Written Report
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Hydrogen Applications in Aviation

An Exploration of Hydrogen Combustion for Regional Flights in Rural Canada

Team 11

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1.0 Introduction

Regional air travel in Northern Canada plays a foundational role in maintaining social and economic connections between rural communities, often composed of a high percentage of indigenous peoples [1], and the rest of the nation. During the Covid-19 pandemic the Government of Canada established a $75-million funding program, meant to last a period of 6-months, to support small air carrier flights to remote communities, highlighting the flights' role in providing "essential goods, services, and access in and out of the community" [2]. This program underscores both the way the flights impact daily life and the cost needed to maintain this method of transportation when economies of scale are no longer available. However, while the pandemic may have placed a spotlight on this need the precarious position of small regional flights in Northern Canada has been playing out over many years, with major airlines continuing to consolidate flights or eliminate them all together [3].

As society makes the shift to a green energy economy it is important to ensure that the chosen solutions allow for continued access to transportation by vulnerable communities. This entails developing reduced carbon architectures for aircraft that maintain an achievable price point for their customers. When focusing on serving communities in Northern Canada Turbo Prop airplanes, such as the De Havilland Canada Dash 8 and the ATR 72, form the backbone for regional flights. A global study by The International Council on Clean Transportation found that the CO_2 intensity for both the Dash 8 and the ATR 72 was just over 125 grams of CO_2 per Revenue Passenger Kilometer (RPK) in 2019 [4].

Focusing on turboprop flights to areas with a high percentage of indigenous people will ensure that the proposed energy solution is designed with the vulnerable indigenous communities as the primary customers. An overview of indigenous peoples in Canada, from the Annual Report to Parliament in 2020, shows that the highest percentage of indigenous people live in Nunavut and the Northwest Territories, with 86% and 51% percent of their populations being made of indigenous peoples respectively [1]. By cross-referencing the census data with publicly available flight data, flights to these regions which employ turboprop aircraft can be identified. Three flights of interest were chosen based on the diversity of population, indigenous percentage, and flight distance.

Departure		Arrival		Flight #	Aircraft	Distance [km]	Indigenous Pop.	Total Pop.	Indigenous %
Calgary	YYC	Yellowknife	YZF	WEN3359	Dash 8	1,292	4,810	19,910	24%
Yellowknife	YZF	Norman Wells	YVQ	SUT7291	ATR 72	687	300	670	45%
Iqaluit	YFB	Clyde River	YCY	AKT5611	ATR 42	800	1,155	1,180	98%

Figure 1: Routes Connecting Indigenous Communities in Canada

Current data from Google Flights shows that the chosen routes range in cost from \$300 USD to almost \$700 USD for a one way ticket to the destination [5]–[7]. There are many factors which influence the cost of a flight with the propulsion system and fuel production being one part of a larger whole. With the adpotion of a new technology in an established market place equivalent or greater utility must be delivered to the consumer for adoption to be viable. Often it is the role of governements to ensure that the long term effects of decisions which affect society are appropriately regulated and taxed to incentivize a positive outcome. It is important for the proposed solution to strike a balance between the cost, utility, and emissions that a new technology brings to consumers the assurance that it is having the intended effect.

2.0 Objective Statement

This report aims to evaluate the feasibility of implementing a hydrogen combustion propulsion system on short-haul routes in rural Canada. In addition to the feasibility assessment, various metrics like the efficiency of the proposed transportation, cost of operation, and reduction of carbon dioxide emissions will be quantified. The report will limit its scope by focusing on the range of operation for the hydrogen combustion aircraft to the three cities stated above to understand the adoption of this new technology on indigenous communities and how the technology will allow those populations to reduce their carbon impact while maintaining attainable costs and utility to the communities.

3.0 Results & Impact

3.1 Energy Transfer

Hydrogen combustion engines utilize liquid or gaseous hydrogen fuel to provide the needed thrust for air travel, not any different than current jet engines [8]. The combustion process for hydrogen (balanced equation shown below), is identical to the combustion cycle for jet fuel with the only difference being that hydrogen combustion occurs in the gaseous state rather than liquid state in kerosene-based jet engines. In a hydrogen jet engine aircraft, liquid hydrogen would be sent to the engines via a fuel delivery system that would keep the hydrogen in the liquid phase until it reached the combustion chamber where the temperature would rise enough to change the hydrogen to the gaseous state. Then the energy from the combustion process will turn a drive shaft within the turbine to generate the power needed for the propellor through a gear box. The main difference in the combustion process is the products of the reaction. Complete combustion of hydrogen fuel in air will result in water and nitrogen as the only products; however, NOx is produced in practical applications of hydrogen combustion.

$$H_2 + \frac{1}{2}(O_2 + 3.76N_2) \rightarrow H_2O + 1.88N_2 \text{ [9]}$$

3.2 Hydrogen Aircraft Sizing

To accurately compare aircraft parameters, the hydrogen aircraft is designed with the same take-off (1000 m) and landing distance (780 m) bounds as the De Havilland Canada Dash 8 Q200. **Table 1** displays the findings of the sizing study. The fuel calculation for the hydrogen aircraft includes the reserve amount needed to fly to an alternate airport 87 nautical miles (nmi) away, a 45-minute loiter above the airport, and 5% of the total fuel amount as a contingency.

Table 1: Preliminary Sizing Results

Parameter	**Original - De Havilland Canada Dash 8 Q200**[10]	**Proposed hydrogen version**
Travel range	1125 nmi	1125 nmi
Passenger capacity (including air hostess and pilots)	40	32
Cruise glide ratio	16 [11]	12.7
Cruise altitude	Max 25000 ft	16363 ft
Cruise speed	0.433 Mach	0.402 Mach
Maximum take-off mass	16,466 kg	12,388 kg
Fuel Type	A-1 Jet fuel	Liquid hydrogen

Fuel energy intensity	43.28 MJ/kg	120 MJ/kg
Mission fuel fraction for travel range	3,915.62 kg [12]	1,552 kg
Required fuel volume	4.89 m^3	21.92 m^3
Length of plane	22.25 m	25.31 m
Wing area	54.4 m^2 [13]	46.1 m^2
Take-off power (per engine)	1,600 kW	1,493 kW

According to calculations, a hydrogen-powered aircraft can meet the travel range (1125 nmi) requirements of a Canadian aircraft serving rural areas with reduced passenger capacity (32 pax).

Fuel storage is one of the major challenging aspects of a hydrogen-powered aircraft. Since the volumetric energy density of hydrogen (5 GJ/ m^3 at 20° C) is one order of magnitude lower than that of A-1 jet fuel (34.7 GJ/ m^3 [14]), the required fuel volume is seven times that of a conventional jet. Gaseous hydrogen is pressurized and stored onboard as liquid hydrogen, which increases the volumetric energy density to 8.5 GJ/m^3 at 15° C. As shown in **Table 1**, this reduces the fuel volume requirement to four times that of conventional jet fuel.

3.3 Limitations

Due to one lesser row of seats, the plane length is reduced by 0.80 m. But then the plane is 3.86 m longer to accommodate the larger fuel tank. While this may be feasible for the specific use case scenario in question, longer travel distances may be impractical due to much larger aircraft size requirements to accommodate the fuel. Aside from the limited fuel storage, the hydrogen combustion aircraft has a 25% lower maximum take-off mass for the same range as the reference aircraft. This will limit the maximum number of people that can be carried on each trip (32 pax for hydrogen aircraft in comparison to 40 pax for reference aircraft) and necessitate more frequent flights for busy routes. Furthermore, the 7% slower cruising speed increases travel time, reducing turnaround time. To address both issues, a company would need to keep a large fleet of hydrogen-powered aircraft on hand. The availability of hydrogen fuel in rural areas adds another constraint to the aircraft's operations. This, however, can be addressed by establishing large fuel storage facilities at the airports.

3.4 Maximum Potential

The maximum potential is assessed based on the amount of CO_2 saved, maximum design range, and maximum efficiency if the aircraft is switched to hydrogen combustion. The tables below, **Table 2** and **Table 3**, display the amount of CO_2 as well as other products produced by the conventional jet aircraft and hydrogen combustion aircraft, respectively. In **Table 2**, it was calculated that the mass of CO_2 produced per L of jet-A fuel for the Dash-8 Q200 would be 2.53 kg. Whereas for a hydrogen combustion aircraft (**Table 3),** the mass of CO_2 produced per L of hydrogen would be 0 kg. Thus, 2.53 kg/L of CO_2 produced by the fuel would be saved by using hydrogen over conventional jet-fuel. When considering the longest travel distance of 697 nautical miles between Calgary and Yellowknife, the mass of CO_2 produced per L of jet-A fuel would be 148 g. By using a hydrogen combustion aircraft, no CO_2 would be produced. Thus, that is a saving of 148 g/L of CO_2 production per RPK when traveling from Calgary to Yellowknife.

The maximum design range was determined to be 1,125 nmi, which can be viewed in Appendix A: Calculations. The propulsive efficiency will be different between the two aircraft due to the lower cruising velocity of the hydrogen system. By using a graph of propulsive efficiency with respect to airspeed, provided in **Figure 3**, and the cruising velocities, in **Table 1**, the propulsive efficiency was estimated to be approximately 75% for the Hydrogen Aircraft and 80% for the Dash-8. The thermal efficiency of the hydrogen combustion aircraft was assumed to be 45% compared to 48-50% for a typical jet fuel aircraft [15]. By multiplying the propulsive and thermal efficiencies together, the overall system efficiency of the hydrogen combustion aircraft comes out to be 33.75%. Whereas for the Dash-8, the overall system efficiency is 38.4%. This makes sense as "compared to fossil-fuel aircraft, LH_2-powered aircraft will be heavier, with an increased maximum takeoff mass (MTOM), and less efficient, with a higher energy requirement per revenue-passenger-kilometer (MJ/RPK)" [14]. It is important to note that the MTOM for the hydrogen combustion aircraft would be lower than the conventional jet, which would enable the hydrogen combustion aircraft to have the same travel range.

Table 2: Conventional Jet Emissions

	Distance (nautical mile)	Fuel efficiency [L/nmi]	Amount of fuel consumed [L]
Calgary to Yellowknife	697.6242	4.351	3035.39
Yellowknife to Norman Wells	370.95		1614.02
Iqaluit to Clyde River	431.965		1879.50

Product	Amount produced			
	per L of jet-A fuel [kg]	Calgary to Yellowknife [kg]	Yellowknife to Norman Wells [kg]	Iqaluit to Clyde River [kg]
H20	3.73	11309.46	6013.62	7002.75
CO2	2.53	7670.44	4078.63	4749.50
kg per RPK		0.1484	0.1484	0.1484
g per RPK		148.4219	148.4219	148.4219
CO	Data not available			
NOx				
Soot particles	5E+15	1.518E+19	8.070E+18	9.397E+18

Table 3: Hydrogen Combustion Aircraft Emissions

	Distance (nautical mile)	Fuel efficiency [L/nmi]	Amount of fuel consumed [L]
Calgary to Yellowknife	697.6242	19.484	13592.82
Yellowknife to Norman Wells	370.95		7227.75
Iqaluit to Clyde River	431.965		8416.60

Product	Amount produced			
	per L of Hydrogen [kg]	Calgary to Yellowknife [kg]	Yellowknife to Norman Wells [kg]	Iqaluit to Clyde River [kg]
H20	0.78	2367.61	1258.94	1466.01
CO2	0.00	0.00	0.00	0.00
CO	0.00	0.00	0.00	0.00
NOx	1.02E-04	0.31	0.16	0.19
NOx to CO2	2.98E+02	92.26	49.06	57.13
kg per RPK		1.79E-03	1.79E-03	1.79E-03
g per PRK		1.79	1.79	1.79
Soot particles	0.00	0.00	0.00	0.00

3.5 Resource utilization

Amanda et. al investigated the water consumption of various LH_2 production processes, such as coal gasification and water electrolysis, which are powered by coal-fired thermal plants or wind farms [16]. Their research considers various aspects of the hydrogen supply chain, including energy source, production, distribution, conditioning, transportation, storage, and distribution. The manufacturing process uses 52-1600 million cubic meters of water per tonne of LH_2 produced and pollutes water and soil with trace metals such as arsenic and lead. Across all scenarios, wind powered LH_2 production is the least polluting and our preferred method of production.

3.6 Upstream, Midstream, and Downstream Environmental Impacts

The upstream environmental impacts of using liquid hydrogen as fuel involves natural gas reforming, a common method of H_2 production. In the present, "95% of the hydrogen produced in the United States is made by natural gas reforming in large central plants" [17]. Also known as steam-methane reforming, the methane (CH_4) is "used to produce hydrogen through thermal processes such as steam-methane reformation and partial oxidation" [17]. [16] Amanda et. al examined the greenhouse gas emissions of the production processes described in the resource utilization section. An estimated 6.1-66 Tonne of CO_2, 1.9-71 kg of CH_4, 7.7-610 kg of SO_x, and 0.97-20 kg of NO_x are emitted per Tonne of LH_2. Their analysis excludes the carbon emissions associated with the construction of the fuel production infrastructure.

When assessing the environmental impacts, the midstream environmental impacts also need to be examined. The midstream environmental impacts are about the emissions of harmful chemicals being produced during combustion. While the use of LH_2 as an aircraft fuel offers environmental benefits such as zero production of CO_2, CO, and hydrocarbons, the downside is the primary and secondary production of H_2O (contributor to global warming) and NO_x. As per the data from **Table 3**, the hydrogen combustion aircraft is going to produce 2,368 kg of H_2O and 0.310 kg of NO_x while operating between cities 1 (Calgary) and 2 (Yellowknife). Over the duration of one year for all 3 flights shown in **Table 2** and **Table 3**, we estimate the production of 10.2*10^6 kg of H_2O and 1,329 kg of NO_x. See Appendix A: Calculations.

3.7 Projected Cost

Our suggested aircraft's operating costs can be divided into two groups Direct Operating Cost (DOC) and Indirect Operating Cost (IOC). DOC contains component costs like those for aircraft R&D and maintenance, among others. IOC are costs for baggage handling, aircraft ground handling, and other services that are not directly related to the flight of the aircraft. The findings from our examination of the operation cost are shown in **Table 4** and **Figure 2**. See Appendix A: Calculations.

Table 4 displays the cost of the flight ticket for the three routes in consideration for green, blue, and grey hydrogen fuels. The flight ticket cost is comparable to the cost of the conventional jet that is currently operating between Calgary and Yellowknife, and Yellowknife and Norman Wells. Iqaluit-Clyde River is a low volume rural route serviced only by Air Canada (monopoly), which could be the reason for the much higher ticket cost for the reference aircraft.

Table 4: Flight Ticket Costs for Fuels and Routes in Canada [18]–[20]

From	Calgary	Yellowknife	Iqaluit
To	Yellowknife	Norman Wells	Clyde River
Cost per passenger - Green Hydrogen fuel	$ 333.38	$ 231.42	$ 247.69
Cost per passenger - Blue Hydrogen fuel	$ 307.99	$ 217.91	$ 231.82
Cost per passenger - Grey Hydrogen fuel	$ 285.25	$ 205.81	$ 217.60
Cost per passenger - Reference aircraft	$ 311.00	$ 459.00	$ 668.00

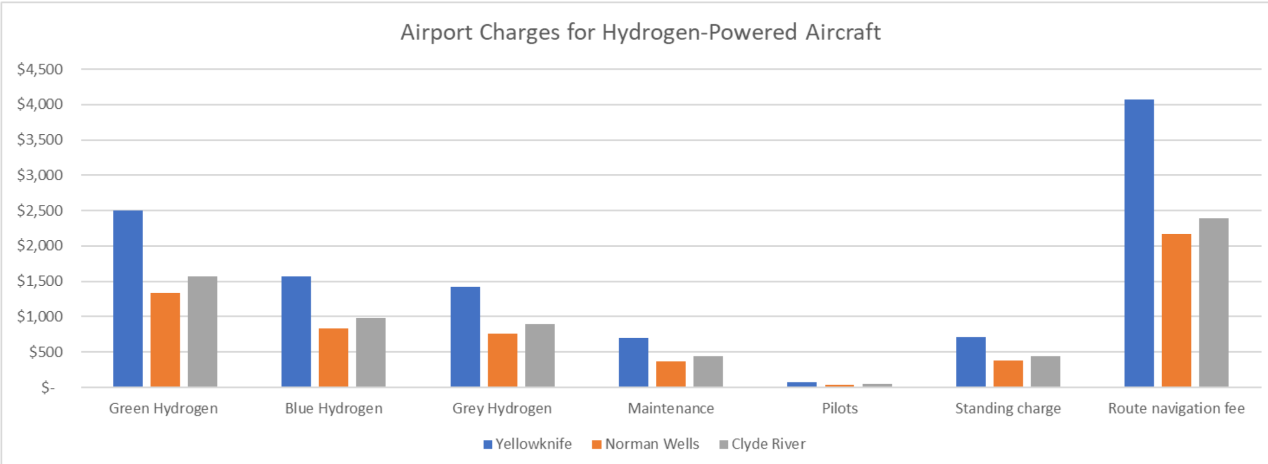

Figure 2: Airport and Air Navigation Charge

4.0 Discussion & Interpretation

4.1 Sustainability

Moving to a hydrogen combustion aircraft has inherited sustainability benefits when looking at the emissions from the aircraft flight path. However, there are some concerns with the upstream production of the hydrogen needed for these aircraft. Expanding the use of green hydrogen technologies will further the sustainability of utilizing hydrogen combustion aircraft.

One way the sustainability of this project could be improved is by retrofitting the existing aircraft and engines to run on hydrogen fuel rather than standard jet fuel. Currently, GE and Airbus are establishing ways to utilize existing engines by changing the materials used throughout the engine and the fuel storage system [21]. These retrofits would allow current turboprop engine planes to be utilized using hydrogen fuel, however these modifications will not enable the flights discussed in this report.

4.2 Scale

While the hydrogen aircraft's ticket price is substantially less than the reference aircraft's for the Iqaluit to Clyde River route (by over 270%), it is equivalent to the price of the reference aircraft for the other itineraries. Therefore, the routes from Calgary to Yellowknife and from Yellowknife to Norman Wells are best suited for scalability from an economic perspective. The availability of hydrogen fuel at both the origin and destination locations would pose the biggest obstacles to scaling. Carrying the fuel mass for both the to-and-from route from the origin will address the hydrogen fuel requirement in the short run. With this approach, the suggested hydrogen aircraft should be capable of traveling up to a location 562.5 nmi (1041.75 km) away. Infrastructure for producing or storing hydrogen will be needed in the long run. A higher margin on the price of a plane ticket can be used to recoup the cost of the infrastructure.

4.3 Indigenous Community

The calculated CO_2 emissions per Revenue Passenger Kilometer for the 3 chosen routes comes out to 148 g which is slightly higher than the global estimate provided by the Council on Clean Transportation for the Dash-8 and ART 72. While the hydrogen combustion system does not produce any CO_2 it does produce NO_x which has an estimated CO_2 equivalence of 298:1 [22]. Even with this high ratio the hydrogen combustion flight only has a resulting CO_2 equivalent production of 1.79 grams per RPK. This entails a reduction of 2 orders of magnitude from the current emissions generated by the chosen flights in Northern Canada. This estimation, combined with the estimated cost to operate the flights, shows a promising direction for the future of the aviation industry while servicing remote indigenous communities.

5.0 Conclusion

Hydrogen combustion presents an opportunity for the aviation industry to advance into a future with reduced CO_2 emissions while continuing to service consumers. The transition to such technology is not without its challenges and tradeoffs, as has been discussed in this report. Developing aircraft which meet the current demands for flight paths will need new geometric proportions to accommodate the increased amount of fuel volume which must be carried. This will entail a longer timeline before the first purpose-built aircraft makes it to production. Retrofits of existing aircraft are possible, but it results in diminished capability when compared to their jet fuel counterparts. Aircraft design and manufacturing must grow alongside improvements to how hydrogen is produced. Current utilization of natural gas reforming leaves much to be desired from an emissions perspective and while there is a significant increase in the adoption of wind for power generation, linking this source to mass production of hydrogen is an infrastructure pathway that has yet to be developed. These technical challenges must be overcome to unlock the reduced carbon emissions potential, which can be achieved via hydrogen combustion technology. The drastic reduction in CO_2 equivalent emissions allows for the continued viability of turboprop flights to rural communities. The continued collaboration and innovation across many industries will allow society to move from theory to reality for hydrogen combustion in the aviation industry.

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Appendix A: Calculations

<u>Preliminary Hydrogen Aircraft sizing</u> [10], [23]–[28]

Assumptions:

1. Specific fuel consumption is taken as 1.916E-08 kg/W/s [25].
2. Fuel-fraction for engine start, taxi, descent and landing is taken as 0.997. Fuel-fraction for taken is assumed to be 0.998 [28].
3. Relative operating empty mass is 0.595 [25]
4. Hydrogen fuel density is 71 kg/m^3 [27]
5. Take-off power for hydrogen powered engine is considered to be same as the reference aircraft [10].

Preliminary Sizing I				
Calculations for flight phases approach, landing, take-off, 2nd segment and missed approach				
<u>Approach</u>				
Factor	k_{APP}	1.643	(m/s²)$^{0.5}$	(for turboprop aircraft)
Conversion factor	m/s -> kt	1.944	kt / m/s	
Given: landing field length		yes		**<<<< Choose according to task**
Landing field length	s_{LFL}	780	m	
Approach speed	V_{APP}	45.9	m/s	$V_{APP} = k_{APP} \cdot \sqrt{s_{LFL}}$
Approach speed	V_{APP}	89.2	kt	
Given: approach speed		no		
Approach speed	V_{APP}	89.2	kt	
Approach speed	V_{APP}	45.9	m/s	$s_{LFL} = \left(\frac{V_{APP}}{k_{APP}}\right)^2$
Landing field length	s_{LFL}	780	m	
<u>Landing</u>				in case of a redesign: $C_{L,max,L}$ can be estimated from:
Landing field length	s_{LFL}	780	m	$C_{L,max,L} = \frac{2 \cdot m_{ML} \cdot g}{\rho \cdot S \cdot V_{S,0}^2}$ $V_{S,0}$ see below
Temperature above ISA (288,15K)	ΔT_L	0	K	
Relative density	σ	1.000		
Factor	k_L	0.137	kg/m³	(for turboprop aircraft)
Max. lift coefficient, landing	$C_{L,max,L}$	2.505		$m_{ML} / S_W = k_L \cdot \sigma \cdot C_{L,max,L} \cdot s_{LFL}$
Mass ratio, landing - take-off	m_{ML} / m_{TO}	0.990		
Wing loading at max. landing mass	m_{ML} / S_W	267.68	kg/m²	$m_{MTO} / S_W = \frac{m_{ML} / S_W}{m_{ML} / m_{MTO}}$
Wing loading at max. take-off mass	m_{MTO} / S_W	270.39	kg/m²	
<u>Take-off</u>				
Take-off field length	s_{TOFL}	1000	m	
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K	
Relative density	σ	1.000		
Factor	k_{TO}	2.25	m³/kg	
Exprience value for $C_{L,max,TO}$	0,8 * $C_{L,max,L}$	2.004		
Maximum lift coefficient, take-off	$C_{L,max,TO}$	2.24		
Stall speed, landing configuration	$V_{S,0}$	35.3	m/s	
Stall speed, take-off configuration	$V_{S,1}$	37.3	m/s	

Take-off safety speed	V_2	44.79	m/s	**Calculating propeller efficiency**
Average take-off safety speed	0,707 * V_2	31.67	m/s	
Propeller disc diameter	d_D	3.96	m	
Propeller disc area	S_D	12.32	m²	
T-O power of ONE engine	$P_{S,TO}$ / n_E	1600000	W	
Disc loading	L_D	106	kWm/kg	$L = \frac{P_{TO}}{\sigma\, \rho_0\, S_D}$
Propeller efficiency	η_P	0.678		<<<< from 7.) Propeller Efficiency
Slope	a	0.460	kg/m³	$a = \frac{P_S / m_{MTO}}{m_{MTO} / S_W} = \frac{k_{TO} \cdot 1.2 \cdot V_{s,1} \cdot g}{S_{TOFL} \cdot \sigma \cdot C_{L,\max,TO} \cdot \eta_{P,TO} \cdot \sqrt{2}}$
Power-to-weight ratio	$P_{STO}/m_{MTO,}$ at m_{MTO}/S_W	124.5	W/kg	

2nd Segment

Calculation of glide ratio

Aspect ratio	A	12.32	
Lift coefficient, take-off	$C_{L,TO}$	1.56	
Lift-independent drag coefficient, clean	$C_{D,0}$ (bei Berechnung: 2. Segment)	0.020	
Lift-coefficient, landing	CL,L	1.482	
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0.023	
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0.000	
Profile drag coefficient	$C_{D,P}$	0.043	
Oswald efficiency factor; landing configuration	e	0.7	
Glide ratio in take-off configuration	E_{TO}	11.78	

n_E	sin(γ)
2	0.024
3	0.027
4	0.030

$$E_{TO} = \frac{C_{L,TO}}{C_{D,P} + \frac{C_{L,TO}^2}{\pi \cdot A \cdot e}}$$

Calculation of power-to-weight ratio

Number of engines	n_E	2		
Take-off safety speed	V_2	44.79	m/s	from Take-Off — **Calculating propeller efficiency**
Disc loading	L_D	106	kWm/kg	from Take-Off
Propeller Efficiency-2nd Segment	ηP	0.678		<<<< from 7.) Propeller Efficiency
Climb gradient	sin(γ)	0.024		
Power-to-weight ratio	$P_{S,TO}$ / m_{MTO}	141.2	W/kg	

$$\frac{P_{S,TO}}{m_{MTO}} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_{TO}} + \sin\gamma\right) \cdot \left(\frac{V_2 \cdot g}{\eta_{P,CL}}\right)$$

Missed approach

Calculation of the glide ratio

Lift coefficient, landing	$C_{L,L}$	1.48	
Lift-independent drag coefficient, clean	$C_{D,0}$ (bei Berechnung: Durchstarten)	0.020	
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0.019	
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0.000	
Choose: Certification basis	JAR-25 bzw. CS-25	no	<<<< Choose according to task
	FAR Part 25	yes	
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0.015	
Profile drag coefficient	$C_{D,P}$	0.054	
Glide ratio in landing configuration	E_L	10.96	

	JAR-25 bzw. CS-25	FAR Part 25
$\Delta C_{D,gear}$	0.000	0.015

n_E	sin(γ)
2	0.021
3	0.024
4	0.027

Calculation of power-to-weight ratio

Approach speed	V_{APP}	45.9	m/s	**Calculating propeller efficiency**
Disc loading	L_D	106	kWm/kg	with Take-Off power setting
Propeller Efficiency-Missed Approach	ηP	0.685		<<<< from 7.) Propeller Efficiency

Climb gradient	sin(γ)	0.024	
Power-to-weight ratio	$P_{S,TO}$ / m_{MTO}	141.2	W/kg

$$\frac{P_{S,TO}}{m_{MTO}} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_{TO}} + \sin\gamma\right) \cdot \left(\frac{V_2 \cdot g}{\eta_{P,CL}}\right)$$

Missed approach

Calculation of the glide ratio

Lift coefficient, landing	$C_{L,L}$	1.48	
Lift-independent drag coefficient, clean	$C_{D,0}$ (bei Berechnung: Durchstarten)	0.020	
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0.019	
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0.000	
Choose: Certification basis	JAR-25 bzw. CS-25	no	<<<< Choose according to task
	FAR Part 25	yes	
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0.015	
Profile drag coefficient	$C_{D,P}$	0.054	
Glide ratio in landing configuration	E_L	10.96	

	JAR-25 bzw. CS-25	FAR Part 25
$\Delta C_{D,gear}$	0.000	0.015

n_E	sin(γ)
2	0.021
3	0.024
4	0.027

Calculation of power-to-weight ratio

Approach speed	V_{APP}	45.9	m/s	**Calculating propeller efficiency**
Disc loading	L_D	106	kWm/kg	with Take-Off power setting
Propeller Efficiency-Missed Approach	ηP	0.685		<<<< from 7.) Propeller Efficiency

Climb gradient	sin(γ)	0.021	
Power-to-weight ratio	$P_{S,TO}$ / m_{MTO}	142.5	W/kg

$$\frac{P_{S,TO}}{m_{MTO}} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_L} + \sin\gamma\right) \cdot \frac{m_{ML}}{m_{MTO}} \cdot \left(\frac{V_2 \cdot g}{\eta_{P,CL}}\right)$$

Max. Glide Ratio in Curise			
Estimation of k_E by means of 1.), 2.) or 3.)			
1.) From theory			
Oswald efficiency factor for k_E	e	0.75	
Equivalent surface friction coefficient	$C_{f,eqv}$	0.004	Roskam / Raymer (see FE-Script)
Factor	k_E	12.14	
2.) Acc. to RAYMER			
Factor	k_E	11.07	for retractable propeller aircraft
3.) From own statistics			
Factor	k_E	11.22	for large propeller driven aircraft: statistics give a value 11,22 --- See 1.) Parameters-Statistic
Estimation of max. glide ratio in cruise, E_{max}			
Factor	k_E chosen	11.22	**<<<< Choose according to task**
Relative wetted area	S_{wet} / S_w	9.6	S_{wet} / S_w = 6,0 ... 6,2
Aspect ratio	A	12.32	(from sheet 1)
Max. glide ratio	E_{max}	12.71	
	or		
Max. glide ratio	$E_{max\ chosen}$	12.71	**<<<< Choose according to task**

Preliminary Sizing II
Calculations for cruise, matching chart, fuel mass, operating empty mass
and aircraft parameters m_{MTO}, m_L, m_{OE}, S_W, T_{TO}, ...

this block provides a min value for power to weight ratio and also the cruise altitude; the input values are lift to drag ratio, the given cruise Mach number, engine parameters and characteristics of the atmosphere

Parameter		Value	
Max. glide ratio, cruise	E_{max}	12.71	(from worksheet 4)
Aspect ratio	A	12.32	(from worksheet 3)
Oswald eff. factor, clean	e	0.85	
Zero-lift drag coefficient	$C_{D,0}$	0.051	
Lift coefficient, $C_{L,md}$	$C_{L,md}$	1.29	$C_{L,md} = \frac{\pi \cdot A \cdot e}{2 \cdot E_{max}}$
Mach number, cruise	M_{CR}	0.433	
CR power of ONE engine	$P_{S,CR}$ / n_E calculated	943060	W
Disc loading, estimated	L_D calculated	104	kWm/kg
Cruise speed	V_{CR}	see below	
Propeller Efficiency-Cruise	ηP	0.870	<<<< from 7.) Propeller Efficiency

Calculating propeller efficiency

Parameter	Value	
V/V_{md}	1.400	chosen
$C_L/C_{L,md}$	0.510	
C_L	0.660	
E	10.291	

$$C_L = \frac{C_{L,md}}{(V/V_{md})^2}$$

$$C_L / C_{L,md} = 1/(V/V_{md})^2$$

$$E = \frac{2 \cdot E_{max}}{\frac{C_L}{C_{L,md}} + \frac{1}{\frac{C_L}{C_{L,md}}}}$$

$$T = T_0 - L \cdot H \qquad L = -\frac{dT}{dH}$$

$$T = T_0 + H \cdot \frac{dT}{dH}$$ temperature at any H

$$\sigma = \frac{\rho}{\rho_0} = \left(1 - \frac{LH}{T_0}\right)^{g/RL-1}$$ relative density

$$p = p_0 \left(1 - \frac{LH}{T_0}\right)^{g/RL}$$ and presure in troposphere

A =	1.88289988
m =	0.74093011
n =	0.92866802

These values apply for the PW 120 familly engines (such for the ATR 72); for more general v

Constants			
Ratio of specific heats, air (adiabatic index)	γ	1.4	
Earth acceleration	g	9.81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Euler number	e	2.718281828	
Lapse rate in troposphere	L	0.0065	K/m
Gas constant	R	287.053	K m² / s²
Standard temperature,sea level	T_0	288.15	K

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot M_{CR}^2}{g} \cdot \frac{\gamma}{2} \cdot p(h)$$

$$P/P_0 = AM^m \sigma^n$$

$$\frac{P_{S,TO}}{m_{MTO}} = \frac{V_{CR} \cdot g}{P_{S,CR}/P_{S,TO} \cdot E \cdot \eta_{P,CR}}$$

							Cruise		2. segment	Missed Approach	Take-off		Landing	
h [km]	h [ft]	T[K]	σ	p(h) [Pa]	m_{MTO} / S_W [kg/m²]	$P_{CR}/P_{S,TO}$	$P_{S,TO}/m_{MTO}$ [W/kg]	a [m/s]	$P_{S,TO}/m_{MTO}$	$P_{S,TO}/m_{MTO}$	$P_{S,TO}/m_{MTO}$	slope, a	m_{MTO}/S_W	$P_{S,TO}/m_{MTO}$
0.0	0	288.15	1.0000	101325	895	1.013	159.4	340.3	141.2	142.5	412.0	0.4604	270	0
0.5	1641	284.90	0.9529	95461	843	0.968	165.8	338.4	141.2	142.5	388.2	0.4604		
1.0	3281	281.65	0.9074	89874	794	0.925	172.5	336.4	141.2	142.5	365.5	0.4604		
1.5	4922	278.40	0.8637	84555	747	0.884	179.5	334.5	141.2	142.5	343.8	0.4604		
2.0	6562	275.15	0.8216	79494	702	0.844	187.0	332.5	141.2	142.5	323.3	0.4604		
2.5	8203	271.90	0.7810	74681	660	0.805	194.8	330.6	141.2	142.5	303.7	0.4604		
3.0	9843	268.65	0.7420	70107	619	0.768	203.1	328.6	141.2	142.5	285.1	0.4604		
3.5	11484	265.40	0.7046	65763	581	0.732	211.8	326.6	141.2	142.5	267.4	0.4604		
4.0	13124	262.15	0.6686	61639	544	0.697	221.0	324.6	141.2	142.5	250.7	0.4604		
4.5	14765	258.90	0.6340	57727	510	0.663	230.7	322.6	141.2	142.5	234.7	0.4604		
5.0	16405	255.65	0.6008	54018	477	0.631	241.0	320.5	141.2	142.5	219.7	0.4604		
5.5	18046	252.40	0.5689	50505	446	0.600	251.9	318.5	141.2	142.5	205.4	0.4604		
6.0	19686	249.15	0.5384	47179	417	0.570	263.4	316.4	141.2	142.5	191.9	0.4604		
6.5	21327	245.90	0.5091	44033	389	0.541	275.7	314.4	141.2	142.5	179.1	0.4604		
7.0	22967	242.65	0.4811	41059	363	0.513	288.6	312.3	141.2	142.5	167.0	0.4604		
7.5	24608	239.40	0.4542	38249	338	0.487	302.4	310.2	141.2	142.5	155.5	0.4604		
8.0	26248	236.15	0.4286	35598	314	0.461	317.0	308.1	141.2	142.5	144.8	0.4604		
8.5	27889	232.90	0.4040	33097	292	0.436	332.6	305.9	141.2	142.5	134.6	0.4604		
9.0	29529	229.65	0.3805	30740	272	0.413	349.1	303.8	141.2	142.5	125.0	0.4604	270	350
9.5	31170	226.40	0.3581	28522	252	0.390	366.7	301.6	141.2	142.5	116.0	0.4604		
10.0	32810	223.15	0.3367	26434	234	0.369	385.5	299.5	141.2	142.5	107.5	0.4604		
10.5	34451	219.90	0.3164	24472	216	0.348	405.5	297.3	141.2	142.5	99.5	0.4604		
11.0	36091	216.65	0.2969	22630	200	0.328	426.9	295.1	141.2	142.5	92.0	0.4604		
11.5	37732	216.65	0.2745	20916	185	0.305	459.2	295.1	141.2	142.5	85.1	0.4604		
12.0	39372	216.65	0.2537	19330	171	0.283	494.1	295.1	141.2	142.5	78.6	0.4604		
12.5	41013	216.65	0.2345	17865	158	0.263	531.6	295.1	141.2	142.5	72.6	0.4604		
13.0	42653	216.65	0.2167	16510	146	0.245	572.0	295.1	141.2	142.5	67.1	0.4604		
Remark:	1 m = 3,281 ft													

Wing loading	m_{MTO} / S_W	269.0	kg/m²	<<<< Design point from matching chart!			
Power-to-weight ratio	$P_{S,TO}$ / m_{MTO}	241.0	W/kg	<<<< Given data is correct when take-off and landing is sizing the aircraft at the same time.			
Speed of sound	a	323.6	m/s	<<<< Interpolated from table above			
Cruise speed, estimated	V_{CR} 1. iteration	140.1	m/s				
Relative power in cruise	$P_{CR}/P_{S,TO}$	0.637					
Relative density in cruise	σ	0.607					
	$T_{Troposphere}$	256.27	K				
Temperature in cruise	T	256.27	K				
Cruise altitude	h_{CR}	4904	m				
Cruise altitude	h_{CR}	16091	ft				
Speed of sound	a	320.9	m/s				
Cruise speed, first iteration	V_{CR} 2. iteration	139.0	m/s				
Relative power in cruise	$P_{CR}/P_{S,TO}$	0.632					
Relative density in cruise	σ	0.602					
	$T_{Troposphere}$	255.73	K				
Temperature in cruise	T	255.73	K				
Cruise altitude	h_{CR}	4987	m				
Cruise altitude	h_{CR}	16362	ft				
Speed of sound	a	320.6	m/s				
Cruise speed, calculated	V_{CR} 3. iteration	138.8	m/s	use for calculating propeller efficiency			
				## The set of relationships between ***power to weight ratio and the***			
Conversion factor	NM -> m	1852	m/NM	***wing loading*** represented in the matching chart give a single pair of values			
Design range	R	1125	NM	that meet all requirements and constraints in an economical manner---->see below			
Design range	R	2083500	m				
Distance to alternate	$s_{to\ alternate}$	87	NM	typical value	200	NM	
Distance to alternate	$s_{to\ alternate}$	161124	m	**Reserve flight distance:**			
Chose: FAR Part121-Reserves	domestic	yes		FAR Part 121	s_{res}		
	international	no		domestic	161124	m	
Extra-fuel for long range		5.0%		international	265299	m	
Extra flight distance	s_{res}	161124	m				
Specific fuel consumption	SFC_P	1.9E-08	kg/W/s	typical value	5.5E-08	kg/W/s	
				Extra time:			
Breguet-Factor, cruise	B_s	47617151	m	FAR Part 121	t_{loiter}		
Fuel-Fraction, cruise	$M_{ff,CR}$	0.957		domestic	2700	s	
Fuel-Fraction, extra flight distance	$M_{ff,RES}$	0.997		international	1800	s	
Loiter time	t_{loiter}	2700	s				
Specific fuel consumption, loiter	SFC_{loiter}	1.9E-08	kg/W/s				
Breguet-Factor, flight time	B_t	339834	s				
Fuel-Fraction, loiter	$M_{ff,loiter}$	0.992					
				Phase	M_{ff} per flight phases [Roskam]		
					index	value	
Fuel-Fraction, engine start	$M_{ff,engine}$	0.997	<<<< Copy	start-up	ES	0.990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0.997	<<<< values	taxi	T	0.995	
Fuel-Fraction, take-off	$M_{ff,TO}$	0.998	<<<< from	take-off	TO	0.995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0.967	<<<< table	climb	CLB	0.985	
Fuel-Fraction, descent	$M_{ff,DES}$	0.997	<<<< on the	descent	DES	0.985	
Fuel-Fraction, landing	$M_{ff,L}$	0.997	<<<< right !	landing	L	0.995	

Fuel-Fraction, standard flight	$M_{ff,std}$	0.918					
Fuel-Fraction, all reserves	$M_{ff,res}$	0.953					
Fuel-Fraction, total	M_{ff}	0.875					
Mission fuel fraction	m_F/m_{MTO}	0.125					
Realtive operating empty mass	m_{OE}/m_{MTO}	0.568		original aircraft			
Realtive operating empty mass	m_{OE}/m_{MTO}	0.595		from statistics for turboprops (Jenkinson 1999)			
Realtive operating empty mass	m_{OE}/m_{MTO}	0.595		**<<<< Choose according to task**			
Choose: type of a/c	short / medium range	yes		**<<<< Choose according to task**			
	long range	no					
Mass: Passengers, including baggage	m_{PAX}	95	kg	in kg	Short- and Medium Range		Long Range
Number of passengers	n_{PAX}	40		m_{PAX}		93.0	97.5
Cargo mass	m_{cargo}	0	kg				
Payload	m_{PL}	3800	kg				
				Redesign? Enter original aircraft data! Compare with results!			
Max. Take-off mass	m_{MTO}	12388	kg	↔	22800	kg	
Max. landing mass	m_{ML}	12264	kg	↔	22350	kg	
Operating empty mass	m_{OE}	7371	kg	↔	12950	kg	
Mission fuel fraction, standard flight	m_F	1552	kg	↔	5000	kg (max.)	
Wing area	S_w	46.1	m²	↔	61	m²	
Take-off power	$P_{S,TO}$	2985467	W	**all eng. together**			
T-O power of ONE engine	$P_{S,TO}$ / n_E	1492734	W	**one engine** ↔	1600000	W	
T-O power of ONE engine	$P_{S,TO}$ / n_E	335567	lb	**one engine**			
Fuel mass, needed	$m_{F,erf}$	1552	kg				
Fuel mass, needed	mF,erf	1606	kg				
Fuel density	ρ_F	71	kg/m³	Reference	https://www.fzt.haw-hamburg.de/pers/Scholz/HOOU/ParameterSelectionLH2.pdf		
Fuel volume, needed	$V_{F,erf}$	21.92	m³	(check with tank geometry later on)			
Max. Payload	m_{MPL}	3800	kg				
Max. zero-fuel mass	m_{MZF}	11171	kg				
Fuel mass, all reserves	$m_{F,res}$	586	kg				
Check of assumptions	check:	m_{ML}		>	mOE+mMPL+mF,res		
		12264	kg	>	11757	kg	
				yes			
				Aircraft sizing finished!			

Length of the hydrogen aircraft is calculated using: [14]

$$L_{cabin} = S_P \left[\frac{PAX}{S_A} \right] + L_{galley}$$

L_{galley} = Length of the galley = 2.07 m

PAX = Number of passengers = 32

S_A = Number of seats abreast= 4

S_p = Seating pitch = 0.7874 m [29]

L_{cabin} = Length of the cabin = 8.36 m

L_{tank} = Volume of hydrogen / fuselage area = 21.92 m^3 / 5.68 m^2 = 3.86 m

$L_{fuselage}$ = length of nose + tail (13.09 m) + length of cabin (8.36 m) + length of tank (3.86 m) = 25.31 m

Assumption: Diameter, and length of nose and tail are taken to be same as reference aircraft.

Downstream environmental impacts -[30]–[32]

Amount of H_2O produced per year from City 1 (Calgary) to City 2 (Yellowknife)

= (0.78 kg of H_2O/1.2 L of H_2)*(13592.82 L of H_2 /flight)*(2 flights/day)*(365 days/year)

= 6,449,793.09 kg of H_2O/year

Amount of H_2O produced per year from City 2 (Yellowknife) to City 3 (Norman Wells)

= (0.78 kg of H_2O/1.2 L of H_2)*(7227.75 L of H_2 /flight)*(1 flight/day)*(365 days/year)

= 1,714,783.688 kg of H_2O/year

Amount of H_2O produced per year from City 4 (Iqaluit) to City 5 (Clyde River)

= (0.78 kg of H_2O/1.2 L of H_2)*(8416.60 L of H_2 /flight)*(1 flight/day)*(365 days/year)

= 1,996,838.35 kg of H_2O/year

Total Amount of H_2O produced per year from the following flights

= (6,449,793.09 + 1,714,783.688 + 1,996,838.35) kg of H_2O /year

= 10,161,415.13 kg of H_2O/year

Amount of NO_x produced per year from City 1 (Calgary) to City 2 (Yellowknife)

= (1.02*10^-4 kg of NO_x /1.2 L of H_2)*(13592.82 L of H_2 /flight)*(2 flights/day)*(365 days/year)

= 843.43 kg of NO_x /year

Amount of NO_x produced per year from City 2 (Yellowknife) to City 3 (Norman Wells)

= (1.02*10^-4 kg of NO_x /1.2 L of H_2)*(7227.75 L of H_2 /flight)*(1 flight/day)*(365 days/year)

= 224.24 kg of NO_x /year

Amount of NO_x produced per year from City 4 (Iqaluit) to City 5 (Clyde River)

= (1.02*10^-4 kg of NO_x /1.2 L of H_2)*(8416.60 L of H_2 /flight)*(1 flight/day)*(365 days/year)

= 261.13 kg of NO_x /year

Total Amount of NO_x produced per year from the following flights

= (843.43 + 224.24 + 261.13) kg of NO_x /year

= 1,328.80 kg of NO_x /year

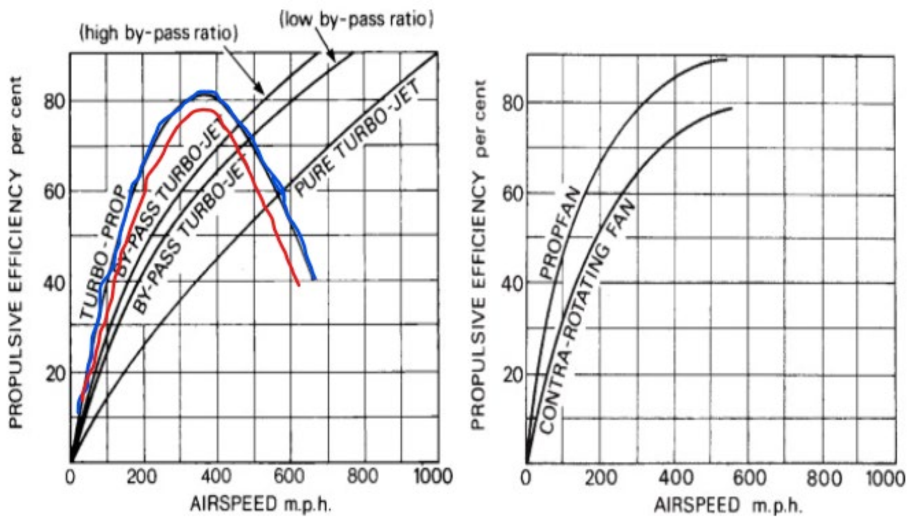


Figure 3: Propulsive Efficiency of Different Aircraft with Respect to Air Speed [33]

Red: Hydrogen Combustion, Blue: Turbo-Prop

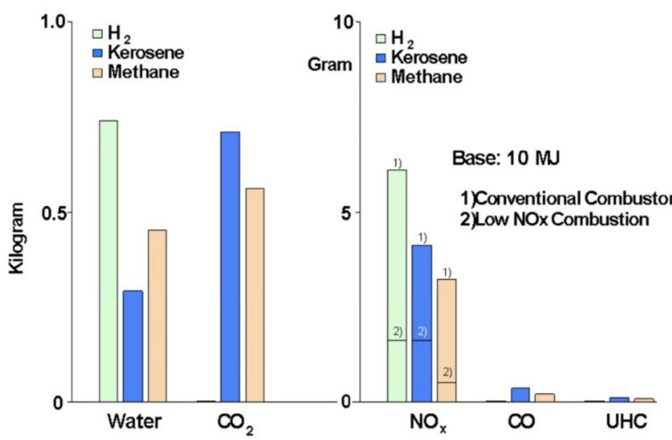


Figure 4: Various Emissions from Combustion of H_2 [34]

<u>Operating Cost Calculation [35]–[45]:</u>

MTOM = Maximum take-off weight

Assumptions:

1. Cost of the hydrogen engine is same as Pratt & Whitney Canada PW100 used in the reference aircraft [46]

2. The cost of the engine spare is 30% of the cost of the engine and the cost of the spares is 10% of the cost of the airframe [46].
3. The cost of the aircraft at end of life is 10% of the total investment cost [46].
4. Interest rate on investment cost is 6% per year (average of interest rate 5.5 and 6.5 [47]).
5. Insurance charge is 0.5% of the aircraft cost [46].
6. Flight is operated for 4200 hours per year:
7. The average lifetime of the aircraft is taken as 15 years.
8. Cost of maintenance of hydrogen aircraft is assumed to be 70% of the cost of maintenance of conventional aircraft.
9. During the calculation, passenger handling charges from a representative US airport were considered.
10. Development cost of hydrogen-aircraft is the same as conventional powered aircraft [46].
11. The operating costs between the three airports under consideration are extrapolated from typical Canadian airports.
12. Profit margin per passenger is $17.75 [37].

Aircraft empty mass OEM = 0.58 * MTOM = 0.58 *12388 kg = 7185.04 kg

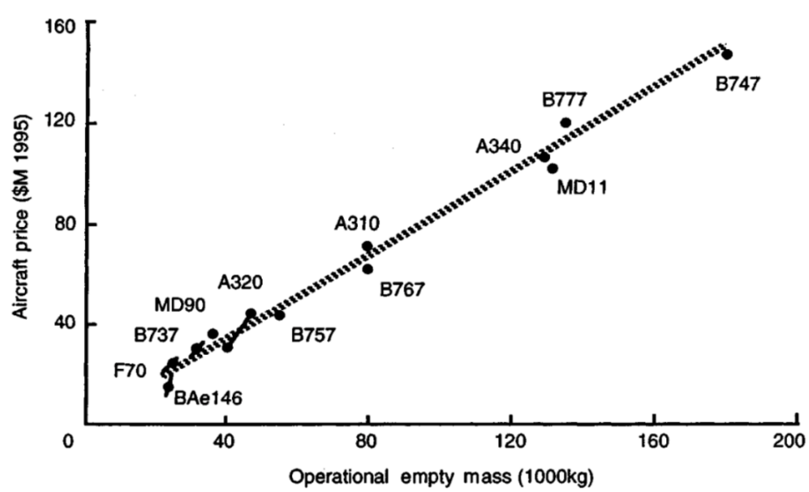


Figure 5: Aircraft Price Estimation Based on Operational Empty Mass [48]

From the cost graph [48], the total aircraft price is estimated = 0.8139 * 7185.04/1000 + 2.1862 = $8.03 Million.

Cost of an engine = $0.8 Million per engine.

Total cost of the engines = 2 * $ 0.8 Million = $1.6 Million

Cost of the airframe = $8.03 Million - $1.6 Million ⇒ $6.43 Million

Total spares cost = (0.3 * $1.6 Million) + (0.1 * $6.43 Million)

⇒ $1.123 Million

Investment cost = cost of airframe + total cost of the engines + total spares cost

⇒ $9.153 Million

Depreciation costs/year = 0.9 * $9.153 Million/15

⇒ $0.549 Million

Interest/year = 0.06 * $9.153 Million/15

⇒ $0.549 Million

Insurance/year = 0.005 * $8.03 Million/15

⇒ $0.040 Million

Total annual standing charge/year = interest/year + insurance/year + depreciation cost = $0.549 Million + $0.040 Million + $0.549 Million ⇒ $1.138 Million

Standing charge/flying hour = $1.138 Million/4200 hours

⇒ $271.95

	Indirect Operating Cost	Unit	Cost per unit at take-off city	Cost per unit at destination city	Number of units	Cost
Airport charges	Terminal Charges	per aircraft	$ 66.35	$ 61.44	1	$ 127.79
	Airport improvement fee	per pax	$ 18.80	$ 18.80	37	$ 1,390.98
	Take-off/landing charge	per 1000 kg	$ 3.09	$ 3.38	12.388	$ 80.10
	Ground Handling charge	per aircraft	$ 118.05	$ 118.05	1	$ 236.09
	Handing of pax	per pax	$ 18.32	$ 18.32	40	$ 1,465.26
	Aircraft Parking fees	per 2 hours	$ 15.05	$ 15.11	1	$ 30.16
	Security Fee	per pax	$ 2.63	$ 2.63	40	$ 210.53
	Common Use fees	per departure	$ 37.59	$ 37.59	1	$ 75.19
	Total cost					$ 3,616.10

Origin: Calgary, Canada Destination: Yellowknife, Canada

Distance = 1279.43 km

	Direct Operating Cost	Unit	Cost per unit	Number of units	Cost
Aircraft charge	Green Hydrogen	per kg	$ 2.63	953.05	$ 2,508.02
	Blue Hydrogen	per kg	$ 1.65	953.05	$ 1,568.59
	Grey Hydrogen	per kg	$ 1.50	953.05	$ 1,425.99
	Maintenance	per blockhour	$ 268.95	2.60	$ 698.72
	Pilots	per hour	$ 30.08	2.60	$ 78.14
	Standing charge	per hour of operation	$ 271.95	2.60	$ 706.53
Air navigation	Route navigation fee	per km per square root of MTOW	$ 0.02859	142402.3408	$ 4,070.78
	Air navigation charge + airport charge + aircraft charge with Green Hydrogen fuel				$ 11,678.28
	Air navigation charge + airport charge + aircraft charge with Blue Hydrogen fuel				$ 10,738.85
	Air navigation charge + airport charge + aircraft charge with Grey Hydrogen fuel				$ 9,897.52

Cost per passenger Green Hydrogen fuel	$ 333.38
Cost per passenger Blue Hydrogen fuel	$ 307.99
Cost per passenger Grey Hydrogen fuel	$ 285.25

Origin: Yellowknife, Canada Destination: Norman Wells, Canada

Distance = 680.753 km

	Direct Operating Cost	Unit	Cost per unit	Number of units	Cost
Aircraft charge	Green Hydrogen	per kg	$ 2.63	507.09	$ 1,334.46
	Blue Hydrogen	per kg	$ 1.65	507.09	$ 834.61
	Grey Hydrogen	per kg	$ 1.50	507.09	$ 758.73
	Maintenance	per blockhour	$ 268.95	1.38	$ 371.77
	Pilots	per hour	$ 30.08	1.38	$ 41.57
	Standing charge	per hour of operation	$ 271.95	1.38	$ 375.92
Air navigation	Route navigation fee	per km per square root of MTOW	$ 0.02859	75768.75693	$ 2,165.96
	Air navigation charge + airport charge + aircraft charge with Green Hydrogen fuel				$ 7,905.78
	Air navigation charge + airport charge + aircraft charge with Blue Hydrogen fuel				$ 7,405.94
	Air navigation charge + airport charge + aircraft charge with Grey Hydrogen fuel				$ 6,958.29

Cost per passenger Green Hydrogen fuel	$ 231.42
Cost per passenger Blue Hydrogen fuel	$ 217.91
Cost per passenger Grey Hydrogen fuel	$ 205.81

Origin: Iqaluit, Canada Destination: Clyde River, Canada

Distance 799.84 km

	Direct Operating Cost	Unit	Cost per unit	Number of units	Cost
Aircraft charge	Green Hydrogen	per kg	$ 2.63	595.80	$ 1,567.90
	Blue Hydrogen	per kg	$ 1.65	595.80	$ 980.61
	Grey Hydrogen	per kg	$ 1.50	595.80	$ 891.46
	Maintenance	per blockhour	$ 268.95	1.62	$ 436.81
	Pilots	per hour	$ 30.08	1.62	$ 48.85
	Standing charge	per hour of operation	$ 271.95	1.62	$ 441.69
Air navigation	Route navigation fee	per km per square root of MTOW	$ 0.02859	83828.86988	$ 2,396.37
	Air navigation charge + airport charge + aircraft charge with Green Hydrogen fuel				$ 8,507.71
	Air navigation charge + airport charge + aircraft charge with Blue Hydrogen fuel				$ 7,920.42
	Air navigation charge + airport charge + aircraft charge with Grey Hydrogen fuel				$ 7,394.46

Cost per passenger Green Hydrogen fuel	$ 247.69
Cost per passenger Blue Hydrogen fuel	$ 231.82
Cost per passenger Grey Hydrogen fuel	$ 217.60

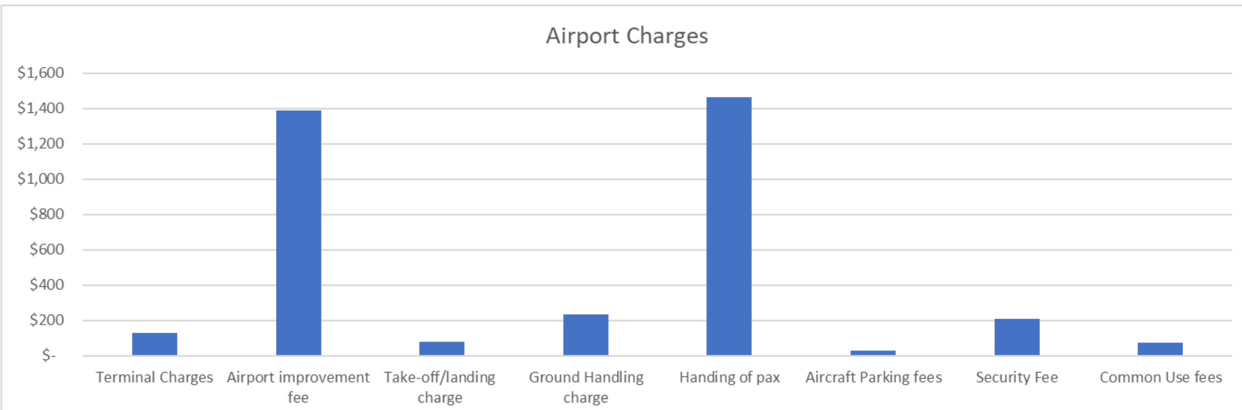


Figure 6: Airport Charges for Hydrogen-Powered Aircraft

Appendix B: Hydrogen Production Figures

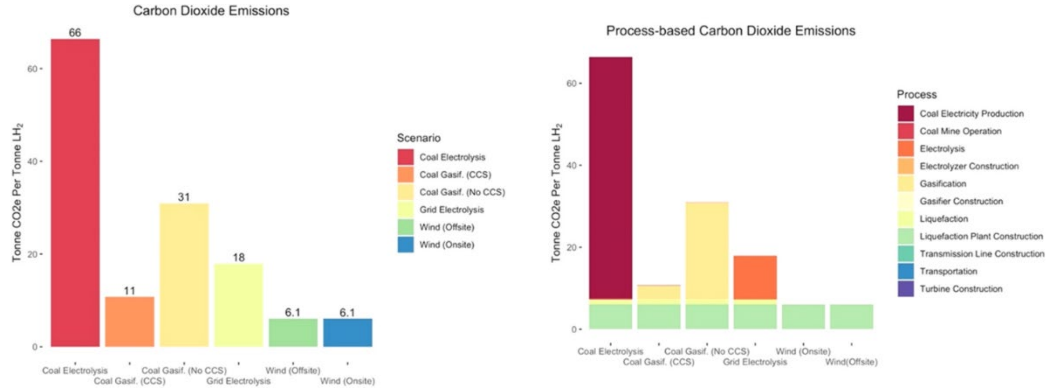


Figure 7: Carbon Dioxide Emissions per Tonne of LH_2 Produced (Left) and Process-Based Carbon Dioxide Emissions (Right) [16]

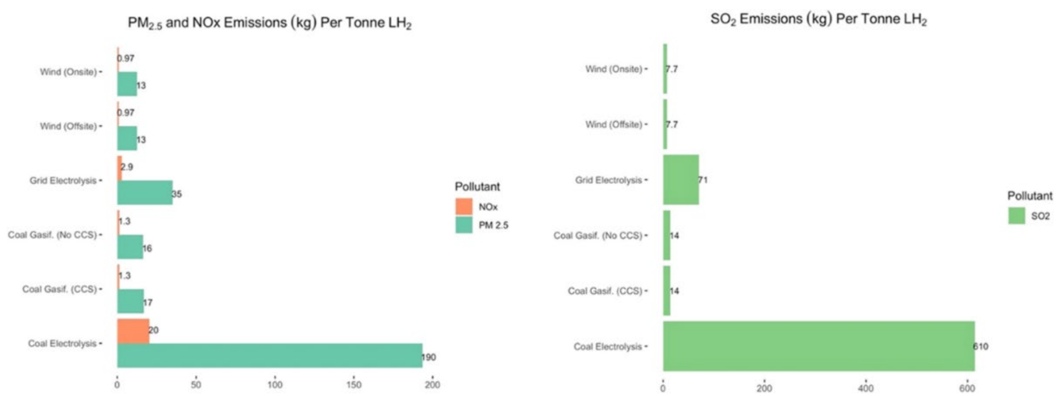


Figure 8: SO_x, NO_x, and $PM_{2.5}$ Emissions per Tonne of LH2 Produced [16]

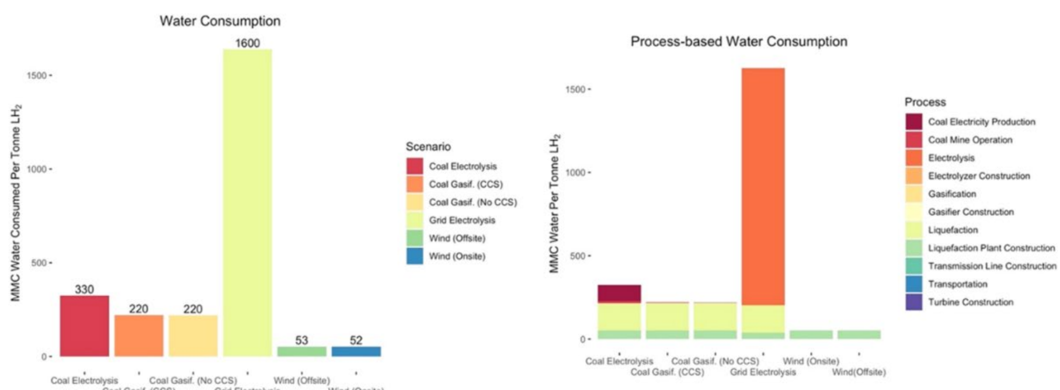
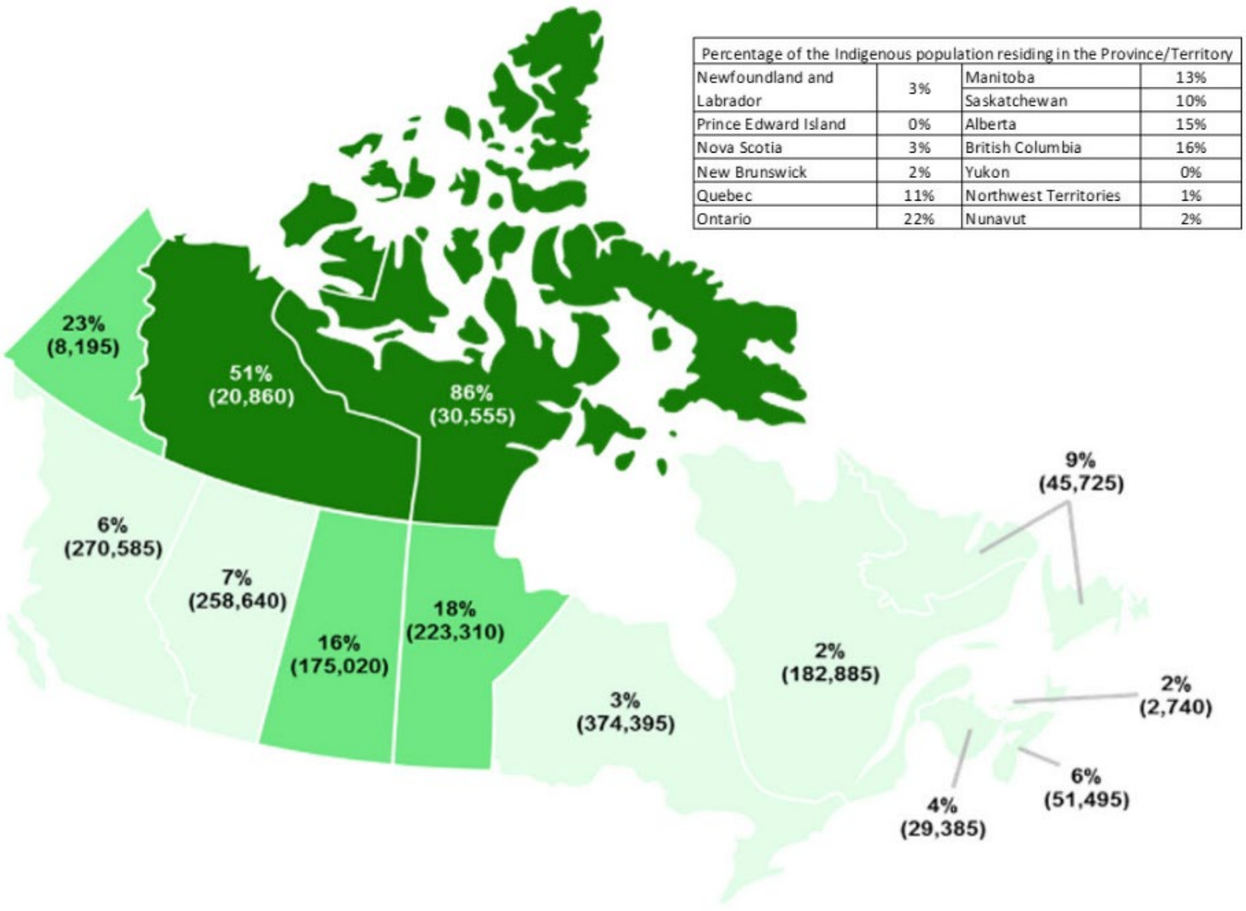


Figure 9: Water Consumption per Tonne of LH_2 Produced (Left) and Process-Based Water Consumption (Right) [16]

Appendix C: Indigenous Peoples



Percentage of the Indigenous population residing in the Province/Territory			
Newfoundland and Labrador	3%	Manitoba	13%
		Saskatchewan	10%
Prince Edward Island	0%	Alberta	15%
Nova Scotia	3%	British Columbia	16%
New Brunswick	2%	Yukon	0%
Quebec	11%	Northwest Territories	1%
Ontario	22%	Nunavut	2%

Figure 10: Indigenous Peoples across Canada [1]