SI HY VA FP

-1

-1

INTAKE	S1,2	D1-6	R7	W1,2
COMPRES	S2,3	D8-19	R20	V8 V9
PREMAS	S3,4,18	D21-24		V21
COMPRES	S4,5	D25-36	R37	V25 V26
PREMAS	S5,30,31	D38-41		
PREMAS	S31,23,6	D42-45		
MIXEES	S18,23,19			
PREMAS	S19,24,20	D46-49		
DUCTER	S20,21	D50-54	R55	
HETCOL	S24,25	D56-59		
MIXEES	S21,25,26			
HETHOT	S24,6,7	D60-63		
COMPRES	S7,8	D64-75	R76	V64 V65
PREMAS	S8,29,9	D77-80		
PREMAS	S9,28,10	D81-84		
BURNER	S10,11	D85-94	R95	
MIXEES	S11,28,12			
TURBIN	S12,13	D96-111		V97
MIXEES	S13,30,14			
TURBIN	S14,15	D112-127		V113
TURBIN	S15,16	D128-143		V129
DUCTER	S16,17	D144-148	R149	
NOZCON	S26,27,1	D150-153	R154	
NOZCON	S17,18,1	D155-158	R159	
PERFOR	S1,0,0	D160,161,162,163,159,7,95,154,0,0,0,0,0		
CODEND				

////

1	0.0	! Altitude
2	0.0	! T ISA deviation
3	0.0	! Flight Mach n
4	0.99	! Pressure recovery
5	0.0	! P ISA deviation
6	0.0	! Relative humidity
8	0.8	! Surge margin
9	0.8754	! CN @DP - PCN @OD
10	1.44	! PR @DP
11	0.91	! Eta_is @DP
12	1	! Error selector
13	4.0	! Map number
14	1.0	! Shaft number
15	1.0	! SF PR
16	1.0	! SF WRTP
17	1.0	! SF Eta_is
18	-1	! Volume (TR)
19	0	! VSV rel to DP

```

21 0.09434      ! Lambda W (BPR / [BPR + 1])
22 0            ! Delta W (absolute flow to out_2)
23 1            ! Lambda P ([P_out_2 - deltaP] / P_in)
24 0            ! Delta P (absolute P change to out_2)

25 0.8          ! Surge margin
26 0.8754       ! CN @DP - PCN @OD
27 5.90         ! PR @DP
28 0.90         ! Eta_is @DP
29 1            ! Error selector
30 5.0          ! Map number
31 2.0          ! Shaft number
32 1.0          ! SF PR
33 1.0          ! SF W RTP
34 1.0          ! SF Eta_is
35 -1           ! Volume (TR)
36 0            ! VSV rel to

38 0.015        ! Lambda W ([W_out_2ary - deltaW] / W_in)
39 0.0          ! Delta W (absolute flow to out_2)
40 1            ! Lambda P ([P_out_2ary - deltaP] / P_in)
41 0            ! Delta P (absolute P change to out_2)

42 0.0          ! Lambda W ([W_out_2ary - deltaW] / W_in)
43 0.0          ! Delta W (absolute flow to out_2)
44 1            ! Lambda P ([P_out_2ary - deltaP] / P_in)
45 0            ! Delta P (absolute P change to out_2)

46 0.15         ! INTERCOOLER SPLITTER- PREMAS
47 0.0          ! Delta W (absolute flow to out_2)
48 1            ! Lambda P ([P_out_2ary - deltaP] / P_in)
49 0            ! Delta P (absolute P change to out_2)

50 0            ! Intercooling/reheating switch
51 0.015        ! Pressure losses (deltaP/P_in)
52 1            ! Eta_comb
53 1000000000   ! Limiting fuel flow
54 -1           ! Volume (TR)

56 0.065        ! HETCOL DELTA P
57 0.6          ! Effectiveness
58 1            ! Type (1,3)
59 0            ! Delta W/W Mass flow leakage

60 0.065        ! INTERCOOLER-HETHOT DELTA P
61 0.755        ! Effectiveness
62 1            ! Type (1,3)
63 0            ! Delta W/W Mass flow leakage

```

```

64  0.817      ! Surge margin
65  1.0        ! CN @DP - PCN @OD
66  5.90       ! PR @DP
67  0.90       ! Eta_is @DP
68  1          ! Error selector
69  3.0        ! Map number
70  3.0        ! Shaft number
71  1.0        ! SF PR
72  1.0        ! SF WRTP
73  1.0        ! SF Eta_is
74  -1         ! Volume (TR)
75  0          ! VSV rel to DP

77  0.01       ! ACCESSORY BYPASS
78  0.0        ! Delta W (absolute flow to out_2)
79  1          ! Lambda P ([P_out_2ary - deltaP] / P_in)
80  0          ! Delta P (absolute P change to out_2)

81  0.201      ! Lambda W ([W_out_2ary - deltaW] / W_in)
82  0.0        ! Delta W (absolute flow to out_2)
83  1          ! Lambda P ([P_out_2ary - deltaP] / P_in)
84  0          ! Delta P (absolute P change to out_2)

85  0.04       ! Pressure losses
86  0.99       ! Eta_comb
87  -1         ! Fuel flow
88  0.0        ! Water flow
89  288.0      ! Water T
90  0.0        ! Water phase (0=liquid, 1=vapour)
91  1.0        ! SF Eta_comb
92  -1         ! Volume (TR)
93  -1         ! Fuel T
94  -1         ! Fuel P coeff [P_fuel/P_cc]

96  0.0        ! Power out or P_out
97  0.7        ! Relative delH/T @DP
98  0.6        ! Relative CN @DP
99  0.92       ! Eta_is @DP
100 -1.0       ! PCN @DP (-1=compressor turbine, 1=FPT)
101 3.0        ! Shaft number (0=FPT)
102 5.0        ! Map number
103 -1.0       ! Power law index
104 1.0        ! SF WRTP
105 1.0        ! SF delH/T
106 1.0        ! SF Eta_is
107 -1         ! Spool rotational speed (TR)
108 -1         ! Spool moment of inertia (TR)
109 -1         ! Volume (TR)
110 -1.0       ! Turbine work split
111 0          ! NGV rel to DP

```

```

112  0.0      ! Power out or P_out
113  0.7      ! Relative delH/T @DP
114  0.6      ! Relative CN @DP
115  0.92     ! Eta_is @DP
116  -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
117  2.0      ! Shaft number (0=FPT)
118  5.0      ! Map number
119  -1.0     ! Power law index
120  1.0      ! SF WRTP
121  1.0      ! SF delH/T
122  1.0      ! SF Eta_is
123  -1       ! Spool rotational speed (TR)
124  -1       ! Spool moment of inertia (TR)
125  -1       ! Volume (TR)
126  -1.0     ! Turbine work split
127  0        ! NGV rel to DP

128  0.0      ! Power out or P_out
129  0.8      ! Relative delH/T @DP
130  0.6      ! Relative CN @DP
131  0.93     ! Eta_is @DP
132  -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
133  1.0      ! Shaft number (0=FPT)
134  5.0      ! Map number
135  -1.0     ! Power law index
136  1.0      ! SF WRTP
137  1.0      ! SF delH/T
138  1.0      ! SF Eta_is
139  -1       ! Spool rotational speed (TR)
140  -1       ! Spool moment of inertia (TR)
141  -1       ! Volume (TR)
142  -1.0     ! Turbine work split
143  0        ! NGV rel to DP

144  0        ! CORE DUCT-DUCTER: Air duct
145  0.015    ! Pressure losses (deltaP/P_in)
146  1        ! Eta_comb
147  100000000 ! Limiting fuel flow
148  -1       ! Volume (TR)

150  -1.0     ! Floating area switch
151  1.0      ! SF Area
152  -1       ! Cone angle
153  -1       ! Inlet Mach n

155  -1.0     ! Floating area switch
156  1.0      ! SF Area
157  -1       ! Cone angle
158  -1       ! Inlet Mach n

160  -1       ! Power out brick (power turbine) or -1
161  -1       ! Propeller efficiency
162  0        ! Switch handle thrust/power
163  0        ! Thrust/power handle

```

```

-1
1 2 1500 ! INLET MASS FLOW
11 6 1758.0 ! COT
-1
-3

```

C6.3 Intercooled engine Design Point Turbomatch input file for Hydrogen fuel with constant Net Thrust engines.

C6.3.2 Design Point-Hydrogen

File created using TURBOMATCH 3.0 (GUI)

```

////
DP SI HY VA FP
-1
-1
INTAKE S1,2 D1-6 R7 W1,2
COMPRES2,3 D8-19 R20 V8 V9
PREMAS S3,4,18 D21-24 V21
COMPRES4,5 D25-36 R37 V25 V26
PREMAS S5,30,31 D38-41
PREMAS S31,23,6 D42-45
MIXEES S18,23,19
PREMAS S19,24,20 D46-49
DUCTER S20,21 D50-54 R55
HETCOL S24,25 D56-59
MIXEES S21,25,26
HETHOT S24,6,7 D60-63
COMPRES7,8 D64-75 R76 V64 V65
PREMAS S8,29,9 D77-80
PREMAS S9,28,10 D81-84
BURNER S10,11 D85-94 R95
MIXEES S11,28,12
TURBIN S12,13 D96-111 V97
MIXEES S13,30,14
TURBIN S14,15 D112-127 V113
TURBIN S15,16 D128-143 V129
DUCTER S16,17 D144-148 R149
NOZCON S26,27,1 D150-153 R154
NOZCON S17,18,1 D155-158 R159
PERFOR S1,0,0 D160,161,162,163,159,7,95,154,0,0,0,0,0
CODEND

////
1 10668.0 ! Altitude
2 0.0 ! T ISA deviation
3 0.8 ! Flight Mach n
4 0.99 ! Pressure recovery
5 0.0 ! P ISA deviation
6 0.0 ! Relative humidity

8 0.8 ! Surge margin
9 0.8754 ! CN @DP - PCN @OD
10 1.44 ! PR @DP
11 0.91 ! Eta_is @DP
12 1 ! Error selector
13 4.0 ! Map number
14 1.0 ! Shaft number
15 1.0 ! SF PR
16 1.0 ! SF WRTP
17 1.0 ! SF Eta_is
18 -1 ! Volume (TR)
19 0 ! VSV rel to DP

```

```

21 0.09434      ! Lambda W (BPR / [BPR + 1])
22 0            ! Delta W (absolute flow to out_2)
23 1            ! Lambda P ([P_out_2 - deltaP] / P_in)
24 0            ! Delta P (absolute P change to out_2)

25 0.8          ! Surge margin
26 0.8754       ! CN @DP - PCN @OD
27 5.90         ! PR @DP
28 0.90         ! Eta_is @DP
29 1            ! Error selector
30 5.0          ! Map number
31 2.0          ! Shaft number
32 1.0          ! SF PR
33 1.0          ! SF WRTP
34 1.0          ! SF Eta_is
35 -1           ! Volume (TR)
36 0            ! VSV rel to

38 0.015        ! Lambda W ([W_out_2ary - deltaW] / W_in)
39 0.0          ! Delta W (absolute flow to out_2)
40 1            ! Lambda P ([P_out_2ary - deltaP] / P_in)
41 0            ! Delta P (absolute P change to out_2)

42 0.0          ! Lambda W ([W_out_2ary - deltaW] / W_in)
43 0.0          ! Delta W (absolute flow to out_2)
44 1            ! Lambda P ([P_out_2ary - deltaP] / P_in)
45 0            ! Delta P (absolute P change to out_2)

46 0.15         ! INTERCOOLER SPLITTER- PREMAS
47 0.0          ! Delta W (absolute flow to out_2)
48 1            ! Lambda P ([P_out_2ary - deltaP] / P_in)
49 0            ! Delta P (absolute P change to out_2)

50 0            ! Intercooling/reheating switch
51 0.015        ! Pressure losses (deltaP/P_in)
52 1            ! Eta_comb
53 1000000000   ! Limiting fuel flow
54 -1           ! Volume (TR)

56 0.065        ! HETCOL DELTA P
57 0.60         ! Effectiveness
58 1            ! Type (1,3)
59 0            ! Delta W/W Mass flow leakage

60 0.065        ! INTERCOOLER-HETHOT DELTA P
61 0.70         ! Effectiveness
62 1            ! Type (1,3)
63 0            ! Delta W/W Mass flow leakage

```

```

64  0.817      ! Surge margin
65  1.0        ! CN @DP - PCN @OD
66  5.90       ! PR @DP
67  0.90       ! Eta_is @DP
68  1          ! Error selector
69  3.0        ! Map number
70  3.0        ! Shaft number
71  1.0        ! SF PR
72  1.0        ! SF WRTP
73  1.0        ! SF Eta_is
74  -1         ! Volume (TR)
75  0          ! VSV rel to DP

77  0.01       ! ACCESSORY BYPASS
78  0.0        ! Delta W (absolute flow to out_2)
79  1          ! Lambda P ([P_out_2ary - deltaP] / P_in)
80  0          ! Delta P (absolute P change to out_2)

81  0.15       ! Lambda W ([W_out_2ary - deltaW] / W_in)
82  0.0        ! Delta W (absolute flow to out_2)
83  1          ! Lambda P ([P_out_2ary - deltaP] / P_in)
84  0          ! Delta P (absolute P change to out_2)

85  0.04       ! Pressure losses
86  0.99       ! Eta_comb
87  -1         ! Fuel flow
88  0.0        ! Water flow
89  288.0      ! Water T
90  0.0        ! Water phase (0=liquid, 1=vapour)
91  1.0        ! SF Eta_comb
92  -1         ! Volume (TR)
93  -1         ! Fuel T
94  -1         ! Fuel P coeff [P_fuel/P_cc]

96  0.0        ! Power out or P_out
97  0.7        ! Relative delH/T @DP
98  0.6        ! Relative CN @DP
99  0.92       ! Eta_is @DP
100 -1.0       ! PCN @DP (-1=compressor turbine, 1=FPT)
101 3.0        ! Shaft number (0=FPT)
102 5.0        ! Map number
103 -1.0       ! Power law index
104 1.0        ! SF WRTP
105 1.0        ! SF delH/T
106 1.0        ! SF Eta_is
107 -1         ! Spool rotational speed (TR)
108 -1         ! Spool moment of inertia (TR)
109 -1         ! Volume (TR)
110 -1.0       ! Turbine work split
111 0          ! NGV rel to DP

```

```

112 0.0      ! Power out or P_out
113 0.7      ! Relative delH/T @DP
114 0.6      ! Relative CN @DP
115 0.92     ! Eta_is @DP
116 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
117 2.0      ! Shaft number (0=FPT)
118 5.0      ! Map number
119 -1.0     ! Power law index
120 1.0      ! SF W RTP
121 1.0      ! SF delH/T
122 1.0      ! SF Eta_is
123 -1      ! Spool rotational speed (TR)
124 -1      ! Spool moment of inertia (TR)
125 -1      ! Volume (TR)
126 -1.0     ! Turbine work split
127 0        ! NGV rel to DP

128 0.0      ! Power out or P_out
129 0.8      ! Relative delH/T @DP
130 0.6      ! Relative CN @DP
131 0.93     ! Eta_is @DP
132 -1.0     ! PCN @DP (-1=compressor turbine, 1=FPT)
133 1.0      ! Shaft number (0=FPT)
134 5.0      ! Map number
135 -1.0     ! Power law index
136 1.0      ! SF W RTP
137 1.0      ! SF delH/T
138 1.0      ! SF Eta_is
139 -1      ! Spool rotational speed (TR)
140 -1      ! Spool moment of inertia (TR)
141 -1      ! Volume (TR)
142 -1.0     ! Turbine work split
143 0        ! NGV rel to DP

144 0        ! CORE DUCT-DUCTER: Air duct
145 0.015    ! Pressure losses (deltaP/P_in)
146 1        ! Eta_comb
147 100000000 ! Limiting fuel flow
148 -1      ! Volume (TR)

150 -1.0     ! Floating area switch
151 1.0      ! SF Area
152 -1      ! Cone angle
153 -1      ! Inlet Mach n

155 -1.0     ! Floating area switch
156 1.0      ! SF Area
157 -1      ! Cone angle
158 -1      ! Inlet Mach n

160 -1      ! Power out brick (power turbine) or -1
161 -1      ! Propeller efficiency
162 0        ! Switch handle thrust/power
163 0        ! Thrust/power handle

```

```

-1
1 2 368.7    ! INLET MASS FLOW
11 6 1309.65 ! COT
-1
-3

```

Appendix D

D 6.3.5 Pre-Combustion Temperature Calculation – Design Point

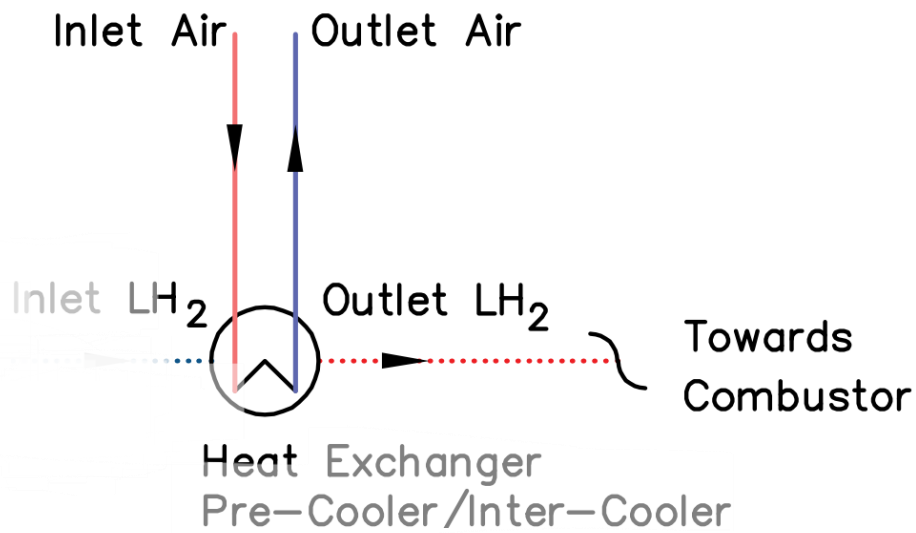
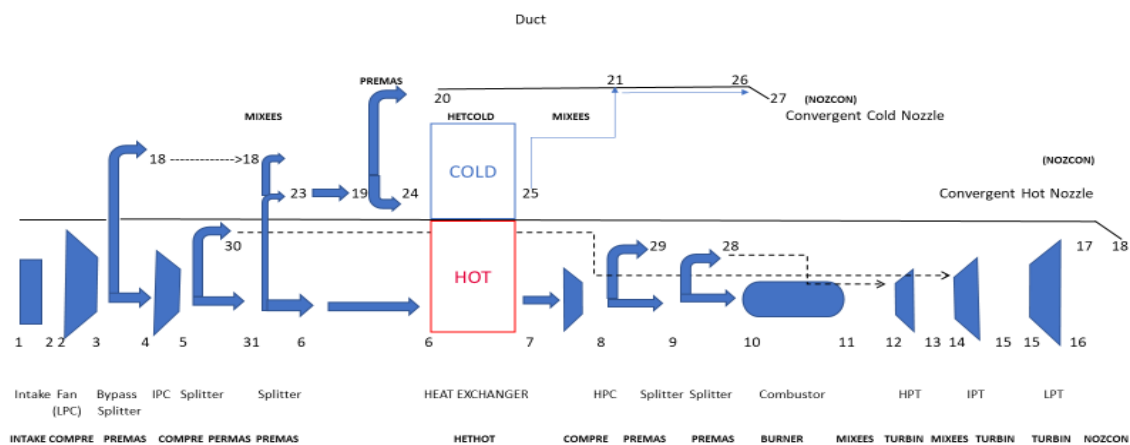


Figure 52 Intercooler air-hydrogen inlet and outlet flows.

$$T_{\text{LH}_2, \text{in}} = 22 \text{ K}; T_{\text{air, in}} = 478.16 \text{ K}$$

$$T_{\text{LH}_2, \text{out}} = ?; T_{\text{air, out}} = ?$$



Turbomatch Design Point Output Parameters

$$W_F \text{ (DP)} = 0.2473 \text{ kg/s} ; T_{F,in} = 22.0\text{K} ; P_F = 1.3 \text{ atm}$$

$$T_6 = 478.16 \text{ K} ; P_{10} = 16.64 \text{ atm} ; W_{24} = 50.088 \text{ kg/s} ; C_{\text{phot(air)}} = 1156.9\text{J/kgK} ; C_{\text{pLH2}} = 7320\text{J/kgK}$$

1. Heat Capacities for the cold and hot sides

$$C_h = W_{24} \times C_p \quad (5.1)$$

$$= 50.88 \times 1156.9 = \mathbf{57946.80 \text{ J/kgK}}$$

$$C_c = W_{FH2} \times C_{pc+} \quad (5.1)$$

$$= 0.2473 \times 7.32000 = \mathbf{1810.24\text{J/KgK}}$$

2. Maximum Intercooler Heat Transfer

$$q_{\max} = \epsilon (T_{m,in} - T_{c,in}) \times C_{m,in} \quad (5.2)$$

$$= 1810.24 \times (478.16 - 22) = \mathbf{825757.25\text{J}}$$

3. Intercooler Heat Transfer ($\epsilon = 0.6$)

$$\epsilon = \frac{q}{q_{\max}} \quad (5.5)$$

$$q = 0.6 \times (825757.25) = \mathbf{495454.35\text{J}}$$

4. Intercooler Outlet (cold side) Temperature Condition (T_{co})

Using equations (5.4)

$$495454.35 = 1810.24 \times (T_{co} - 22)$$

$$T_{co} = \mathbf{\underline{295.7\text{K}}}$$

Therefore, the temperature of the gaseous hydrogen exiting the intercooler at DP is 295.7K.

5. Intercooler Outlet (Hot side) Temperature Condition (T_{HO})

Using equations (5.4)

$$495454.35 = 57946.81 \times (478.16 - T_{HO})$$

$$T_{HO} = \mathbf{469.61K}$$

Therefore, the temperature of the air exiting the intercooler is 469.61K.

6. Required Combustion Chamber Injection Fuel Pressure

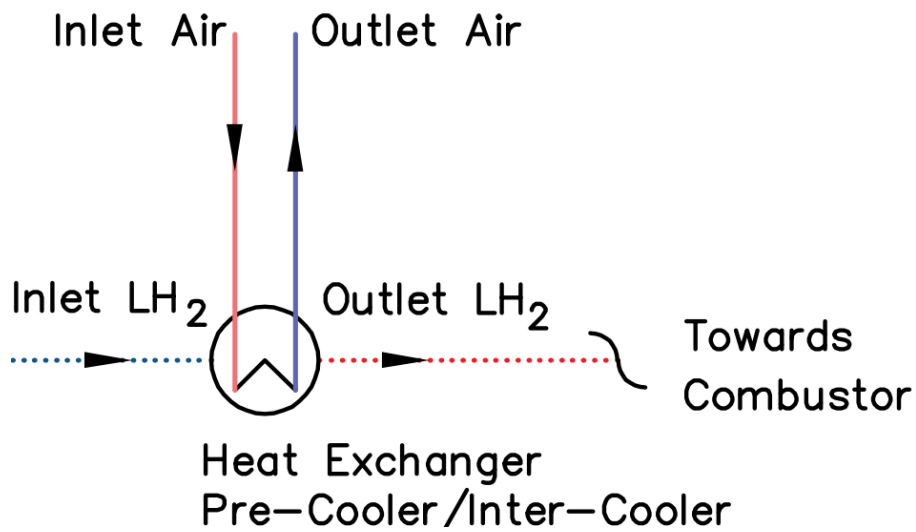
Assumptions

Fuel pump pressure is assumed to be 5% of the combustion chamber pressure.

A 6% pressure drop is assumed through the cold side of the intercooler.

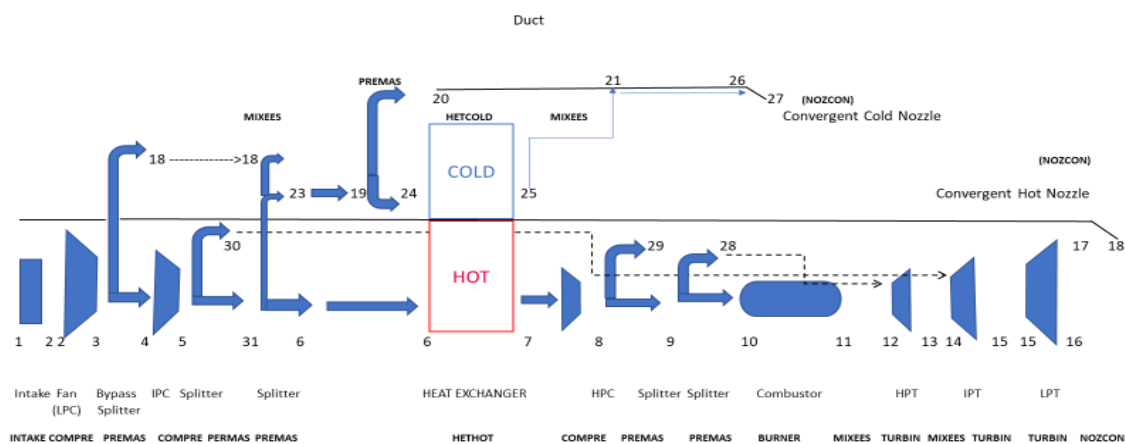
$$\text{Therefore, the fuel pump required pressure at DP} = \frac{17.47}{1.22} = \mathbf{14.3 \text{ atm}}$$

Therefore, the fuel pump pressure to the combustion chamber is 14.3 atm.



$$T_{\text{LH}_2, \text{in}} = 22 \text{ K}; T_{\text{air, in}} = 555.7 \text{ K}$$

$$T_{\text{LH}_2, \text{out}} = ?; T_{\text{air, out}} = ?$$



Turbomatch Off-Design Point Output Parameters

$$W_F (\text{ODP}) = 1.5425 \text{ kg/s}; T_{F, \text{in}} = 22.0 \text{ K}; P_F = 1.3 \text{ atm}$$

$$T_6 = 555.7 \text{ K}; P_{10} = 46.4 \text{ atm}; W_{24} = 203.77 \text{ kg/s}; C_{\text{phot(air)}} = 1156.9 \text{ J/kgK}; C_{\text{pLH}_2} = 7320 \text{ J/kgK}$$

7. Heat Capacities for the cold and hot sides

$$C_h = W_{24} \times C_p \quad (5.1)$$

$$= 203.77 \times 1156.9 = \mathbf{235746.14 \text{ J/kgK}}$$

$$C_c = W_{FH2} \times C_{pc} \quad (5.1)$$

$$= 1.5425 \times 7.32000 = \mathbf{11291.1 \text{ J/KgK}}$$

8. Maximum Intercooler Heat Transfer

$$q_{\max} = \epsilon (T_{m,in} - T_{c,in}) \times C_{m,in} \quad (5.2)$$

$$= 11291.1 \times (555.7 - 22) = \mathbf{6026006.7 \text{ J}}$$

9. Intercooler Heat Transfer ($\epsilon = 0.755$)

$$\epsilon = \frac{q}{q_{\max}} \quad (5.5)$$

$$q = 0.755 \times (825757.25) = \mathbf{4549635.06 \text{ J}}$$

10. Intercooler Outlet (cold side) Temperature Condition (T_{co})

Using equations (5.4)

$$4549635.06 = 235746.14 \times (555.7 - T_{co})$$

$$T_{co} = \mathbf{536.40 \text{ K}}$$

Therefore, the temperature of the gaseous hydrogen at ODP exiting the intercooler is 536.40K.

11. Intercooler Outlet (hot side) Temperature Condition (T_{ho})

Using equations (5.4)

$$4549635.05 = 11291.1 \times (T_{HO} - 22)$$

$$T_{HO} = \underline{\underline{424.93K}}$$

Therefore, the temperature of the air exiting the intercooler is 424.93K.

12. Required Combustion Chamber Injection Fuel Pressure

Assumptions

Fuel pump pressure is assumed to be 5% of the combustion chamber pressure.

A 10% pressure drop is assumed through the cold side of the intercooler.

Therefore, the fuel pump required pressure at ODP = $\frac{51.03}{1.17} = \mathbf{43.62 \text{ atm}}$

Therefore, the fuel pump pressure to the combustion chamber is 43.62 atm.

Appendix E

E 7.1 Orion Aircraft Performance Models for Baseline and Intercooled HVLER Airliner combusting Cryogenic Hydrogen at Equivalent Thrust.

E 7.1.1 Baseline Model Input Files

```
!WING
Area                      = 443
AreaEff                   = 443
AspectRatio               = 9.461
ChordThickRatio           = 0.105
SweepAngle                = 32.6
TaperRatio                = 0.175
RootThickRatio            = 0.110
OuterThickRatio           = 0.05
Laminar                   = 0.1
Type                      = 1

!WINGLET
CDper                     = 1.0

!TAIL
Switch                    = 1.0
Area                      = 83.04324
AspectRatio               = 4.48
ChordThickRatio           = 0.11
SweepAngle                = 33.55
TaperRatio                = 0.3780
RootThickRatio            = 0.256
OuterThickRatio           = 0.065

!FIN
Area                      = 51.0688
Span                      = 9.442
ChordThickRatio           = 0.11
SweepAngle                = 40
TaperRatio                = 0.390
RootThickRatio            = 0.115
OuterThickRatio           = 0.053

!FUSELAGE
Type                      = 1
Diameter                  = 7.850124
Length                    = 70.4

!NACELLE
Type                      = 1
Switch                    = 1
EngineNo                  = 2
Diameter                  = 4.06
Length                    = 7.08
```

```

!LANDING GEAR
AcLGType                = 2,1,1,1,1

!FLAPS
ExtRatioTakeOff          = 1.10
ExtRatioApproach         = 1.15
ExtRatioLanding          = 1.20
AngleTakeOff             = 10.0
AngleApproach            = 20.0
AngleLanding             = 35.0
Slots                   = 2
CLMax                   = 2.80
CLDes                   = 0.007730
DragPolar               = 0

!WEIGHTS
MTOW                    = 309069
OEW                     = 238494
FuelMax                 = 48560
PLMax                   = 35880

!ENGINE
TETMax                  = 1868.3
TakeoffTET              = 1820.1
ClimbTET                = 1740
DescentTET              = 1145
ApproachTET             = 1231.3
TaxiTET                 = 978.4

!FUEL
FuelType                = HY

!EMISSIONS
EIEITakeoff             = 16.61
EIClimb                 = 12.58
EIDescent               = 6.13
EITaxi                  = 4.49

!DESIGN
Altitude                 = 35000
Mach                    = 0.80

```

```

|!-----FLIGHT-----
Altitude (ft) = 35000                !Cruise altitude
Cruise Mach no. = 0.80              !Cruise Mach number
Cruise ISAdev = 0                   !Cruise ISA temperature deviation
Climb Mach no. = 0.75               !Climb Mach number
Climb ISAdev = 0                    !Climb ISA temperature deviation
Descent Mach no. = 0.70            !Descent Mach number
Descent ISAdev = 0                 !Descent ISA temperature deviation
Range (nmi) = 5211                 !flight range OR...
TOW (kg) = 294434                  !Take-off weight
Payload (kg) = 31866               !Aircraft payload (max)
Taxi Time Out (mins) = 6           !Taxi time (minutes)
Taxi Time In (mins) = 6            !Taxi time (minutes)
Origin Airport Altitude (ft) = 0    !Take-off altitude
Destination Altitude (ft) = 0       !Landing altitude
OriginISAdev (K) = 0               !Origin airport temperature deviation
DestinationISAdev (K) = 0          !Destination airport temperature deviation
Diversion Switch = 0               !Aircraft diversion as part of the mission (1) or not (0)
Takeoff derate = 1.0               !Derate from max thrust (default 1.0)
!-----MODE OPTIONS-----
Mode selection = 11
Trajectory type = 2                !Don't change
Climb/descent segs = 2              !Number of points per climb/descent segment (default 2)
Cruise segs = 10                   !Number of cruise segments (default 10)
!-----INPUT FILES-----
aircraft input = performanceInput/aircraftdataHVLER.txt
engine input = performanceInput/turbofanOffdesignpointHYDROGEN6.0V1.0EQUIVTHRUST-ODP.dat
mission input = performanceInput/MissionInputLong.txt
BLI input = 0
trajectory input = 0
!-----RESERVES-----
Diversion Range (nmi) = 0           !Aircraft diversion range
Diversion Altitude (ft) = 22000     !Diversion to alternate cruise altitude
Diversion Mach no. = 0.65           !Diversion to alternate cruise altitude
Hold Time (mins) = 30               !Hold time over alternate/airport
Hold Altitude (ft) = 5000           !Hold time over alternate/airport
Reserve Fuel (%) = 3.5              !Aircraft reserve fuel (% of total onboard)

```

```

!-----CLIMB SCHEDULE---
StartAlt(ft) CAS(kts) TET(K)
1500,193.7,-1
3000,250,-1
10000,290,-1
18000,290,-1
!-----DESCENT SCHEDULE--
StartAlt(ft) CAS(kts) TET(K)
18000,290,-1
10000,290,-1
3000,250,-1
1000,193.7,-1
!-----DERATE-----
Calculate Ratings = 1                                !1 if takeoff, climb etc ratings should be set internally
take_off = 1
max_climb = 0.87
max_cruise = 0.895
approach = 0.20
loitre = 0.45
flight_idle = 0.16
taxi = 0.15
ground_idle = 0.15
!-----
!ADDITIONAL ENGINE PERFORMANCE STATION VECTOR DATA (STATION, ITEM)
!Station | Item
1 4
9 4
9 6
14 6
!-----
!ADDITIONAL ENGINE PERFORMANCE BRICK DATA (DESCRIPTION, BRICK NO, ITEM)
!BrickNo | Item      (WARNING: The BrickNo is defined according to the tabular output file of turbomatch )
!The description is a SINGLE WORD name for your custom variable that will be used in the output file
Alt 1 1
!-----
!USER SPECIFICATIONS
!Define the custom engine operating parameters for each flight phase
!Fill in with both station and brick information - stations first, then bricks
!Do NOT specify mass flow, PCN, TET in brick inputs
!Put a -1 if no user specified operating parameters are used in a segment
!TAKEOFF
-1
!CLIMB
-1
!CRUISE
-1
!DESCENT
-1
!APPROACH (LANDING)
-1
!GROUND IDLE
-1

```

E 7.2 Orion Aircraft Performance Baseline Model Flight Output Summary.

```

---OVERALL PERFORMANCE-----
Ramp Weight      =      309046 kg
Payload          =      31866 kg
Block Fuel Burn  =      36267 kg
Onboard Fuel     =      38686 kg
Total Mission Time =      11.83 hrs
Flight Range     =      5211 nmi
Flight ETRW      =      1.4430
-----

---SEGMENT PERFORMANCE-----
-----TAXI OUT SEGMENT-----
Time              =      6.00 mins
Fuel Burn         =      117 kg
-----TAKEOFF SEGMENT-----
Altitude          =      0 m
Time              =      139.13 s
Runway Length     =      2100 m
Fuel Burn         =      348 kg
-----CLIMB SEGMENT-----
Time              =      27.97 mins
Range             =      169 nmi
Fuel Burn         =      2355 kg
-----CRUISE SEGMENT-----
Mach Number       =      0.800
Max Altitude      =      35000 ft
Time              =      636.37 mins
Range             =      4900 nmi
Fuel Burn         =      32747 kg
-----DESCENT SEGMENT-----
Time              =      29.90 mins
Range             =      142 nmi
Fuel Burn         =      513 kg
-----LANDING SEGMENT-----
Altitude          =      0 m
Time              =      89.31 s
Runway Length     =      1130 m
Fuel Burn         =      70 kg
-----TAXI IN SEGMENT-----
Time              =      6.00 mins
Fuel Burn         =      117 kg
-----DIVERSION-----
Mach Number       =      0.650
Altitude          =      22000 ft
Time              =      0.00 mins
Range             =      0 nmi
Hold Altitude     =      5000 ft
Hold Time         =      30.00 mins
Fuel Burn         =      1111 kg
-----

```

---DIRECT OPERATING COST---			
	Cost (US\$)		
Fuel	\$15754	21.00%	
CO2	\$0	0.00%	
NOx	\$0	0.00%	
Crew	\$870	1.16%	
Maint.	\$17136	22.84%	
Insurance	\$1965	2.62%	
Interest	\$21615	28.81%	
Deprec.	\$17685	23.57%	

TOTAL	\$75025	100.00%	

---EMISSIONS---			
Segment	CO2(kg)	H2O(kg)	NOx(kg)

TAKEOFF	0.0	833.4	0.0
CLIMB	0.0	5197.4	0.0
CRUISE	0.0	74792.7	0.0
DESCENT	0.0	8923.2	0.0
LANDING	0.0	234.9	0.0
TAXI	0.0	3.3	0.0

TOTAL	0.0	90279.6	0.0

E 7.1.2 Intercooled Aircraft Model Input Files

```
!WING
Area                = 443
AreaEff              = 443
AspectRatio          = 9.461
ChordThickRatio      = 0.105
SweepAngle          = 32.6
TaperRatio          = 0.175
RootThickRatio       = 0.110
OuterThickRatio      = 0.05
Laminar              = 0.1
Type                = 1

!WINGLET
CDper                = 1.0

!TAIL
Switch              = 1.0
Area                = 83.04324
AspectRatio          = 4.48
ChordThickRatio      = 0.11
SweepAngle          = 33.55
TaperRatio          = 0.3780
RootThickRatio       = 0.256
OuterThickRatio      = 0.065

!FIN
Area                = 51.0688
Span                = 9.442
ChordThickRatio      = 0.11
SweepAngle          = 40
TaperRatio          = 0.390
RootThickRatio       = 0.115
OuterThickRatio      = 0.053

!FUSELAGE
Type                = 1
Diameter            = 7.850124
Length              = 70.4

!NACELLE
Type                = 1
Switch              = 1
EngineNo            = 2
```

Diameter	=	4.06
Length	=	7.08
!LANDING GEAR		
AcLGType	=	2,1,1,1,1
!FLAPS		
ExtRatioTakeOff	=	1.10
ExtRatioApproach	=	1.15
ExtRatioLanding	=	1.20
AngleTakeOff	=	10.0
AngleApproach	=	20.0
AngleLanding	=	35.0
Slots	=	2
CLMax	=	2.80
CLDes	=	0.007730
DragPolar	=	0
!WEIGHTS		
MTOW	=	309069
OEW	=	238494
FuelMax	=	48560
PLMax	=	35880
!ENGINE		
TETMax	=	1868.3
TakeoffTET	=	1820.1
ClimbTET	=	1740
DescentTET	=	1145
ApproachTET	=	1231.3
TaxiTET	=	978.4
!FUEL		
FuelType	=	HY

!FUEL		
FuelType	=	HY
!EMISSIONS		
EIEITakeoff	=	16.61
EIClimb	=	12.58
EIDescent	=	6.13
EITaxi	=	4.49
!DESIGN		
Altitude	=	35000
Mach	=	0.80

```

|!-----FLIGHT-----
Altitude (ft) = 35000                                !Cruise altitude
Cruise Mach no. = 0.80                                !Cruise Mach number
Cruise ISAdev = 0                                     !Cruise ISA temperature deviation
Climb Mach no. = 0.75                                 !Climb Mach number
Climb ISAdev = 0                                       !Climb ISA temperature deviation
Descent Mach no. = 0.70                               !Descent Mach number
Descent ISAdev = 0                                     !Descent ISA temperature deviation
Range (nmi) = 5211                                    !flight range OR...
TOW (kg) = 294434                                     !Take-off weight
Payload (kg) = 27184 !Aircraft payload (max)
Taxi Time Out (mins) = 6                             !Taxi time (minutes)
Taxi Time In (mins) = 6                               !Taxi time (minutes)
Origin Airport Altitude (ft) = 0                     !Take-off altitude
Destination Altitude (ft) = 0                         !Landing altitude
OriginISAdev (K) = 0                                  !Origin airport temperature deviation
DestinationISAdev (K) = 0                             !Destination airport temperature deviation
Diversion Switch = 0                                  !Aircraft diversion as part of the mission (1) or not (0)
Takeoff derate = 1.0                                  !Derate from max thrust (default 1.0)
!-----MODE OPTIONS-----
Mode selection = 11
Trajectory type = 2                                   !Don't change
Climb/descent segs = 2                                !Number of points per climb/descent segment (default 2)
Cruise segs = 10                                      !Number of cruise segments (default 10)
!-----INPUT FILES-----
aircraft input = performanceInput/aircraftdataHVLERIC.txt
engine input = performanceInput/turbofanOffdesignpointIC9.0V9.0HYDROGENEQNT-ODP.dat
mission input = performanceInput/MissionInputLong.txt
BLI input = 0
trajectory input = 0
!-----RESERVES-----
Diversion Range (nmi) = 0                             !Aircraft diversion range
Diversion Altitude (ft) = 22000                       !Diversion to alternate cruise altitude
Diversion Mach no. = 0.65                             !Diversion to alternate cruise altitude
Hold Time (mins) = 30                                  !Hold time over alternate/airport
Hold Altitude (ft) = 5000                             !Hold time over alternate/airport
Reserve Fuel (%) = 3.5                                !Aircraft reserve fuel (% of total onboard)

```

```

!-----CLIMB SCHEDULE---
StartAlt(ft) CAS(kts) TET(K)
1500,193.7,-1
3000,250,-1
10000,290,-1
18000,290,-1
!-----DESCENT SCHEDULE--
StartAlt(ft) CAS(kts) TET(K)
18000,290,-1
10000,290,-1
3000,250,-1
1000,193.7,-1
!-----DERATE-----
Calculate Ratings = 1                                !1 if takeoff, climb etc ratings should be set internally
take_off = 1
max_climb = 0.87
max_cruise = 0.895
approach = 0.20
loitre = 0.45
flight_idle = 0.16
taxi = 0.15
ground_idle = 0.15
!-----
!ADDITIONAL ENGINE PERFORMANCE STATION VECTOR DATA (STATION, ITEM)
!Station | Item
1 4
9 4
9 6
14 6
!-----
!ADDITIONAL ENGINE PERFORMANCE BRICK DATA (DESCRIPTION, BRICK NO, ITEM)
!BrickNo | Item      (WARNING: The BrickNo is defined according to the tabular output file of turbomatch )
!The description is a SINGLE WORD name for your custom variable that will be used in the output file
Alt 1 1
!-----
!USER SPECIFICATIONS
!Define the custom engine operating parameters for each flight phase
!Fill in with both station and brick information - stations first, then bricks
!Do NOT specify mass flow, PCN, TET in brick inputs
!Put a -1 if no user specified operating parameters are used in a segment
!TAKEOFF
-1
!CLIMB
-1
!CRUISE
-1
!DESCENT
-1
!APPROACH (LANDING)
-1
!GROUND IDLE
-1

```

E 7.2.1 Orion Aircraft Performance Intercooled Model Flight Output Summary.

```

----OVERALL PERFORMANCE-----
Ramp Weight      =      309027 kg
Payload          =      27184 kg
Block Fuel Burn  =      40562 kg
Onboard Fuel     =      43349 kg
Total Mission Time =      11.97 hrs
Flight Range     =      5211 nmi
Flight ETRW      =      1.8919
-----

---SEGMENT PERFORMANCE-----
---TAXI OUT SEGMENT-----
Time              =      6.00 mins
Fuel Burn        =      163 kg
---TAKEOFF SEGMENT-----
Altitude          =      0 m
Time              =      106.00 s
Runway Length     =      1788 m
Fuel Burn        =      401 kg
---CLIMB SEGMENT-----
Time              =      14.72 mins
Range            =      84 nmi
Fuel Burn        =      1984 kg
---CRUISE SEGMENT-----
Mach Number       =      0.800
Max Altitude      =      35000 ft
Time              =      633.80 mins
Range            =      4880 nmi
Fuel Burn        =      36031 kg
---DESCENT SEGMENT-----
Time              =      54.55 mins
Range            =      247 nmi
Fuel Burn        =      1731 kg
---LANDING SEGMENT-----
Altitude          =      0 m
Time              =      89.66 s
Runway Length     =      1099 m
Fuel Burn        =      88 kg
---TAXI IN SEGMENT-----
Time              =      6.00 mins
Fuel Burn        =      163 kg
---DIVERSION-----
Mach Number       =      0.650
Altitude          =      22000 ft
Time              =      0.00 mins
Range            =      0 nmi
Hold Altitude     =      5000 ft
Hold Time         =      30.00 mins
Fuel Burn        =      1321 kg
-----

```

```

----DIRECT OPERATING COST-----
| Cost (US$)
-----
Fuel          | $17620      22.86%
CO2           | $0          0.00%
NOx           | $0          0.00%
Crew          | $870        1.13%
Maint.        | $17336     22.49%
Insurance     | $1965       2.55%
Interest      | $21615     28.04%
Deprec.       | $17685     22.94%
-----
TOTAL         | $77091     100.00%
-----

---EMISSIONS---
Segment | CO2(kg) | H2O(kg) | NOx(kg)
-----
TAKEOFF | 0.0     | 1056.6  | 0.0
CLIMB   | 0.0     | 4748.2  | 0.0
CRUISE  | 0.0     | 81795.6 | 0.0
DESCENT | 0.0     | 12493.6 | 0.0
LANDING | 0.0     | 506.9   | 0.0
TAXI    | 0.0     | 4.7     | 0.0
-----
TOTAL   | 0.0     | 101017.2 | 0.0
-----

```