

Impact of Technology Trajectories on the Performance, Emissions, Life Cycle Aspects and Sustainability Assessment of Future Net Zero Regional Aircraft Variants

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The sustainability assessment of five Net Zero regional aircraft variants assuming entry into service by 2035 and 2050 is presented. Sustainable Aviation Fueled, Hydrogen Gas Turbine, Full Electric, Hybrid Electric and Fuel Cell-Electric variants are evaluated. The impact of technology trajectories at aircraft level is analyzed in terms of payload-range capabilities, tailpipe carbon emissions and energy consumption per passenger. The efficiency and carbon intensity of energy and fuel production infrastructures are combined with overall sustainability metrics that include engineering, environmental, social, economic and policy factors. Variations in the ranking of the Net Zero aircraft are analyzed along with the strong dependencies of the outcomes on the technology trajectories, choice of metrics and level of evaluation considered. The influence of coupled multi-spatial and temporal factors on the sustainability outcomes is further discussed. Although zero tailpipe emission variants are feasible, early entrants with conservative technology targets cannot meet the baseline payload range capabilities and lead to large variations in energy efficiency at aircraft level. For these technology levels SAF variants offer the highest potential in mission energy improvements ~4% while all other variants lead to an energy penalty compared to the baseline. Advanced versions of the variants converge to similar energy savings close to ~13% for 2035 and ~23% for 2050. Compared to SAF, advanced hybrid electric variants could lead also to tailpipe carbon reductions of 15%-20% and ~35% for 2035 and 2050 respectively. Two energy scenarios are used to estimate the life cycle carbon emissions of these aircraft, utilizing projections for 2030 and 2050. Under 2030 energy infrastructure scenarios, hydrogen aircraft produce higher life cycle emissions than contemporary aircraft, while SAF variants, when accounting for carbon reuptake, demonstrate benefits. With the 2050 energy infrastructure scenarios, all aircraft configurations and technology projections achieve reduced life cycle emissions compared to contemporary aircraft. The study demonstrates that aircraft emissions and sustainability are dependent on both aircraft technology and energy infrastructure, with discussions concluding on the impacts that these technologies have to aviation sustainability.

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I. Nomenclature

<i>BED</i>	=	battery energy density
<i>BoP</i>	=	balance of plant
<i>CHARM</i>	=	Cranfield Hydrogen and hybrid electric Aircraft Research Model
<i>EER</i>	=	energy efficiency ratio
<i>E-HEART</i>	=	enabling hybrid and hydrogen electric aircraft research tool
<i>DoH</i>	=	degree of hybridization
<i>GT</i>	=	gas turbines
<i>LC</i>	=	liquid cooling
<i>MTOM</i>	=	maximum takeoff mass
<i>nmi</i>	=	nautical miles
<i>OEM</i>	=	operating empty mass
<i>NPPC</i>	=	net performance power coefficient of thermal management system
<i>TMS</i>	=	thermal management system
<i>TOM</i>	=	takeoff mass
<i>PEM</i>	=	proton exchange membrane
<i>SAF</i>	=	sustainable aviation fuel
<i>Pax</i>	=	passengers
<i>VCC</i>	=	vapor compressor cycle

II. Introduction

Decarbonization of aviation requires the development of disruptive technologies along with major investments in energy and air-transport infrastructures. Radical changes in the operations, governance and business models across different sectors affecting the wider aviation and energy eco-systems are also required. Currently, there are major international initiatives and significant efforts covering various decarbonization pathways to enable transition to net zero aircraft operations and sustainable air-transport Ref. [1-3]. A comparison of these pathways comes with major difficulties and needs to consider metrics that extend beyond the technical evaluation and performance analysis of the technologies and aircraft considered. While there is a plethora of high-quality studies and research projects covering a wide range of net zero aviation aspects, the available open literature appears fragmented with research efforts and publications focusing largely on individual elements and discreet levels of analysis that can be summarized and classified as follows:

Core and enabling “net zero” technologies required for specific decarbonization strategies Ref. [4-15]. Research at this level forms the basis of technological developments informing and feeding into system and aircraft level studies. Available literature includes fundamental developments that cover the design and performance of high efficiency and power dense motors (covering various topologies Ref. [5-8] as well as superconducting machines Ref. [9]), semi-conducting materials, gate drivers and multi-level architectures for power electronic components Ref. [10-12], high voltage electric distribution systems including insulation and fault protection technologies Ref. [13-14], proton exchange membrane fuel cells operating over wide ranges of temperatures and pressures Ref. [15-19], battery systems including different chemistries and types, i.e. solid state battery technologies Ref. [20-23], thermal management technologies Ref. [24] as well as on-board storage, pressurization, refueling and distribution technologies for liquid hydrogen systems Ref. [25-26]. Studies at this level are agnostic of the impact on the aircraft and life cycle levels and the developments are often based on generic and top-level requirements cascaded down by system and aircraft level studies.

System and aircraft level studies that focus on the design and optimization of specific variants (i.e. electric Ref. [27-29], hybrid electric Ref. [30-35], hydrogen fuel cell aircraft Ref. [36-43]). These studies offer assessments and comparisons against existing or advanced baseline aircraft that utilize SAF or Jet A fuel and consider the impact of selected technology factors over a limited range of input values. Research at this level forms the backbone of sustainable propulsion systems and aircraft design offering a wealth of information on modelling, design and optimization methods as well as implementation of Model Based System Engineering approaches. Studies inform the development of enabling and core technologies outlined above and cascade requirements to component level research and design. Findings are also used to inform techno-economic and environmental analysis studies. A wide range of model fidelity levels are available including large data sets for the evaluation of the different designs. However, outputs are sensitive to technology parameters, modelling fidelity, sizing requirements and rating approaches as well as inputs and assumptions related to safety and failure cases, off-design performance of systems and components,

ageing and degradation effects. Despite the existence of large data sets, comparison and interpretation of outcomes become challenging.

Life cycle studies: an increasing number of studies that consider techno-economic, environmental and life cycle aspects of Net Zero aircraft are becoming available over recent years. Studies at this level will usually take one of following approaches. High level and generic methods covering the environmental impact and life cycle analysis of specific technologies and/or energy pathways, i.e. batteries, fuel cells, SAF, hydrogen production, etc Ref. [45-47]. Such studies are agnostic to the specific requirements, design and performance aspects of the aircraft variants and they usually feed into the more detailed studies that are based on specific aircraft, technology and performance inputs, as well as energy pathways Ref. [48-52].

While, such studies offer a valuable insight into the wider impact of technologies and the introduction of novel aircraft, currently they are not an integral part of the technology development, systems integration and aircraft design process. Instead, they rely on additional levels of analysis that are based on either top level and generic or very discreet inputs, making an overall comparison between various decarbonization pathways, technologies and future Net Zero aircraft variants challenging.

A. Gap, Motivation and Relevance of Present Paper

Although significant progress has been made over the years in aligning methods and fidelity levels across various studies there are fundamental differences in the design, sizing and performance aspects of different variants with research teams focusing their efforts on developing capabilities relevant to specific variants and technologies. As a result, there are only limited number of studies that present a comprehensive and consistent comparison that covers competing technologies and Net Zero aircraft variants. Comparisons between different studies available in open literature become challenging due to different metrics and assumptions used in the modelling and evaluation of the concepts considered. Large research projects such as those in Ref. [1-2] are bridging the gaps between the various levels of analysis for specific aircraft concepts and associated disruptive technologies Ref. [9]. However, publicly available information across the various levels covering different sustainability pathways, technology trajectories and aircraft variants is limited.

The present paper is driven and informed by the above literature and complements existing efforts as it attempts to bridge the three levels of analysis discussed. An overarching approach is presented that enables the comparison of five Net Zero regional aircraft variants over two time-horizons. This is done by considering the impact of projected technology trajectories at three levels of evaluation that capture different drivers and metrics in terms aircraft/mission, life cycle and overall sustainability aspects. The consideration of two horizons enables the development and maturation of key technologies including step changes in their projected trajectories to be captured and assessed.

While regional aircraft only account for ~5-10% of the total aviation emissions they serve as intermediate steps for upscaling the development of disruptive technologies and required infrastructures for larger applications. Net Zero regional aircraft could potentially enter service through a phased approach and the creation of local and regional hubs that are not limited by the lack of global energy and airport infrastructure. In addition, as the operations of these aircraft are characterized by frequent taxing, take-off and landing cycles, emissions during these phases have a more pronounced impact on local, national and regional communities. Despite the limited payload-range capabilities and relatively small contribution to global aviation impact development and introduction of advanced Net Zero emission regional aircraft presented in this paper will constitute a significant milestone and a major achievement in the transition to net zero and sustainable aviation.

III. Overall Approach and Method

The paper and the overall approach are split into 4 parts. The first part focuses on the modelling and simulation of the baseline regional aircraft and the Net Zero variants that include:

- SAF variant
- SAF – Hybrid Electric variant
- Hydrogen Gas Turbine variant
- Full Electric variant
- Hydrogen Electric with PEM Fuel Cell variant

The variants are based on an existing 42-74 passenger regional aircraft Ref. [53] that is further modified to capture the operational, performance and sizing characteristics of the selected variants and their associated technologies.

The second part focuses on the performance analysis of the aircraft at mission level. The impact of different technology targets and trajectories over two time horizons (2035 and 2050) is modelled and discussed in terms of:

- payload and range

- tailpipe carbon emissions
- energy consumption per passenger relative to baseline

The third part includes an assessment that considers life cycle metrics that account for the carbon intensity and efficiency of the energy infrastructure as well as the cost and processes of producing and storing the energy carrier/fuel for the different variants considered. The impact of different hydrogen production methods is considered along with the production of SAF and the energy required to charge the batteries of the electric variants.

The final part focuses on the overall sustainability assessment and ranking of the 5 Net Zero variants. The sustainability framework developed and discussed in Ref. [52] is adapted to the variants and technologies considered and is used for the analysis. The framework considers a variety of metrics that account for engineering, environmental, policy, social and economic aspects. Inputs are informed by the analysis and findings derived in the previous parts of the paper. First, scenarios for 2030 and 2050 energy grids are defined. These estimate the carbon intensity of electricity, SAF production, and liquid hydrogen production for the two energy scenario years. A sustainability discussion is then performed using these and other inputs informed by the analysis and findings derived in the previous parts of the paper. To provide specific examples of the use cases of regional aircraft, two examples are provided: a route between two major airport, Toronto and Boston, and a route between a major airport and a remote airport, Anchorage to Fairbanks, Alaska. These cases are used to highlight the non-quantitative sustainability impacts that transitions to these types of alternative fuels may impose on future air services, and the impacts these decisions may have to regional, rural, and remote communities.

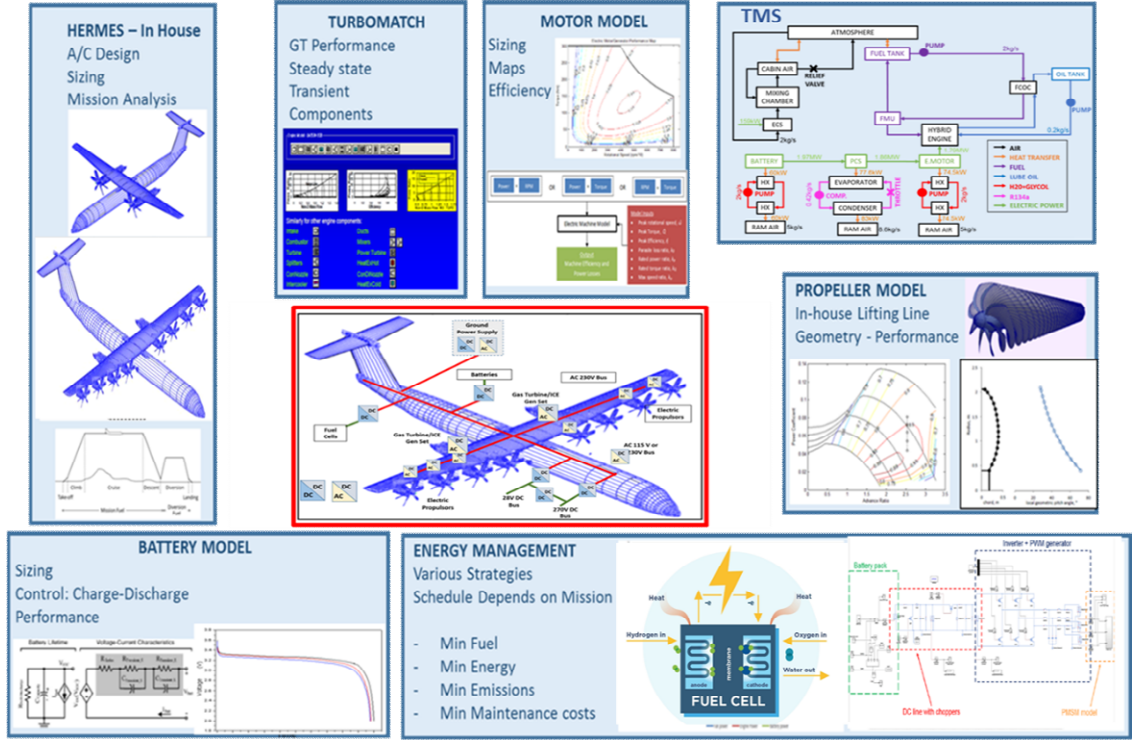


Fig. 1: Cranfield Hydrogen and hybrid electric Aircraft Research Model

IV. Modelling of Baseline & Net Zero Aircraft Variants

The baseline aircraft represents an existing 74 passenger aircraft with Maximum Take-Off Mass (MTOM) of ~23,000kg. Aircraft characteristics used for the modelling and comparison of the baseline can be found in Ref. [29, 53, 54, 55] while representative performance models have been presented by the authors in Ref. [36, 38, 58]. The Cranfield Hydrogen and hybrid electric Research Model (CHARM) has been used for the modelling and analysis of the baseline and Net Zero variants, Figure 1. CHARM enables the modelling and evaluation of the integrated aircraft along with its systems by considering the full mission profile. The phases of the mission profile including take-off, climb, cruise, descent, landing, diversion and loitering are modelled in sequence. A component build-up method is used to model the aerodynamic characteristics of the aircraft. These characteristics are then combined with the off-design performance of the integrated power and propulsion systems for the variants modeled to evaluate the overall

performance at component, system, aircraft and mission levels. The following components have been included in the simulations:

- Thermodynamic design and off design performance of baseline, hydrogen and SAF gas turbines capturing impact of power setting, flying speed and altitude on component operating conditions, stability margins and engine efficiency
- Propeller performance capturing impact of power requirements, flying speed and altitude on propeller operating point and efficiency
- Performance modeling of Proton Exchange Membrane (PEM) fuel cell and Balance of Plant (BoP) capturing impact of power setting, flying speed and altitude on operating pressure, temperatures, voltage, current, power output, and overall efficiency
- Variation of efficiency and performance characteristics of motors and power electronics for Fuel Cell variants as a function of power setting and operating conditions
- Battery and electric component efficiencies assumed to be constant for full electric variants
- Thermal management system considering mass, power requirements and drag penalty

More information on the modelling of the above components is included in Appendix A and Ref. [29, 36, 38, 58]

A. Aircraft, Powertrain Components and Energy/Fuel Storage Sizing

Baseline and Net Zero variants are sized based on a constant MTOTM (23,000 kg). For each variant and technology trajectory, energy requirements and payload capabilities are calculated for given sets of mission range (200, 300, 400, 500 nautical miles). For the hydrogen gas turbine and hydrogen fuel cell variants in addition to the maximum take-off mass limit a volumetric constraint is added that limits the maximum number of passengers and/or the available volume required for hydrogen storage.

The impact of the different technologies is considered using technology factors. Batteries are sized using energy density while motors and power electronics are sized using power density. Cables for the electrical distribution systems are sized by considering power requirements, distribution voltage and resulting cable mass per length as a function of cable material and technology level, i.e., copper, aluminium and superconductive electrical distribution system, details can be found in [29]. Mass of the fuel cell is based on power density of the pack, while hydrogen tanks are sized using the total energy requirements and the tank gravimetric efficiency which is a function of size, shape, insulation material and tank pressurisation requirements [29]. Improvements in aircraft technologies include structural and aerodynamic efficiencies. Structural efficiency is based on the empty operational mass over the maximum take off mass of the variant.

A mass buildup approach is used to calculate the available energy and payload for the range considered as a function of the selected technology targets. The calculation starts with the constant maximum take-off mass and the selected Operating Empty Mass (OEM) to Maximum Take Off Mass (MTOM) ratio which is a technology factor. For the advanced SAF variants the OEM is adjusted by also considering the power density of the gas turbine. For the hydrogen gas turbine, the OEM is adjusted by considering the power density of the gas turbine and the gravimetric efficiency of the hydrogen tanks. For the full electric, hydrogen fuel cell and SAF/hybrid electric variants the OEM is adjusted based on the power density of the additional components, i.e., motors, cables, power electronics, thermal management system and hydrogen tanks. For each range the energy requirements are calculated based on a full mission performance analysis. The energy storage system for each variant is sized using an iterative procedure that considers the energy density of the different energy carriers and the total energy requirements of the mission. Passengers are added until the maximum seating capacity (baseline and SAF variants), available volume (hydrogen variants) or maximum take-off mass (full electric, SAF/hybrid, hydrogen/fuel cell electric) is reached.

B. Technology Targets and Trajectories

Technology targets are defined over 2 horizons – 2035 and 2050, Fig 2. For the 2035 horizon, three levels of technology targets are considered:

- A target that assumes a minimum level of development for all technologies.
- An ambitious but expected level which is based on a minimum level of development (bottleneck) for high-risk components/technologies (i.e., energy density for batteries & power density for fuel cells) coupled with more ambitious and advanced developments for the remaining technologies (thermal management, motor and power electronics power densities, high voltage DC distribution systems).
- An advanced level of technology – ambitious technology targets for fuel cell power density (2 kW/kg including BoP) and battery packs (600Wh/kg) are also assumed in addition to the technological advances considered in the previous step.

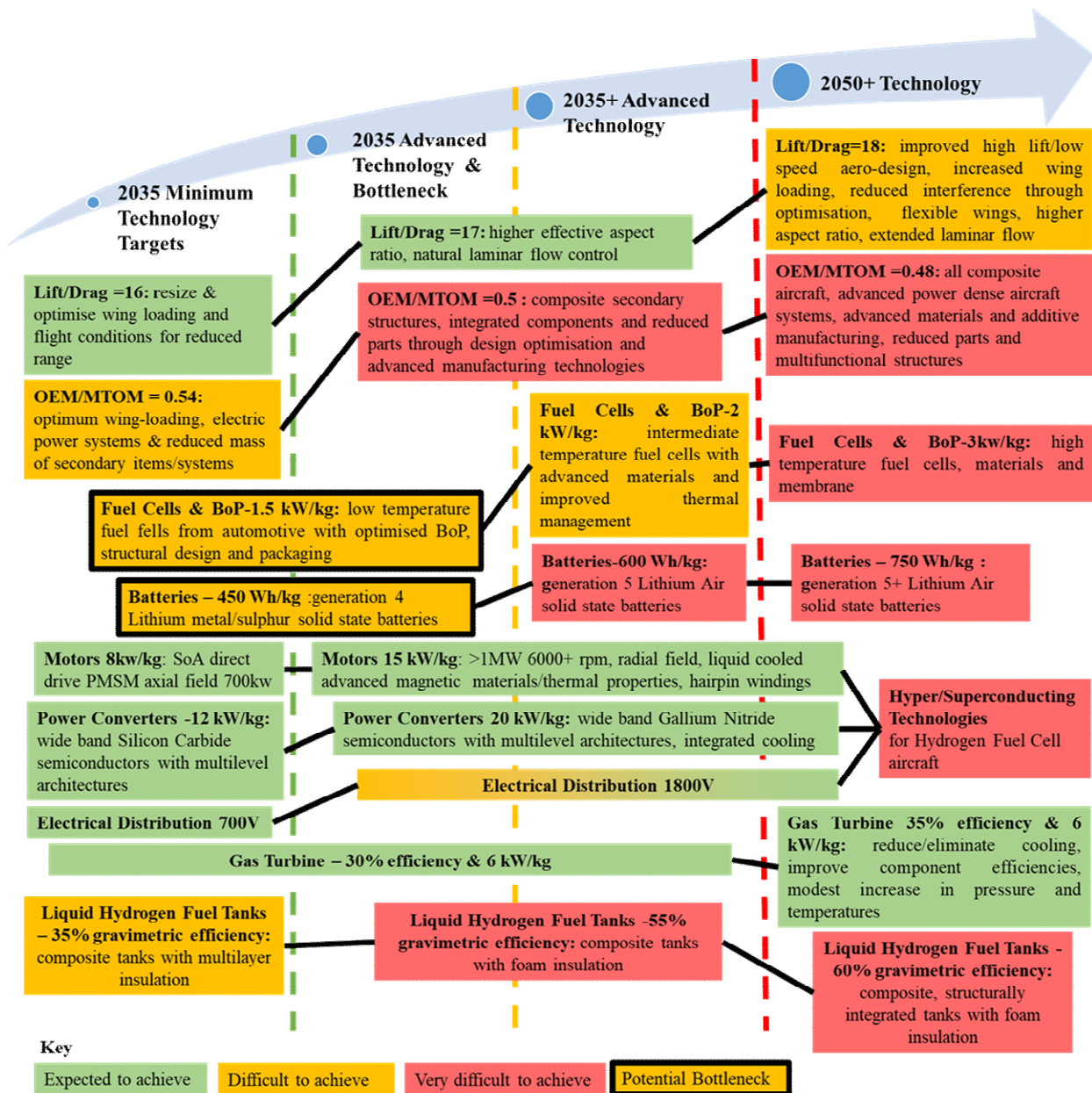


Fig. 2: Technology Trajectories Used for the Evaluation of the Net Zero Aircraft Variants

In the case of gas turbines (both SAF and hydrogen) no efficiency improvements are envisaged for 2035 due to the small size of the engines, associated Reynold number effects along with their impact on component efficiencies which lead to modest overall pressure ratios and turbine entry temperatures. Instead, technology improvements will be towards increased life, reduced maintenance costs and improved power densities coupled with modification to the aerodynamic and structural efficiencies of the aircraft.

In the case of fuel cells, technology improvements also include ability to operate at higher temperatures which reduce power and mass requirements of the thermal management system. Technology improvements and associated trajectories are summarized in Tables 1-4. For the aircraft and gas turbine technologies the Advanced 2035 targets are the same as the Advanced 2035 + Bottleneck. Although the projected targets are ambitious and require significant investments there are no major bottlenecks envisaged.

Table 1 – Aircraft and Gas Turbine Technology Targets

	Aircraft		Gas Turbines	
	OEW/MTOW	L/D	Power Density [kW/kg]	η_{GT}
Minimum Expected	0.54	16	6	30%
Advanced 2035 + Bottleneck	0.5	17	6	30%
Advanced 2035	0.5	17	6	30%
2050	0.48	18	6	35%

Table 2 - Electrical & Thermal Management Technology Targets

	Electric			Batteries		TMS	
	Motor Power Density [kW/kg]	Power Electronics Power Density [kW/kg]	Cable mass per length [kg/m]	Voltage [V]	BED [Wh/kg]	Power Density [kW/kg]	NPPC [kW/kW]
Minimum Expected	8	12	35	700	450	2	3
Advanced 2035 + Bottleneck	15	20	15	1800	450	4	3
Advanced 2035	15	20	15	1800	600	4	4
Full Electric 2050	15	20	15	1800	750	5	5
Hydrogen Superconductive 2050	25	25	5	500	-	5	5

Table 3 - Fuel Cell & Hydrogen Technology Targets

	Fuel Cell		LH2 Tank	
	Fuel Cell Power Density [kW/kg]	Fuel Cell Temperature Celcius	η_{tank}	
Minimum Expected	1.5	70	0.35	
Advanced 2035 + Bottleneck	1.5	70	0.55	
Advanced 2035	2	120	0.55	
2050	3	150	0.6	

Table 4 – Passenger & Take Off Mass for Different Variants

Technology Level	Range [nm]	SAF Gas Turbine		SAF Hybrid Electric		Fuel Cell		Full Electric		Hydrogen Gas Turbine	
		Pax	TOM kg	Pax	TOM kg	Pax	TOM kg	Pax	TOM kg	Pax	TOM kg
Minimum	200	74	20190	74	22967	Not Feasible	Not Feasible	14	22271	63	19593
	300	74	20408	72	22930			Not	22331	63	19668
	400	74	20625	70	22976			Not	22296	63	19743
	500	74	20841	69	22925			Feasible	22261	63	19818
Advanced 2035 + Bottleneck	200	Same as Advanced 2035	Same as Advanced 2035	72	22151	51	22996	42	22312	Same as Advanced 2035	Same as Advanced 2035
	300			71	22934	49	22942	14	22273		
	400			70	22997	48	22984	Not	22330		
	500			70	22944	46	22931	Feasible	22291		
Advanced 2035	200	74	19062	72	21516	66	22972	58	22345	64	17968
	300	74	19232	72	22480	66	23000	37	22316	64	18025
	400	74	19403	71	22982	65	22932	16	22287	64	18082
	500	74	19575	70	22954	64	22960	Not Feasible	22258	64	18139
2050	200	74	18558	74	20475	66	20781	74	22179	66	17402
	300	74	18717	74	21211	66	20783	60	22312	66	17455
	400	74	18877	74	21945	66	20785	45	22349	66	17508
	500	74	19037	74	22677	66	20787	29	22291	66	17561

V. Net Zero Aircraft Variants Performance Characteristics

A. Baseline and Future SAF Variants

Due to the relatively short ranges considered, the baseline and SAF variants operate at a reduced TOM and the number of passengers remains constant for all ranges.

B. Hydrogen Gas Turbine Variants

The number of passengers used for the hydrogen aircraft variants is limited by hydrogen volumetric constraints rather than mass considerations. The variants are not resized to maintain a constant number of passengers and TOM is lower than the conventional and SAF variants. As a result, the variants operate at reduced aerodynamic efficiency compared to the rest of the aircraft and they would benefit by -resizing and re-optimizing their design. Compared to conventional and SAF variants the hydrogen gas turbine aircraft also exhibit smaller variations in their mass during the mission. This effect is more pronounced in the case of the advanced variants as the aerodynamic and structural efficiency of the aircraft and the thermal efficiency of the gas turbine improve thus requiring even less energy.

C. Full Electric Variants

In all cases one of the gas turbines is maintained and used for the diversion and hold phases of the mission. As discussed in [29] having one gas turbine and the additional fuel required for a 100 nm diversion and 30 minutes hold will still be lighter than using batteries for these phases of the mission. Aircraft mass remains constant and is limited by the maximum landing mass of the aircraft. This constraint imposes an additional penalty on the passenger capacity of the full electric aircraft. Compared to SAF and hydrogen gas turbine variants, the full electric variant has improved aerodynamic efficiency due to the higher mass. However, propeller loading and efficiency are negatively affected due to increased loading which is the net result of increased mass and overall drag as well as the elimination of the residual thrust provided by the exhaust of gas turbine. The residual thrust amounts to around 10-15% of the total thrust/power requirement. Due to constant aircraft mass, time spent at climb increases while time spent at descent is reduced. Performance characteristics of full electric aircraft are very much affected by the mass of batteries leading to reduced number of passengers and range. Full electric variants would also benefit from redesigning and resizing that could reduce the size and mass of the fuselage and could offer some additional benefits to the values presented here.

D. Fuel Cell Variants

Increased mass and elimination of the thrust component from the gas turbine leads to reduced propeller performance. Aerodynamic efficiency is higher than all other variants due to the higher mass and the reduced wing loading of regional aircraft. The passenger capacity of 2035 variants is limited by MTOM while advanced 2050 variants are limited by volumetric constraints associated with the storage of liquid hydrogen and they would benefit from re-sizing and reoptimizing the design of the aircraft. Fuel cell aircraft also spent more time at climb conditions due to the small variation in their mass and exhibit faster rates of descent. Passenger capacity is severely limited in the case of 2035 variants, however, fuel cell aircraft can fly similar ranges with SAF and hydrogen gas turbine variants at reduced capacity. In the case of advanced fuel cell variant and 2050 targets use of super/conductive technologies include the additional mass of the cooling system estimated at 400 kg.

E. Hybrid Electric Variants

Hybrid electric variants have the highest potential for improvements in energy performance compared to all other variants. At lower technology levels there is a penalty in terms of number of passengers with the limitation driven by the increased mass of the batteries. However, this penalty is relatively small compared to the full electric and fuel cell variants. Hybrid variants exhibit some unique performance characteristics compared to all other variants. A key design and operational variable for such aircraft is the Degree of Hybridization (DoH) defined as the ratio of electric power into the propeller divided by the total power into the propeller. The parameter affects the sizing and rating of the electrical and energy storage systems. DoH needs to be considered at the design point as well as the off-design conditions of the aircraft. Different optimums exist when considering the impact of DoH on fuel or total energy consumption. In terms of fuel consumption per passenger higher DoH can be achieved as fuel is replaced with battery energy. However, the maximum DoH will be reduced if minimizing mission energy per passenger becomes the primary objective. It is also noted that fuel reduction benefits will always be higher than energy reductions compared to conventional variants. It is also possible to have reduced block fuel and increased total energy compared to conventional aircraft. For the purposes of this study the hybridization ratio has been computed in relation to the minimum fuel consumption per passenger for the technology levels and ranges considered. The overall performance of the aircraft is also affected by the energy management strategy, i.e. the DoH at off-design conditions. The energy

management strategy is based on full electric taxi-out and taxi-in and constant degree of hybridization for the climb and cruise segments. It is assumed that no electric power is used during descent.

The DoH was allowed to vary for different ranges but was capped at a maximum of 50% (i.e. 50% of the power to the propeller was provided by the electrical motor) as any further increase in DoH would affect the sizing of the overall propulsion system and the gas turbine. Various energy management strategies could be adopted that could also improve non-CO₂ emissions and/or maintenance costs. Using constant DoH throughout the mission profile offers a representative performance analysis for the sizing of the system while more specific energy management strategies would depend on operational aspects. A further improvement in the overall performance could be achieved if the descent phase could be completed without the use of the gas turbine – this would be the optimum energy management strategy as the fuel consumed during descent in the case of a regional aircraft is around 15-25% of the total fuel and its where the gas turbine operates at its lowest efficiency. Eliminating the use of the gas turbine during this phase could offer a 15-25% reduction in total fuel and would require relatively modest amounts of electric energy and battery mass. Such an energy management strategy, however, presents significant challenges and risks associated with the requirement to re-start the gas turbines for landing and/or sizing the batteries for an aborted landing. Given the challenges this energy management strategy has not been included in this study. Instead, a constant DoH throughout the climb and cruise sections (capped at 50% of the total cruise power) was used and was adapted for different ranges.

In the case of the 2035 variants and the shorter ranges, DoH reach 50%. However, as the range increases the DoH reduces due to the mass constraints. For these cases the electrical equipment, i.e. motors, power electronics, and distribution system have been sized for 50% DoH regardless of the range while the mass of the batteries has been adjusted to meet the optimum DoH for each range. This would require battery packs to be removed or added when the range of the aircraft changes and would increase time on ground, complexity of operation, risks related to human errors and would incur additional complexities affecting availability, storage and charging of batteries. While inclusion of a parallel hybrid electric configuration can improve the overall performance of the propulsion powertrain – due to the high efficiency of the batteries and electric components- as the DoH increases the efficiency of the gas turbine reduces due to the reduced power setting, overall pressure ratio and turbine entry temperature. From a gas turbine perspective, having a constant amount of power (rather than a constant percentage of power) will increase performance penalties at cruise and descent. Such a strategy, however, will favor the design and operation of the electrical system which can be designed to operate at, or close to, its maximum efficiency since the power will be constant (there will still be some variations due to the discharging of the battery and its impact on efficiency and output voltage). If a constant percentage of power is kept throughout the mission profile, i.e. constant DoH, the efficiency of the gas turbine can be managed by sizing the gas turbine for the cruise conditions. In such a case the efficiency of the electrical system will experience larger variations leading to reduced efficiency losses. However, for the degrees of hybridization considered in this study the impact of the gas turbine efficiency on the overall performance of the aircraft dominates and was found that compared to constant amount of electric power – which leads to a variable degree of hybridization- maintaining a constant degree of hybridization offers the better performance.

VI. Aircraft & Mission Level Comparison of Net Zero Variants

Clean Aviation targets for future regional aircraft include 30% reduction in CO₂ by 2035 and 50% reduction by 2050 compared to a 2020 baseline. The reductions are based on technological improvements and not on use of SAF. Based on the technology trajectories/targets used in the study, improvements in aerodynamic, gas turbines and structural efficiencies alone (i.e., technologies considered for the SAF variant) cannot achieve the above targets. Even the 2050 SAF variant does not meet the 30% fuel reduction target. For the 2035 cases, the hybrid electric variant can only meet these targets with the development of advanced technology trajectories and a minimum battery energy density of 450 Wh/kg. Even at this level of technology for ranges longer than 400 nm CO₂ reductions are limited to 25%. However, the 30% target could be achieved by optimizing the design of the aircraft to increase the number of passengers. It is noted however that these targets are extremely challenging, especially when considering operational constraints, safety margins as well as degradation and ageing effects.

There are 4 major points of interest that the analysis captures in relation to the five Net Zero variants examined, Figure 3:

- Range and passenger capabilities of zero tail-pipe emission variants and how these vary with technology trajectories including definition of minimum technology levels for given payload-range capabilities.
- Relative changes in overall performance trends including identification of kink points for the energy consumption per passenger compared to the baseline as a function of range and technology trajectories
- Comparative performance of different variants and how cross-over points are affected by range and technology horizons/trajectories

- Step changes in performance due to technological developments and their drivers

For the minimum 2035 technology targets, zero emission variants that include full electric and hydrogen-fuel cell concepts are not feasible due to the increased mass of the power and energy storage systems.

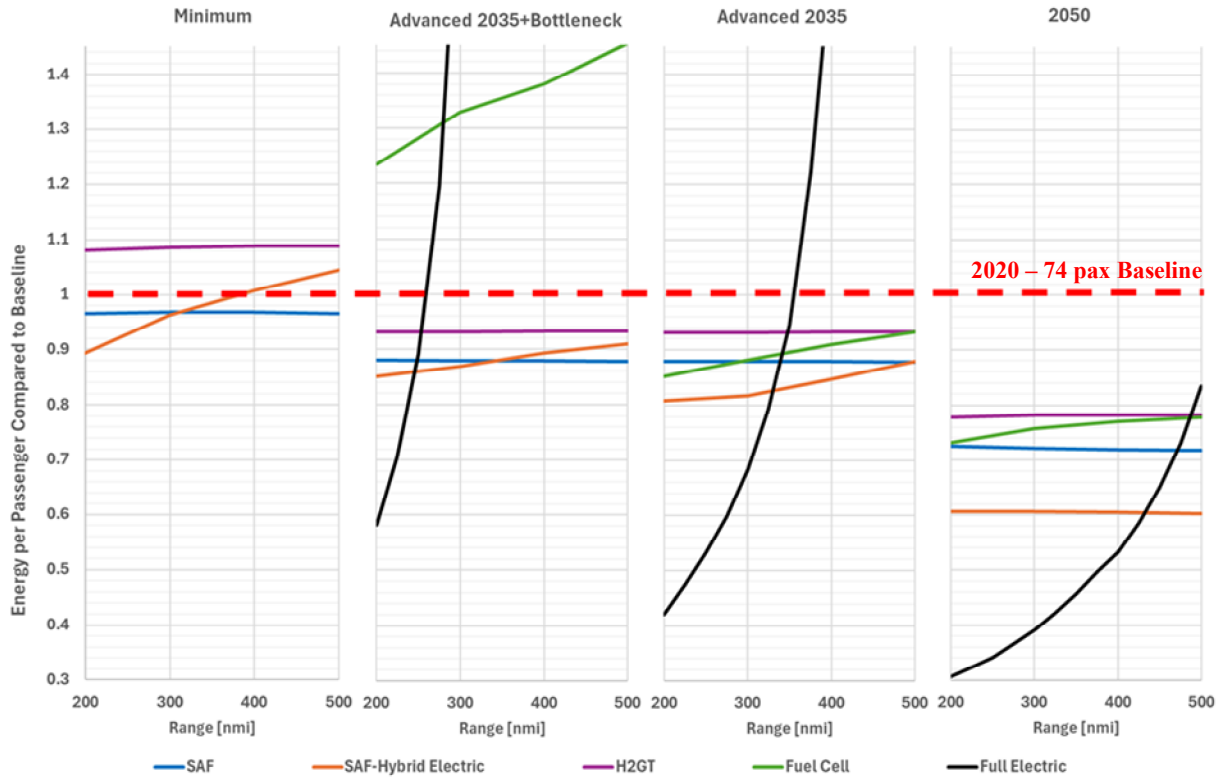


Fig. 3: Relative energy consumption per passenger for different Net Zero variants compared to baseline

Full electric variants and 2035 technology trajectories that include major advancements in motors, power electronics, thermal management system, aerodynamics and structures combined with a battery energy density of 450 Wh/kg offer limited payload range capabilities: 200-250 nm and ~42 passengers. Although such an aircraft can have a superior performance in terms of energy efficiency for ranges up to 200 nm (especially compared to similar conventional variants that are sized to carry 50 passengers – Figure B.1 in Appendix B) the limited range capability is a serious constraint especially if degradation and ageing effects are also considered.

A trade-off exists between energy consumption per passenger versus number of passengers. Improving energy density of the battery to 600 Wh/kg offers potential improvements in terms of passenger/range capabilities enabling 37 passengers over 300 nm and leads to exceptional energy performance benefits. However, a major limitation of such an aircraft is that the relative energy consumption per passenger exhibits a highly non-linear trend that changes geometrically with range leading to an asymptote and limiting the operational flexibility of the aircraft.

Fuel cell variants– technology trajectories for 2035 that go beyond the minimum targets can offer acceptable payload range capabilities (although still below the baseline, i.e. 500 nm with 40+ passenger). Moderate improvements in fuel cell power density compared to automotive state of the art applications that are under development (~1.5 kW/kg) can potentially be combined with aggressive improvements, in electrical and thermal management technologies as well as aerodynamic and airframe structural efficiencies to enable ranges up to 400 nm with 40-50 passengers. Even at such advanced levels of technology and despite the improved overall efficiency of the fuel cell system there is a major energy per passenger penalty relative to the baseline aircraft (20%-50% increase in energy per passenger) mainly because of the reduced payload capabilities.

Advanced 2035 technologies coupled with increased power densities for fuel cells (2 kW/kg) and higher operating temperatures (~120 degrees Celsius) can lead to a step change in performance and offer around 10% improvement in mission energy consumption per passenger compared to existing aircraft. Energy consumption per passenger figures

would be comparable to other Net Zero variants. The step change in performance is mainly driven by increased number of passengers which becomes possible due to the reduction in fuel cell mass and the reduced power requirements of the thermal management system- i.e., higher fuel cell operating temperatures. The reduced mass for the fuel cell is due to improved power density as well as reduced power requirements for the operation of the thermal management system. Reduced cooling requirements have a positive impact on the sizing and mass of the thermal management system as well as the drag penalty associated with its operation. The net effect leads to increased passenger capacity. In the case of very ambitious 2050 technology targets a 25-30% improvement in mission energy can be achieved compared to existing aircraft and overall energy efficiency is comparable to the SAF and hydrogen gas turbine variants. For the 2050 fuel cell variant a cross over point exists as passenger capacity is limited by hydrogen storage volume requirements and not by take-off mass limitations. Energy consumption per passenger changes linearly relevant to the baseline and as technologies improve the rate of change reduces. The driver for the change is the limited payload capacity at longer ranges due to mass or volume constraints.

Hydrogen gas turbine variants - First generation (i.e., 2035 minimum technology targets) variants will result in increased energy consumption per passenger compared to the baseline aircraft (~8% penalty) as any performance benefits due to improved aerodynamic and structural efficiency and reduced operating weight are counteracted by the reduced payload capability imposed by the volumetric limitations of hydrogen storage. The constant number of passengers due to the sizing of tanks also means that relevant energy consumption per passenger remains constant with range. For the mission ranges considered here, such aircraft will operate at a significantly reduced take-off mass and this offers the opportunity to resize and re-optimize the design of the aircraft to achieve energy efficiencies similar to SAF variants. Advanced variants for 2035 and 2050 will also have comparable performance to Fuel Cell and SAF variants in terms of energy per passenger consumption leading to ~7%-10% improvement for advanced 2035 technologies and 22%-25% for 2050 technologies.

SAF gas turbine variants – offer constant energy consumption per passenger relative to the baseline aircraft with increase in range as the number of passengers remains constant and is limited by the maximum seating capacity of the aircraft. Advances in aerodynamics and structural efficiency by 2035 could offer 4-12% improvements in energy efficiency. No step changes in performance are expected and improvements are more gradual compared to other technologies as most of the benefits are driven by aerodynamic and structural improvements rather than implementation of potentially disruptive technologies. Confidence levels in achieving required targets are increased and development/certification costs will be significantly lower compared to all other variants. Further improvements in technology by 2050 that also include increased gas turbine efficiency could lead to ~30% benefits in mission energy compared to today's aircraft.

Hybrid electric SAF variants- have the potential to outperform all other variants as they combine advantages of different technologies. At entry level and minimum technology targets, energy consumption per passenger relative to the baseline aircraft increases linearly with range. This effect is driven by the mass of electrical equipment and batteries which leads to the need to remove passengers at longer ranges. For short ranges energy performance per passenger is improved offering significant benefits ~10% compared to existing aircraft and ~5% compared to SAF variants. However, for ranges longer than 300 nm, hybrid variants underperform compared to existing aircraft. The relative energy consumption per passenger changes with range when further technological improvements are introduced. The variation in relative energy per passenger compared to the baseline with increase in range represents the net effect of three constraints: MTOM, maximum seating capacity and maximum DoH. Different technological trajectories and ranges will activate different constraints altering the trend and gradient of the relative energy efficiency. Rescaling and re-optimizing the design of the aircraft for a constant number of passengers would offer additional performance benefits (estimated at ~2%-4%) however, overall performance figures would be similar to the ones presented here. The relative energy reduction remains constant with range for the 2050 technologies as the maximum DoH of 50% is reached for all ranges. In the case of hybrid electric variant, fuel and tailpipe CO₂ reductions are also important. Figure 4 summarizes the fuel and CO₂ reduction per passenger relative to the baseline aircraft.

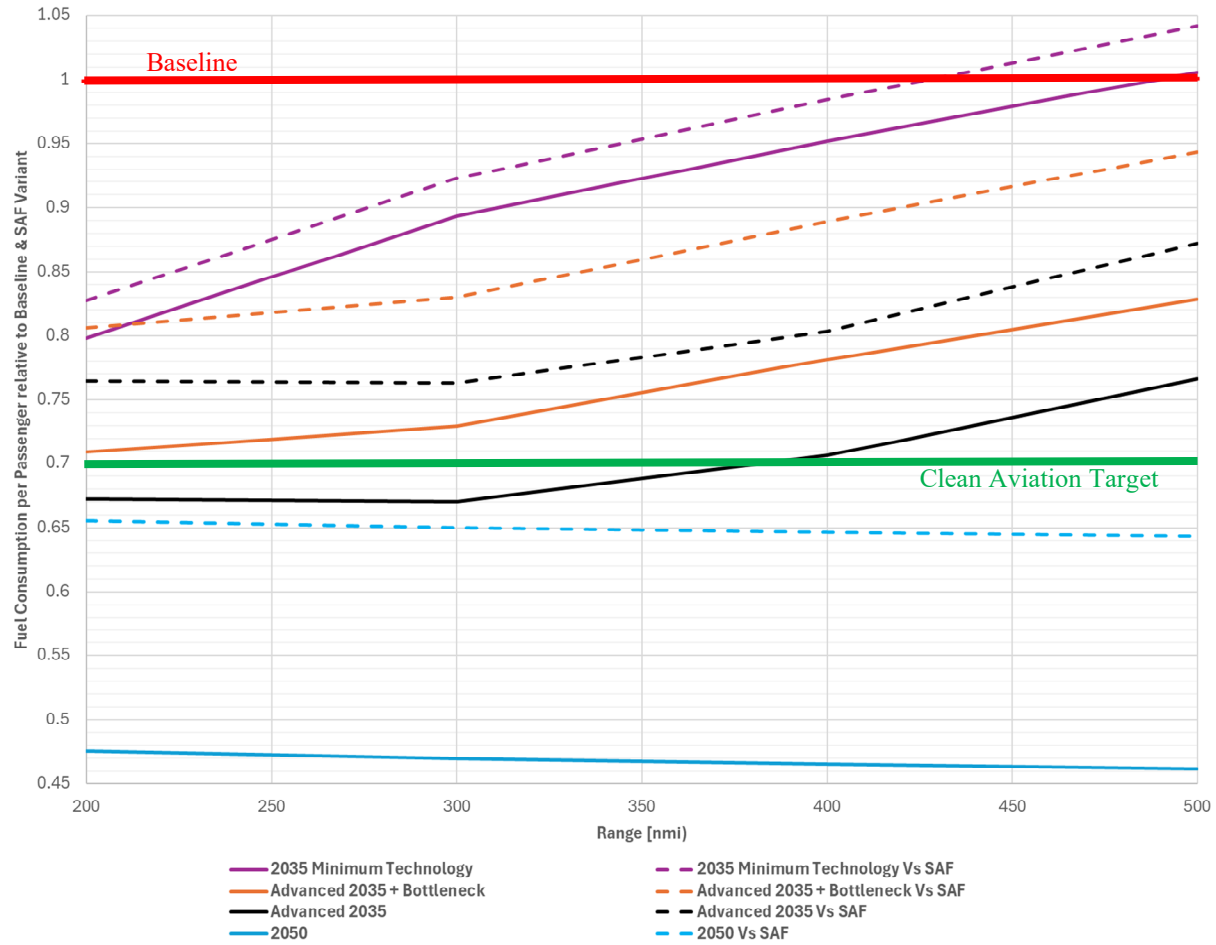


Fig. 4: Fuel reduction of SAF hybrid electric variant compared to baseline

Overall, the following points emerge from the aircraft/mission level analysis:

- All 2035 advanced technology variants exhibit comparable energy per passenger performance. Scaled and optimized versions of these variants could reach ~15% reduction in energy consumption per passenger compared to current aircraft. Although in terms of energy, performance will be comparable, other metrics including carbon and non-carbon emissions, operational flexibility, operational and capital costs as well as life cycle carbon emissions could vary significantly. While hybrid SAF variants with advanced 2035 technology operating at 500 nm have the same energy consumption per passenger as the SAF variants, fuel consumption (and CO₂) per passenger for the hybrid variant is still 13% lower than the SAF variant.
- 2050 hybrid SAF variants have the largest potential for further reductions in energy consumption~40%. All other variants have similar performance in terms of energy consumption offering ~30% reduction.
- At lower technology levels hydrogen gas turbine variants have better performance than fuel cell variants in terms of energy consumption and passenger. Although the performance of the two variants is comparable for the advanced 2035 and 2050 cases the technology trajectories are very different. For the fuel cell variants to be able to reach the same performance as the hydrogen gas turbine, major and high-risk advances are required that include very high-power densities for the electrical and thermal management systems, high operating temperatures for the fuel cells and in the case of 2050 variants inclusion of superconductive technologies. Although, fuel cell variants would not produce NO_x and are expected to have lower maintenance costs and in the long term the cost of fuel cells could be lower than that of gas turbines the technologies required are currently at very low technology readiness level and are considered as high-risk technologies.
- Full electric variants are only feasible if battery energy densities above 550-600 Wh/kg can materialize. Even then, range will be limited to 350-400 nautical miles, and this will be a hard constraint with very

limited opportunities for further improvements and scaling. While development costs for such aircraft carry major risks and uncertainties if technology targets can be achieved in the next 25 years such aircraft could have reduced operating costs and could serve regional hubs. It is possible that advanced hybrid electric variants with battery energy densities >600 Wh/kg and DoH >50% could operate as full electric aircraft for ranges shorter than 300-400 nm with the gas turbine only used for diversion and hold.

VII. Energy & Fuel Production Infrastructure Impacts on Life Cycle Environmental Emissions

To estimate the life cycle environmental emissions associated with the production pathways of the energy carriers of the aircraft in this study, it is necessary to create a model that describes the assumed energy infrastructure and production pathways that support the alternative aviation energy carriers. Three energy carriers are utilized on board the aircraft in this work: SAF, LH2, and electricity. Electricity is used in both the generation of power-to-liquid SAF and some processes for creating hydrogen. The electrical grid composition is based on the estimates provided by the IEA's Net Zero by 2050 roadmap [60], with gCO₂e estimates provided by a NLR publication [61] augmented by other sources as needed. The electrical grid compositions for 2030 and 2050 are provided below, in Table 5, alongside the carbon intensity values in grams CO₂e per MJ, where grams CO₂e are measured in GWP100. Since many projections occur at decade scale, these are labelled '2030' as most projections reflect a 2030 scale.

Table 5 – Distribution and carbon intensity of power grids based on generation technology for 2030 and 2050

Generation Technology	2030 Distribution	2050 Distribution	Total Life Cycle gCO ₂ e/MJ
Photovoltaic Solar	18.63%	32.79%	11.95
Hydropower	15.62%	11.90%	5.83
Wind	21.10%	34.53%	3.61
Nuclear	10.16%	0.60%	3.61
Natural gas	16.42%	7.69%	135.01
Oil	0.65%	0.00%	233.35
Coal	8.11%	0.00%	278.08
Fossil w/ CCS	1.42%	2.01%	30.84
Hydrogen	2.41%	2.51%	10.56
Other Renew	5.49%	7.99%	8.66

This electricity model can now be used in conjunction with hydrogen roadmap to estimate the carbon intensity of liquid hydrogen generation across the two target years [62]. To assess this, various feedstocks and production pathways for gaseous hydrogen were used from existing literature, combined with the estimates from past works [60-62]. These feedstocks are shown in Table 6, along with the 2030 and 2050 distributions and the life cycle carbon intensity, again in grams CO₂e per MJ. In addition to this, an additional life cycle gCO₂e/MJ amount was added due to the electricity used to liquefy the hydrogen, also based on past blueprints [62].

Table 6 – Distribution and carbon intensity of hydrogen production methods based on generation technology for 2030 and 2050

Feedstock	2030 Distribution	2050 Distribution	Life Cycle gCO ₂ e/MJ
Natural gas	32.88%	2.45%	102.1
Coal	21.87%	1.06%	191.5
Coal w/ CCS	4.61%	4.14%	11.8
Natural gas w/ CCS	17.15%	26.67%	50.02
Renewable electricity, water	16.62%	33.00%	0
Grid electricity, water	5.99%	31.54%	Variable, see Table 5
Nuclear electricity, water	0.87%	1.15%	1.39

Finally, SAF production was estimated by estimating a mix of (HEFA) and Alcohol to Jet (AtJ) pathways, along with projections for Power-to-Liquid (PtL) methods. Projections from past studies were used to create the 2030 and 2050 cases. Table 7 contains the distribution of the crops, assumed to be static across both study years. Table 8 contains details on the assumptions for PtL SAF generation. Table 9 shows the percentage blends assumed for 2030 and 2050.

Table 7 – Distribution of SAF production methods based on crop for HEFA and AtJ pathways

HEFA	Distribution	AtJ	Distribution
Soy Oil (US)	24.72%	Corn Grain (US)	25.97%
Carinata Oil (US)	2.81%	Miscanthus (US)	17.53%
Soy Oil (Brazil)	19.10%	Switchgrass (US)	17.53%
Carinata Oil (Brazil)	2.81%	Sugarcane (Brazil)	25.97%
Rapeseed Oil (EU)	28.09%	Miscanthus (EU)	12.99%
Palm (Malaysia/Indonesia)	22.47%		

Table 8 – Energy required for PtL SAF production from 2030 and 2050

PtL	Energy Required, 2030 (MJ)	Energy Required, 2050 (MJ)
H2 Energy	1.504	1.357
Electrical Energy	0.32	0.144

Table 9 – Blend of HEFA, AtJ, and PtL SAF production pathways to create SAF in 2030 and 2050

Blend	2030 Distribution	2050 Distribution
HEFA	48.78%	13.53%
ATJ	33.94%	35.67%
PTL	17.28%	50.80%

Combining the above results provides the carbon intensity per MJ shown in Table 10 across the two assumed energy grid years, 2030 and 2050. All fuel carriers see significant decreases in carbon intensity between the 2030 and 2050 scenario years, owing to the increased reliance on renewable energy sources, and the substantial benefits that renewable electrical energy has to the generation of lower-carbon SAFs, in the form of power to liquid.

Table 10 – Resulting carbon intensity of SAF, hydrogen, and electricity per MJ for 2030 and 2050

Fuel	2030 Carbon Intensity	2050 Carbon Intensity
SAF, g CO ₂ e/MJ	73.92	45.29
Hydrogen, g CO ₂ e/MJ	140.59	35.53
Electric, g CO ₂ e/MJ	51.66	21.94

These values represent the impact of the fuel production life cycle. Assessment of per-flight emission impacts was performed by multiplying these values against the flight energy, and adding the in-flight CO₂ generated. This total well to tank and tank to wake value was then scaled relative to a constant available seat mile (ASM) value, effectively correcting the energy and life cycle values on a constant passenger-mile basis. The aircraft of this study were then assessed against the two energy scenarios, 2030 and 2050. The resulting emissions were normalized to the contemporary baseline fossil fuel Jet A aircraft. These results are shown in Figures 5 and 6. In the figures, SAF (blue) and SAF with hybrid electric (orange) are shown both in solid lines, representing no accounting for CO₂ reuptake,

and in dashed lines, representing accounting with carbon reuptake. Reuptake is the accounting method by which, through the assumption of fungible carbon, that the growth of crops sequesters carbon dioxide from the atmosphere, and is credited as reducing the net CO₂ emissions of the production process. This reuptake is critical for the 2030 energy scenario, where all SAF versions except for the 2050 technology SAF-hybrid showed higher emissions relative to the contemporary aircraft when not accounting for reuptake. Battery-electric aircraft show lower emissions for the technology horizons where they can complete missions. Under the 2030 energy scenario, no hydrogen aircraft produces fewer life cycle emissions than a contemporary aircraft.

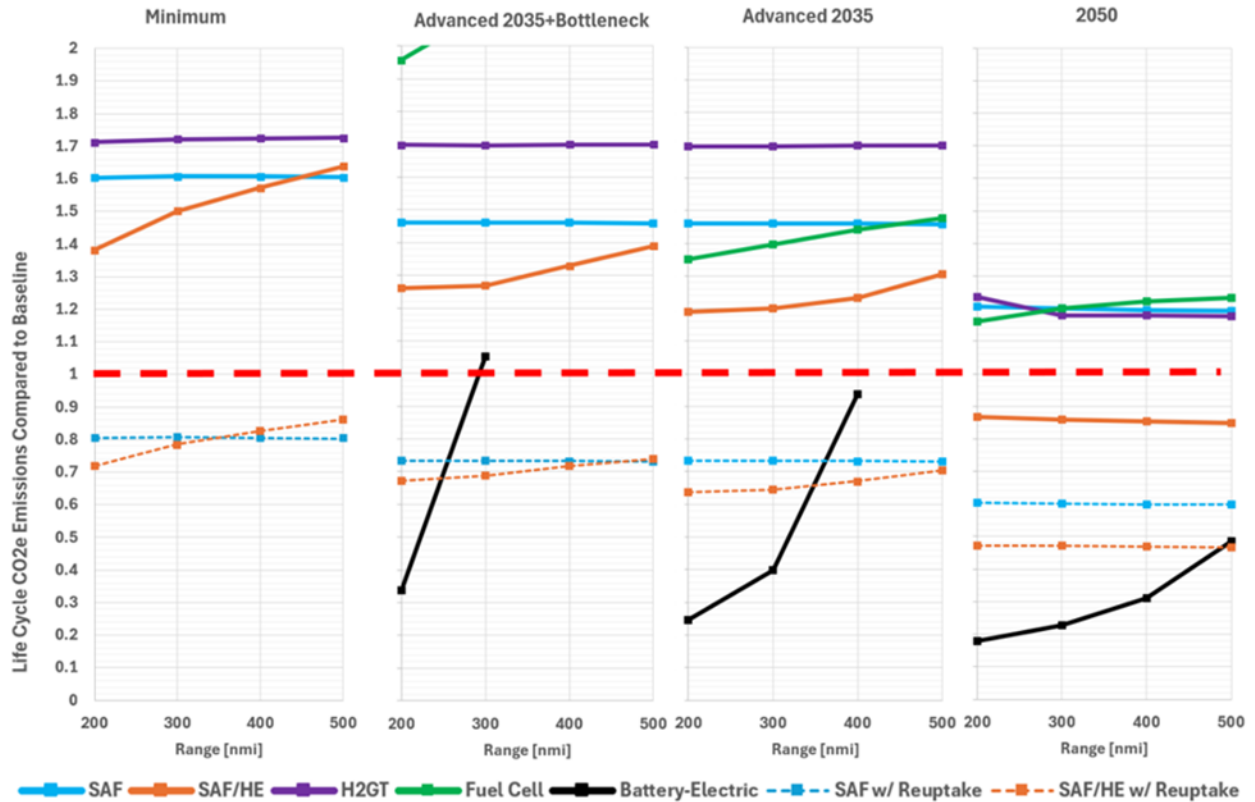


Fig. 5: Emissions relative to baseline for the studied aircraft for the 2030 energy scenario

By contrast, the 2050 energy scenario, depicted in Figure 8, shows that a hydrogen gas-turbine aircraft has lower life cycle emissions even with the minimum technology version as compared to a contemporary aircraft. This trend continues, where once hydrogen fuel cells become viable, the life cycle CO₂e is approximately 35% that of the contemporary case. SAF also sees benefit, with power-to-liquid become a majority of the SAF production pathway providing mild decreases to the life cycle carbon. With 2050 technology and a 2050 energy scenario, all aircraft configurations have reduced life cycle emissions as compared with a contemporary aircraft.

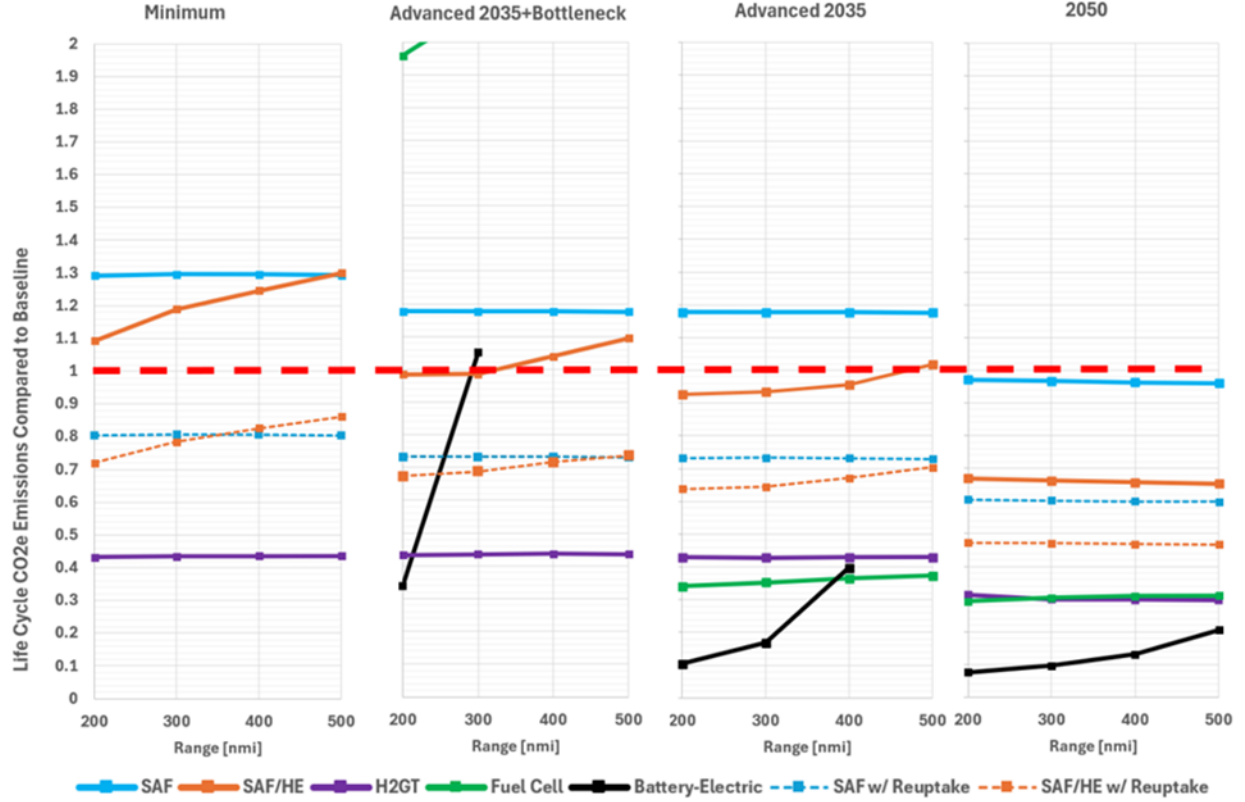


Fig. 6: Emissions relative to baseline for the studied aircraft for the 2050 energy scenario

VIII. Sustainability Analysis and Discussion

This section focuses on the quantitative and qualitative assessment of these aircraft in the context of regions in which they operate. This analysis primarily focuses on the interaction between the aircraft and externalities that result in substantial impacts to local communities near the city pairs as sustainability is highly dependent on location and place [63]. This discussion is provided to highlight the necessary integration of local and regional goals into sustainability planning, especially when regarding future technology developments. Two routes flown by regional turboprop aircraft were chosen to discuss the impacts of these potential aircraft and energy carriers to these extant routes. These two routes are:

1. Toronto, CA to Boston, Massachusetts: large airport to large airport
2. Anchorage, Alaska to Fairbanks, Alaska: large airport to remote airport

These two city pairs represent two of the use cases of regional aircraft: regular routes between developed regions and airports and connecting remote communities with the international ecosystem. Key information, derived from the Bureau of Transportation Statistics T-100 dataset, is provided below in Table 11 [64]. The remainder of this section is a discussion of specific sustainability issues using these two city-pairs as references.

Table 11 – Information on chosen routes

Route	Distance (Nmi)	Flights taken, round-trip
Toronto - Boston	377	2,608
Anchorage - Fairbanks	227	253

A. Environmental effects

As shown above in Figure 7 and 8, the composition of the electrical grid, hydrogen production pathway, and SAF production pathway all have significant impacts on the resulting life cycle emissions associated with the aircraft. The figures used above represent global averages from roadmaps and blueprints [60,62]. Some remote regions, such as Fairbanks, have energy grids that are primarily oil-based, and challenging to decarbonize. This is also true for islands, such as those in the Aegean and across the Pacific. Due to Fairbanks having oil and natural gas in large quantities, a hydrogen aircraft needing fuel in Fairbanks will likely refuel using hydrogen produced from methane reformation, a highly carbon intensive process. This can lead to hydrogen that is approximately 3x more carbon intensive than the 2050 energy scenario or more depending on the electrical generation. Due to the harsh conditions of Fairbanks, SAF cannot be locally produced outside of PtL, which itself will likely be largely fossil fuel powered. In these cases, burning conventional, locally produced jet fuel may have lower carbon emissions than SAFs.

Flights from major cities, such as Toronto and Boston, will not have such effects. These cities are both tightly woven into their national power grids and existing national jet fuel infrastructure. Such infrastructure can be used to directly support both all-electric and SAF fueled aircraft. Hydrogen infrastructure does not exist at these airports at time of writing but is theoretically feasible at both airports.

Additionally, one major local community effect of regional aviation is local pollution [65]. The primary issues with aircraft of this size are NOx emissions. While all-electric and fuel cell aircraft produce none, it is possible, depending on specifics of the engine, that hydrogen gas turbines may produce more NOx per take-off than conventional jet fuel. The characterization of this problem is left for future work.

Finally, another key element is the usage of land to grow energy crops for SAF. Using the distribution of crops from Table 7 and the blend of pathways from Table 9, past literature has shown estimates for the total land use per MJ of these crops [66]. This creates Table 12 which estimates, for the assumptions in Tables 7 and 9, the total acres per MJ of SAF. Table 13 provides the estimated land area required, in acres, to accomplish all 1,304 flights performed by regional turboprop aircraft between Boston and Toronto in 2025. As technology improves and efficiency gains are seen, a 25% reduction in land area is seen corresponding directly with increased efficiency. A 34% reduction in land area is seen when advancing to the 2050 scenario year, primarily caused by the shift to addition PtL which is not required to utilize cropland. While these numbers are relatively small in terms of agricultural area, these can be prohibitive for self-sufficiency for austere locations such as Fairbanks, which does not have a lot of suitable agricultural land, or geographically constrained locations such as islands.

Table 12 – Land per MJ of SAF for 2030 and 2050 scenario years

Year	Land Use (Acres / MJ)
2030	1.78×10^{-5}
2050	1.17×10^{-5}

Table 13 – Land needed to fulfill SAF demand across different energy scenario years, technology to complete 1,304 round-trip Boston – Toronto routes

Scenario Year	Technology	Range, NMi	SAF GT Area Needed, acres	SAF HE Area Needed, acres
2030	Minimum	400	1,871	1,742
2030	Advanced 2035 + Bottleneck	400	1,699	1,310
2030	Advanced 2035	400	1,699	1,310
2030	2050	400	1,391	899
2050	Minimum	400	1,232	1,147
2050	Advanced 2035 + Bottleneck	400	1,119	863
2050	Advanced 2035	400	1,119	863
2050	2050	400	916	592

Engineering effects

Aircraft that use novel energy carriers have unique challenges to ground service equipment and energy carrier storage. These topics have had significant study, so a brief discussion as it pertains to the city pairs will be provided here. The primary effects on the engineering of the regional air transportation system due to these novel aircraft will likely be through the handling of the energy carriers. As mentioned above, geography presents significant challenges to these systems. The cold temperatures in Alaska may pose challenges to the battery-electric systems, while the urban nature of Boston's airport may prove difficult to build out significant hydrogen infrastructure. Hydrogen refueling and electrical charging balanced with local grid conditions also remain significant areas of concern.

B. Economic effects

Aircraft economics are typically centered around conversations on aircraft direct operating costs. Direct operating costs are primarily composed of crew costs, maintenance costs, and energy costs. Since this study assumes that the MTOM of the aircraft stays constant, it is assumed that payload and passengers must be removed to accommodate the new power systems. To highlight this, Table 14 provides the estimated reduction in maintenance hours that must accompany these aircraft to maintain an equivalent price. The hydrogen-powered aircraft see the necessity for significant reduction in maintenance, as the reduced seat count reduces available seat miles considerably. Similarly, the battery-electric and hybrid versions assume some necessary reductions due to the MTOM effects of the batteries.

Additionally, the energy results in Section VI also provide insights to the necessary energy prices to achieve cost parity with contemporary aircraft. These results are summarized in Table 15. These values are normalized to constant available seat miles. Positive values represent that, to achieve cost parity with contemporary aircraft, fuel may cost up to that percentage more per MJ than Jet A. Negative values represent that the alternative fuel must cost that percentage less than Jet A per MJ to achieve operational cost parity. A trend is observed that newer, more efficient technologies enable lower costs, as indicated by greater, positive values in Table 15, indicating that at energy cost parity these novel aircraft have fuel costs 20 – 70% lower than contemporary aircraft.

Table 14 – The required maintenance hour reduction due to reduced ASM capability by energy carrier, technology horizon, and range

	Range (NMi)	Fuel Cell	H2 GT	SAF GT	Hybrid SAF	Battery- Electric
Minimum	200	-	14.9%	0.0%	0.0%	81.1%
	300	-	14.9%	0.0%	3.2%	-
	400	-	14.9%	0.0%	5.4%	-
	500	-	14.9%	0.0%	6.8%	-
Advanced 2035 + Bottleneck	200	31.1%	13.5%	0.0%	0.0%	43.2%
	300	33.8%	13.5%	0.0%	4.1%	81.1%
	400	35.1%	13.5%	0.0%	5.4%	-
	500	37.8%	13.5%	0.0%	5.0%	-
Advanced 2035	200	10.8%	13.5%	0.0%	0.0%	21.6%
	300	10.8%	13.5%	0.0%	0.0%	50.0%
	400	12.2%	13.5%	0.0%	4.1%	78.4%
	500	13.5%	13.5%	0.0%	5.4%	-
2050	200	10.8%	10.8%	0.0%	0.0%	0.0%
	300	10.8%	10.8%	0.0%	0.0%	18.9%
	400	10.8%	10.8%	0.0%	0.0%	39.2%
	500	10.8%	10.8%	0.0%	0.0%	60.8%

Table 15 – The required energy cost relative to Jet A for constant ASM by energy carrier, technology horizon, and range

Aircraft Technology	Range (NMi)	Fuel Cell	H2 GT	SAF GT	Hybrid SAF	Battery-Electric
Minimum	200	-	-8.0%	3.5%	10.7%	-87.4%
	300	-	-8.6%	3.2%	6.8%	-
	400	-	-8.8%	3.2%	4.7%	-
	500	-	-8.9%	3.4%	2.5%	-
Advanced 2035 + Bottleneck	200	-23.5%	-7.1%	3.5%	15.0%	41.8%
	300	-33.0%	-7.0%	3.2%	16.7%	-80.6%
	400	-38.0%	-7.3%	3.2%	15.5%	-
	500	-45.3%	-7.3%	3.4%	13.6%	-
Advanced 2035	200	14.8%	-7.1%	12.1%	19.2%	57.9%
	300	11.9%	-7.0%	12.1%	18.2%	31.6%
	400	9.0%	-7.3%	12.1%	18.7%	-60.8%
	500	6.8%	-7.3%	12.2%	16.9%	-
2050	200	26.8%	22.1%	27.5%	39.3%	69.3%
	300	24.2%	25.6%	27.8%	39.4%	60.8%
	400	22.9%	25.6%	28.1%	39.5%	46.8%
	500	22.2%	25.8%	28.3%	39.8%	16.7%

C. Social effects

Alternate energy regional aircraft, such as the ones shown in this work, have several key advantages in terms of social effects. The first is affordability, as shown in Table 12, which helps to provide more people with the opportunity to fly and access transportation. These improvements in aircraft efficiency should help to push aircraft direct operating costs down, creating lower ticket prices and enabling more people to fly. This is especially important in routes such as Anchorage to Fairbanks where flights are one of the few consistent ways to access the community from the outside world. Additionally, batteries and fuel cells produce no NOx emissions, reducing the negative health impacts of individuals living near airports. SAF combustion has also been associated with lowered pollutants, such as VOCs and soot [67]. Noise reductions due to more electrified systems, such as those used on battery-electric aircraft and fuel cell aircraft, also provide nuisance reduction.

While there are some clear social benefits, alternative fuels can pose a challenge to rural communities such as Fairbanks. As outlined in Subsections VIII.A and VIII.B above, rural communities may have limited options for electrical generation and hydrogen production and may have significant logistical challenges associated with importing SAF or hydrogen. Thus, policies concerning net-zero or near-zero aviation emissions when including well-to-tank (fuel production) emissions can massively penalize these remote communities, threatening their access to the globe. Thus, policy becomes a major factor.

D. Policy effects

Beyond the clear challenges of certification of new aircraft and alternative energy carriers, integration and certification of those fuels, and standardizing these fuels across international borders such as Canada and the United States, another challenge of how to handle remote airport energy becomes apparent when considering these alternative fuels. Oil and gas rich regions dependent on regional aviation such as Fairbanks may find it cheapest to produce aviation hydrogen from methane reformation, a process that produces significant CO₂. Policymakers will have to assess both the scope of aviation net zero goals, but also how they are implemented for these types of rural communities. The 253 round-trip flights a year from Anchorage to Fairbanks produced an estimated total of 1,253 metric tons of CO₂e, including well-to-tank emissions. This is significant, but the alternatives could be worse: using 100% steam reformation and assuming an electrical grid of 50% natural gas and 50% oil, these 253 flights on the 2050

technology fuel cell aircraft could produce 2,157 metric tons of CO₂e, a 72% increase. These types of analyses are critical for policymakers to ensure that rural and remote communities are not priced out or mandated out of the global air system.

IX. Conclusions

The assessment of net zero regional aircraft presented in this study demonstrates that preferred solutions vary substantially depending on the metrics and evaluation level considered. Performance assessed at aircraft and mission level differs from life cycle evaluations, which differ from overall sustainability assessments that incorporate perspectives from engineering, environmental, economic, social, and policy factors. The technology trajectory, energy infrastructure scenario, and spatial-temporal context fundamentally alter which variant performs best. Four key findings emerge:

1. Energy infrastructure maturity dominates life cycle performance: The 2030 energy scenario results in hydrogen aircraft producing higher life cycle emissions than contemporary aircraft despite zero tailpipe emissions. Under the 2050 scenario, all configurations achieve emission reductions. This is due to increased renewables and lower-carbon means of energy, hydrogen, and SAF production, demonstrating that aircraft and energy infrastructure development must proceed in parallel.
2. Different variants excel in different contexts: SAF variants offer consistent performance with lowest technical and infrastructure risk. Battery-electric aircraft achieve superior energy efficiency but face fundamental range limitations of 200-250 nm even with 450 Wh/kg batteries. Hydrogen fuel cell variants provide the greatest long-term emission reductions but require breakthrough power densities (>2 kW/kg), high operating temperatures (>120°C), and renewable energy grids to reduce life cycle emissions. Hybrid-electric configurations balance performance and flexibility, achieving 13-40% tailpipe CO₂ reductions across technology horizons, but are still dependent on a cleaner energy scenario to see significant improvements over baseline contemporary aircraft.
3. Broader sustainability factors affect deployment potential: Infrastructure investment requirements, maintenance cost reductions, local air quality impacts, noise reduction benefits, accessibility for rural and remote communities, and certification pathways all influence practical viability. The Alaska case studies illustrate how regional energy grids, climate conditions, and community connectivity needs affect optimal technology selection independent of nominal performance metrics.
4. Regional aircraft variants offer technically feasible pathways to net-zero aviation, but no single solution dominates all evaluation criteria, mission profiles, and time horizons. Successful transition requires portfolio development of multiple technologies matched to specific operational contexts, coordinated energy infrastructure investment, and adaptive policies addressing regional disparities in technology readiness and infrastructure availability.

Appendix A. Modelling of Net Zero Variants

A. Gas Turbine and Propeller

Gas turbine design and off design performance for the SAF, hydrogen gas turbine and SAF/hybrid electric variants is modelled using the Cranfield developed Turbomatch tool [59], a component-based gas turbine simulation tool. Turbomatch allows for the properties of different fuels including hydrogen to be captured during the thermodynamic performance and analysis of the engine. The tool also allows for the modelling and analysis of hybrid electric turboprop engines with varying degrees of hybridization over the mission profile. The impact of atmospheric conditions and power setting to meet thrust/power requirements for the different mission phases are computed in terms of power and thrust outputs, specific fuel consumption, efficiency, pressure and temperatures at different components, gas composition and component stability margins. In the case of hybrid electric gas turbines the impact of electrification on the operating conditions, efficiency of the gas turbine and its components is also captured. As such the tool enables different energy management strategies to be modelled and assessed including variable degrees of electrification throughout the mission profile.

The propeller design and performance analysis is done through the use of the QMIL and QPROP tools developed by MIT [56, 57]. Use of representative propeller characteristics enables variations in efficiency throughout the mission and its different phases to be captured including impact of flying speed and altitude as well as aircraft weight and aerodynamic efficiency of different variants and technology trajectories on the loading and efficiency of the propeller as discussed in [36].

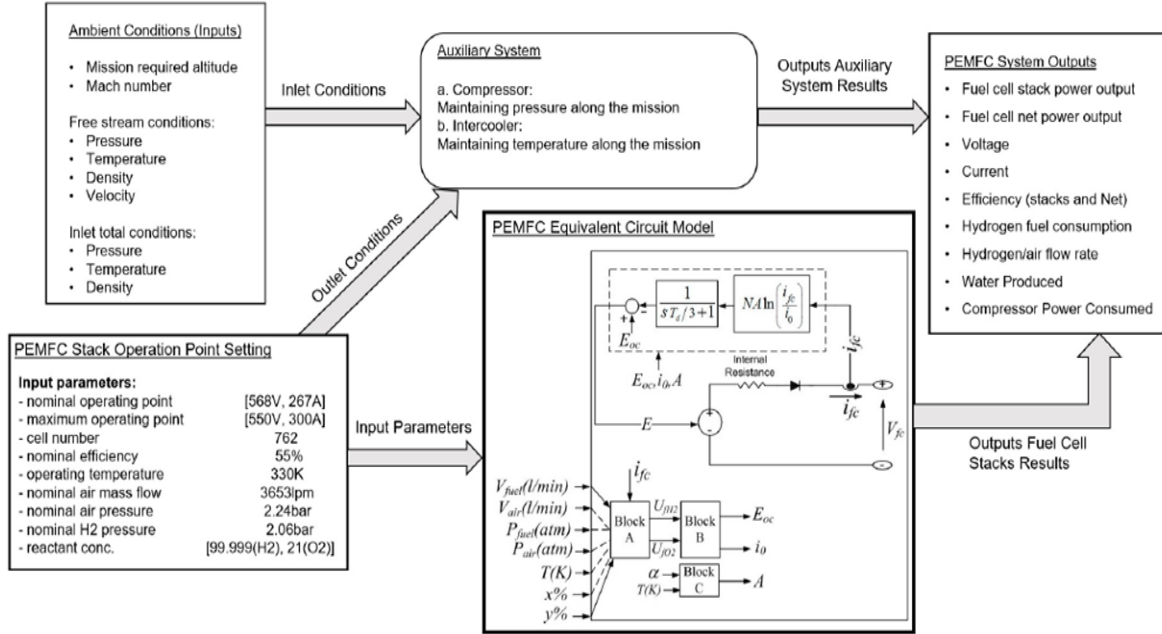


Fig. A.1: Equivalent Circuit Model for Fuel Cell

B. Fuel Cell and Electrical System

The performance of the fuel cell is modelled using an adapted equivalent circuit model shown in Figure 3 and presented in Ref. [36, 38]. The model captures the combined impact of varying power setting and atmospheric conditions on the fuel stack as well as the BoP. Performance analysis for the electrical components of the Fuel Cell variant is based on Cranfield's Enabling Hybrid and hydrogen Electric Research Tool (E-HEART) Ref. [36, 38, 58]. A baseline electrical system along with its components has been sized based on power requirements, propeller rotational speed, distribution voltage and thermal management requirements. Derived efficiency maps for the components are used for the performance analysis as a series of look up tables. The assumptions and modelling approach including further information on the design of the components are given in Ref. [36, 38, 58]. In the case of the full electric variants and due to the high efficiency, all system components have been modelled assuming constant efficiencies. In the case of advanced Fuel Cell variants power densities of electrical components have been scaled based on selected technology targets while component characteristics/maps have been scaled accordingly without redesigning the components.

C. Thermal Management System

The impact of the thermal management system is captured by considering 4 inter-related effects and the method described by the authors in [29]:

- Mass of the system is captured parametrically by using a technology factor of kW/kg which represents the ratio of cooling capacity over system mass. Cooling requirements and resulting capacity are computed at aircraft level by considering component efficiencies, system architecture and power requirement variations along with the temperature limitations of the components. For the purposes of the analysis the cruise conditions have been used to size the thermal management system.
- System power requirements and efficiency – the metric takes into consideration the parasitic power required to operate the pumps, compressors and other components of the integrated thermal management

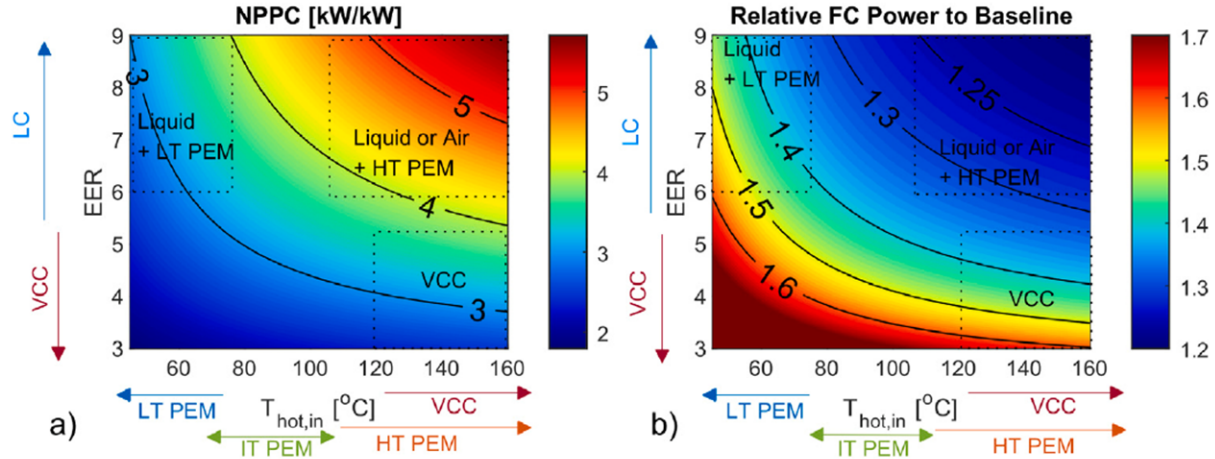


Fig. A.2 : Thermal Management Performance Maps for Fuel Cell Variant

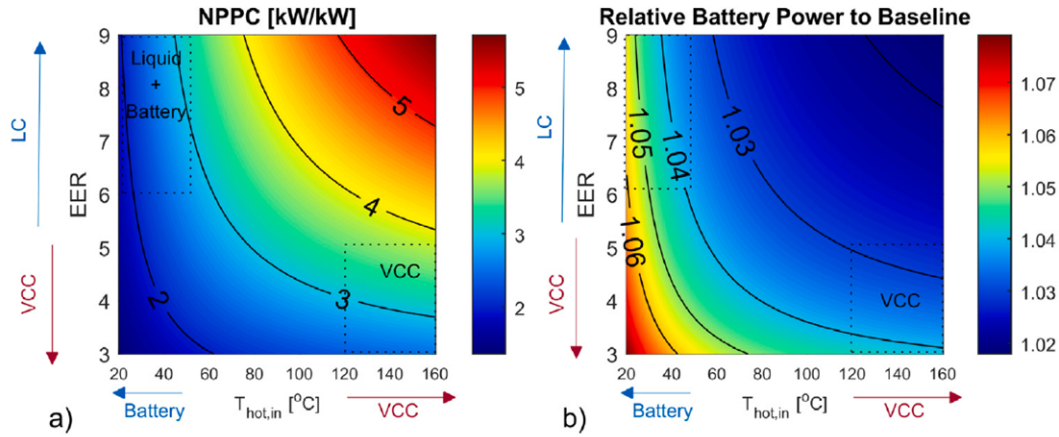


Fig. A.3: Thermal Management Performance Map for Full Electric Variant

system. This is captured by the Energy Efficiency Ratio which is the ratio of the heat dissipated divided by the power required to operate the thermal management system. The ratio represents a technology factor used to capture the efficiency of different technologies and thermal management architectures. A vapour cycle can have an EER around 4-5, meaning that the heat dissipated is 4 to 5 times higher than the power required to run the pumps and compressors of the system. Similarly, a liquid-air cooled system would have an EER around 9-10 meaning that the heat dissipated will be 9 to 10 times the power required for the pumps and the fans/compressor of the system.

- Parasitic aerodynamic/cooling drag due to the operation of the thermal management system. The drag associated with the use of atmospheric/ram air to dissipate the heat of the propulsion system is computed as additional power and energy consumption. The additional power is computed by considering a constant efficiency and constant pressure losses for the heat exchangers and by computing the amount of ambient air required for cooling based on ambient temperature, component efficiency and power requirements as well as operational temperature limits of cooled components. The analysis is done at cruise conditions.
- The aerodynamic and system efficiency factors are used to resize the propulsion system required to provide the power. The energy requirements are also included in the overall performance of the aircraft

Aerodynamic effects and power requirements are combined in the Net Power Performance Coefficient that represents the ratio of the heat dissipated over the total aerodynamic drag power and the power required to operate the system itself. EER, NPPC and the additional power required by the prime mover are considered as a function of the inlet temperature at the hot side of the heat exchanger which is chosen to be 15 degrees below the maximum temperature

of the component to be cooled, i.e. fuel cell and battery. The hot inlet temperature is therefore treated as a technology factor that has a direct impact on the overall performance of the TMS and the aircraft, as a result the impact of different thermal management architectures and technologies can be captured by varying the above technology factors and computing the impact using characteristics curves/maps shown in Figures A.2 and A.3, with more information included in [36].

Appendix B. Comparison of Net Zero Variants Against Baseline with 52 and 74 Passengers

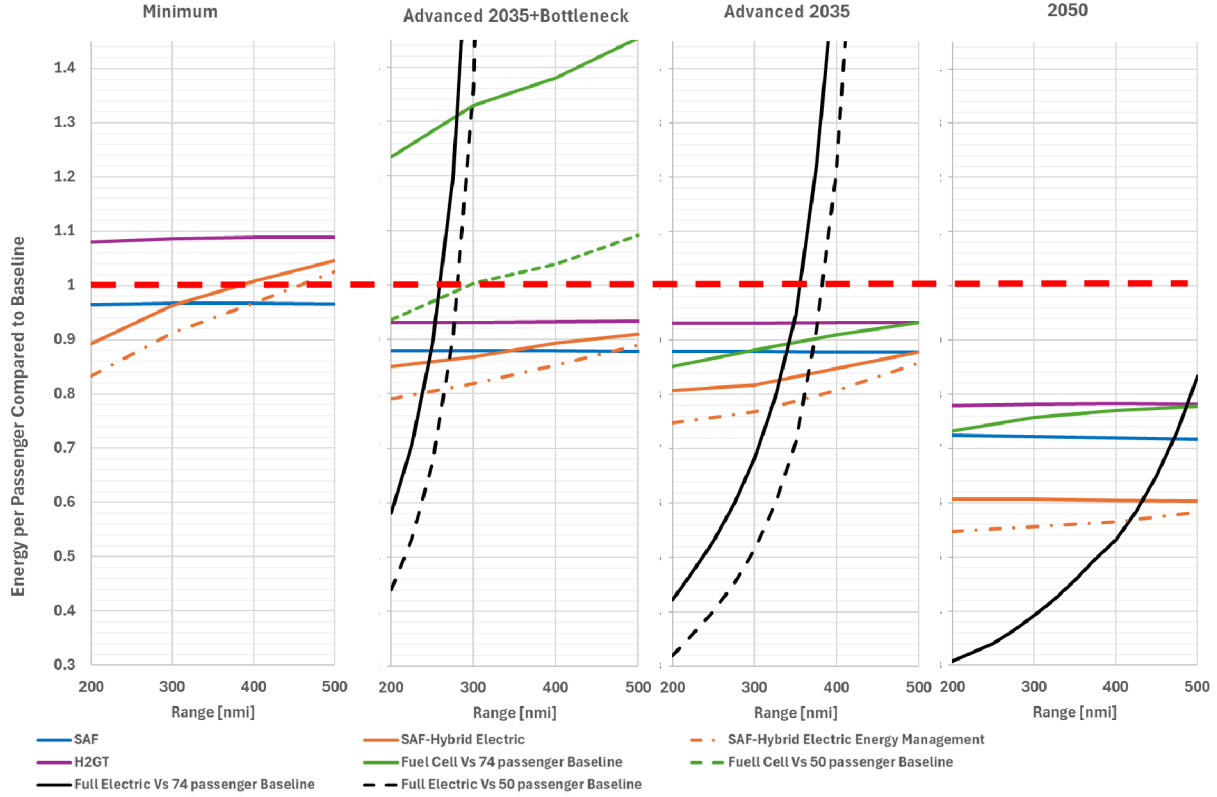


Fig. B.1: Comparison of Net Zero Aircraft Variants against Baseline with 52 and 74 passengers

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Impact of technology trajectories on the performance, emissions, life cycle aspects and sustainability assessment of future net zero regional aircraft variants

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