EVALUATION AND SIMULATION OF PARALLEL HYBRID ELECTRIC PROPULSION WITH REAL FLIGHT DATA

Heather Murphy[1], Conor Gallagher[1], Charles Stuart[1], Stephen Spence[1] & Steven Fitzgerald[2]

[1]Dept. of Mechanical and Manufacturing Engineering, Trinity College Dublin
[2]Ryanair DAC, Ireland

Abstract

This study aims to explore the feasibility and limitations of hybrid electric aircraft within the short-haul commercial aviation industry. It investigates a number of parallel hybrid electric propulsion models varying in technology level (current 2023 state of the art, 2035 conservative projections and 2035 optimistic projections) developed in the multi-physics modelling tool NPSS and simulated over a sample of real-world missions of various ranges: Long – 1308nmi, Medium – 519nmi and Short – 300nmi, employing the open-source Python based mission modelling tool SUAVE. The electric drivetrain was set up to provide supplementary power to both the low and high pressure shafts of the turbofans engines during cruise, reducing the power demand of the turbofan's core and reducing fuel consumption. The objectives of this research are to firstly define each models' maximum degree of hybridization under allowable weight and technological constraints, and secondly to quantify the fuel, cost and energy saving benefits of parallel hybrid electric propulsion. Finally, to identify the influence of electrical component technology level and ultimately determine the feasibility of future parallel hybrid aircraft.

Keywords: Hybridisation, Parallel Hybrid Propulsion, Multi-Physics modelling

1. Introduction

The aviation industry is crucial to modern society, however it significantly contributes to global carbon emissions [1]. Due to high costs, strict safety regulations and technological limits being reached, incremental advancements in aircraft engine efficiency and airframe aerodynamics are greatly outpaced by the growth in air traffic. To meet low carbon targets, disruptive changes like hybridization are required. Both Sustainable Aviation Fuel (e-SAF) and hydrogen show potential in cutting the industry's carbon footprint but face challenges for widespread adoption, where feedstock and infrastructure scarcity gives rise to high prices relative to kerosene. Hybrid-electric aircraft, seen in concepts from NASA, Boeing, Airbus, and collaborations with Rolls-Royce also show potential [2–5]. Combining hybrid electric propulsion, e-SAF or hydrogen could leverage fuel-saving benefits (and hence reduce direct operating costs and alleviate resource supply pressures), but further investigation into weight penalties and feasible hybridization levels is required to determine the net benefits (if any) over complete real world missions. This research explores several Parallel Hybrid (PH) electric propulsion models, each representing different technology levels and feasible degrees of hybridization. These models are applied to simulate three real flight missions with different ranges, leveraging flight data obtained through Trinity College Dublin's partnership with Ryanair's Sustainable Aviation Research Center. The ultimate goal is to assess the viability and constraints of PH propulsion in the short-haul commercial aviation sector and quantify the resulting fuel and energy savings in real-world operational scenarios.

Moreover, the study conducts a comprehensive cost analysis, comparing a conventional propulsion aircraft fully fueled by e-Sustainable Aviation Fuel (e-SAF) with an aircraft employing hybrid-electric propulsion fueled by e-SAF.

2. Hybridisation

Hybridization involves the combination of fuel and electric-powered propulsion systems. The provision of electric propulsion can reduce fuel burn by replacing or supplementing fuel-provided propulsion. However, this is not necessarily the case for all configurations.
Battery specific energy density (BSED) is the main technological barrier in the development of hybridization. When compared to typical aircraft fuel, kerosene, batteries at their current state of development ($BSED = 250 - 300Wh/kg$) are 48 times less energy dense [6].
Specific energy density and power density (directly relating to achievable range and acceleration respectively) are components of what is commonly referred to as the Battery Trilemma [7]. In an ideal scenario, batteries should possess (1) high specific energy and energy density (in terms of mass and volume), (2) a high charge acceptance rate and (3) a long lifespan (by calendar and cycle life) in order to ensure the battery can maintain is capacity over a large amount of cycles. However, improving one of these aspects often degrades another - which is where challenges lie in the development of batteries. The cost of increasing battery specific energy whilst maintaining acceptable charge acceptance rates is cell life whereby the electrolyte undergoes rapid degradation [7].
The projected enhancement of achievable BSED is a key performance metric in determining the feasibility of hybrid-electric aircraft, as weight is a dominant factor in the Breguet range equation [Eq.1]. Battery weight arguably holds higher priority than fuel weight, as batteries do not get lighter as they discharge in the same manner that a conventional aircraft decreases in mass due to in-flight fuel burn.
The Breguet range equation can be expanded to include the efficiency (η_o) and weight of the electric drive system (W) and determine the range (R) a certain battery can deliver, showing that range is proportional to the weight of the energy source and the BSED (SE_{batt}) [8]. - See Eq. 1; 'L/D' = Lift/Drag Ratio OEW: Operating Empty weight.

$$R_{batt} = \frac{SE_{batt}}{g} * \frac{L}{D}\eta_o(\frac{W_{batt}}{W_i}) \qquad W_i = OEW + W_{payload} + W_{fuel} + W_{elec} + W_{batt} \tag{1}$$

Parallel hybrid configurations (see Figure 1) provide energy using both propulsors using fuel and electrochemical batteries, whereby the gas turbine continues to burn fuel and provide sufficient power, especially during phases of high power requirement (i.e.: take-off). The gas turbine is coupled with an electric motor, powered by a pre-charged battery, which may supplement propulsion, even replacing the engine power during phases of lower power requirements.

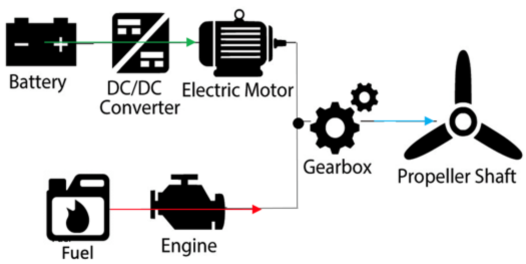

Figure 1 – Parallel Hybrid Configuration

The contribution of thrust delivered by the batteries and electric motor is characterised by the degree of hybridisation (DoH) - a description of the proportion of power provided by the battery powered motor as a fraction of the total power (see Eq.2 below)

$$DOH = H_P = \frac{P_{batt-motor}}{P_{total}} \tag{2}$$

This configuration enables not only portions of the flight to take place with reduced or zero in-flight emissions alongside fuel-burn savings, but also enables the downsizing of gas turbine core components for certain power management strategies (i.e.: cases where additional electrical power supplements take-off power also. Using electrical power during cruise only does not permit engine core downsizing as a similarly sized core is necessary to provide sufficient thrust during take-off). Since

battery power may also supplement propulsion during power intensive phases, the sizing of the turbine engines may be reduced and hence consume less fuel.
Parallel hybrid (PH) is considered a favourable drivetrain configuration compared to series hybrid or turboelectric due to its basic physical layout, operational simplicity and safety aspects. Unlike Full battery electric (from a battery capacity perspective) and unlike Series hybrid architectures (from a motor power rating perspective), PH does not require a battery to provide sufficient energy to the propulsion unit for the entire duration of flight nor a motor to deliver sufficient power for maximum thrust. The PH configurations are also favorable for safety due to redundancy (without turbofan core downsizing) in the event that either powertrain (gas turbine or electric motor) fails.

3. Methodology & Validation

3.1 Modelling & Simulation Tools

This study involves modeling of conventional and PH propulsion systems, which are simulated over real-world missions of varying ranges to estimate the net benefits of the modelled hybrid aircraft compared to the conventional baseline model.
Propulsion modelling was carried out using using NASA's Numerical Propulsion System Simulation (NPSS) tool, a widely adopted C++ based multi-physics modeling tool in the aerospace industry. Its integrated use of component performance maps for efficiency values at off-design operating conditions is its main advantage, alongside the facilitation of user-definable elements and functions - enabling integration of non-conventional propulsion systems and energy storage [8]. NPSS's functionality allows user-defined functions for the creation of unique objects making it highly suitable for expansion to hybrid-electric propulsion.
The flight mission simulations were performed using SUAVE (Stanford University Aerospace Vehicle Environment), an open-source Python-based aircraft conceptual design tool. SUAVE's capabilities include utilizing a suite of multi-fidelity, physics-based methods for aerodynamics, and the mission analysis capabilities which solve the linear equations of motion, offering high flexibility and low computational times - making it attractive for rapid simulation and is widely used in recent literature for mission analysis [9–11]. A considerable advantage of SUAVE in relation to this study is that it does not require specific energy sources to be modelled but simply for an available energy quantity to be defined - making it an energy-source-agnostic tool [9]. This allows for the application of unconventional propulsion systems like parallel hybrids in mission models, unlike other tools such as FLOPS, which assumes only fuel as an energy source [12]
The Boeing 737-800 aircraft (x2 CFM-56-7B26 engines) was chosen as a baseline model due to its dominance in the short-haul aviation sector. Trinity College Dublin's partnership with Ryanair (which operates a predominantly Boeing 737-800 fleet, at 411 out of 548 aircraft [13]) through the Ryanair Sustainable Aviation Centre contributes to this selection. This partnership provides access to real-world operational schedules and flight data, aiding in model validation, and facilitating detailed simulation of real flight missions.

3.2 Validation: NPSS Conventional Baseline Model

The turbofan energy network defined in NPSS has been adapted to model a CFM-56-7B26 as per manufacturer specification sheets, and provides the foundation for the verification process. A full description of the baseline validation and calibration approach employed for both the propulsion and airframe models, achieving fuel burn accuracy for the complete aircraft model (i.e.: average total mission fuel burn) within $\approx$5%, is given in the work of Gallagher et. al [14]. Only the key results have been included and described herein for the sake of brevity.
Design case (Top of Climb - TOC) and additional off-design cases (Rolling Take Off - RTO), cruise and Sea Level Static (SLS) operating points are included to achieve a full scope validation against ICAO (International Civil Aviation Organization) experimental data (SLS points) and data provided by a NASA numerical study by Jones et al. [15] at TOC and RTO conditions. Validation is based on Thrust Specific Fuel Consumption (TSFC), and model calibration was performed by tuning the component design variables: component pressure ratio, efficiency, burner temperature, and bypass ratio (BPR). The validation results, demonstrate high accuracy for the majority of operating points, with <1% relative error for the high powered SLS/TOC operations and are summarized in Table 1.

Table 1 – Validation of CFM56 7B-26/3 Model Error Table

Case	Operating Point	Thrust (lb)	Model.SFC (lbm/hr.lbf)	ICAO.SFC (lbm/hr.lbf)	[15] SFC (lbm/hr.lbf)	Error	Priority
Design	TOC	5,960	0.624	-	≈ 0.65	-3.9%	Med.
Off Design: 1	SLS 100% Power	26,300	0.3651	0.3617	-	-0.27%	High
Off Design: 2	SLS 85% Power	22,355	0.3485	0.3511	-	-0.45%	High
Off Design: 3	SLS 30% Power	7,890	0.3132	0.3455	-	-5.92%	Low
Off Design: 4	SLS 7% Power	1,841	0.4734	0.5107	-	1.69%	Low
Off Design: 5	RTO	20,951.17	0.4679		≈ 0.474	-1.28%	Med
Off Design: 6	Cruise	5,364	0.6024	-	≈ 0.63	-2.83%	Low
Spec Sheet:	BPR-SLS 100%		5.1469	5.1		0.92%	High
Spec Sheet:	OPR at TOC		32.7591	32.7		0.18%	High

The calibration/validation process prioritizes each case in a hierarchy. High power operating points with high accuracy data available (i.e.: SLS 100%, SLS 75%) are calibrated high priority (aiming to minimize the model error in these cases the most). Medium priority assigned to those with low accuracy data but operating at high power (RTO and TOC), and low priority to low power operating points despite having reliable data (SLS 30%, SLS 7%, Cruise) due to lower absolute error resulting from low absolute fuel flow at these points.

3.3 Validation: SUAVE Mission Simulation

The conventional aircraft combined the SUAVE and NPSS models for mission simulation and has been validated against real fuel burn data recorded by Ryanair on a number of commercial flights. The validation process proves the baseline Boeing 737-800 aircraft (powered by CFM56-7B 26/3 turbofan engines) has been modelled to a high degree of accuracy, attaining a mission block fuel burn error as low as 0.09% in some sample cases. The fuel flow and block fuel burn have been used as validation parameters across a number of sample missions varying in mission length. Figure 2 compares the model's predicted average fuel flow with actual flight recorded fuel flow for a recent Ryanair flight mission of 1308nmi. High accuracy of fuel-flow predictions over climb/cruise segments (1.5-2.7%) support as evidence for an accurate model.

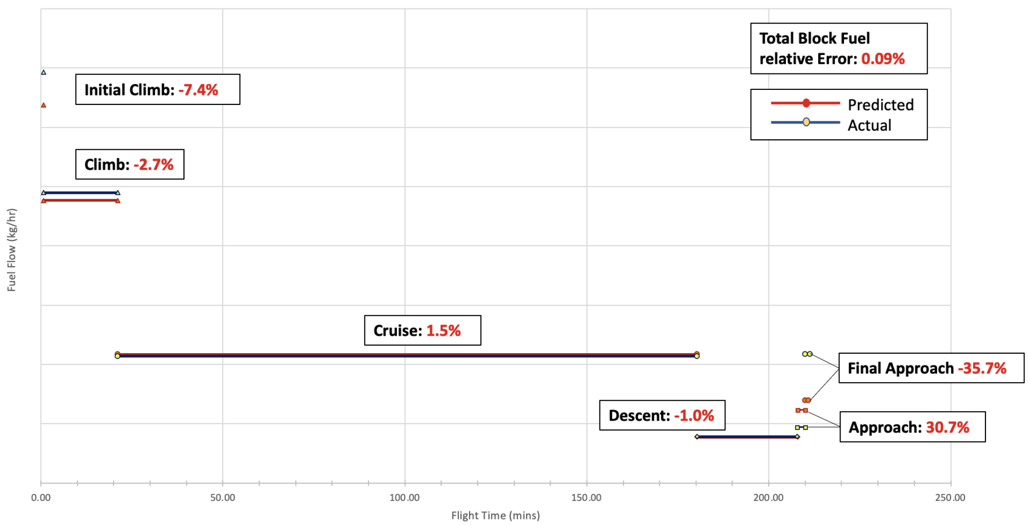

Figure 2 – Average Fuel Flow(kg/s) Boeing 737-800 - 1308nmi Ryanair mission

Several error sources can explain discrepancies between the SUAVE predicted and recorded fuel burn. These variations highlight areas for model improvement. Such sources include (1) the use of ground speed only and not true airspeed due to unavailability of the data - hence the impact of wind forces acting on the aircraft are not considered and (2) excluding the impact of high lift devices (flaps/slats), landing gear and nacelle spillage drag – leading to significant error in the final approach phase, however due to the short duration of this final segment and low fuel burn, the absolute error is minimal and hence this discrepancy is deemed acceptable in the context of the comparative study being conducted in this instance.

4. Parallel Hybrid-electric Model

4.1 Parallel Hybrid-electric: Propulsion model

The parallel hybrid electric model is developed by extending the baseline model to include an electric drivetrain (ED). The ED provides supplementary power to the low and high pressure (LP,HP) shafts of the turbofan during cruise, reducing the power demand from the turbofan core and reducing fuel consumption. The configuration includes a dual shaft electric motor ensuring both the HP and LP shafts are supplied with proportional amounts of power, eliminating the risk of a high disparity in the power requirements of the LP and HP turbine from occurring (see component schematic Figure 3 including description legend with mechanical ports naming convention following; 'Cmpl' = Compressor, 'Trb' = Turbine, 'L'= Low Pressure, 'H' = High Pressure).

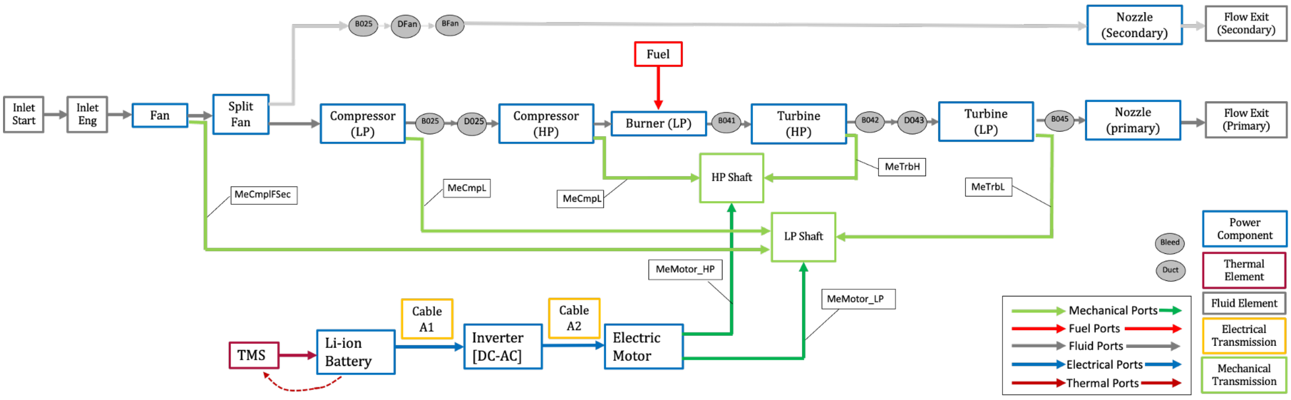

Figure 3 – NPSS PH Propulsion Schematic - Dual motor configuration for HP and LP Shaft boosting

Based on in-depth literature research, Table 2 outlines the values used to define three PH electric aircraft models:

(1) 2023 State of the Art (SoA) model.
(2) Conservative projected 2035 technology model.
(3) Optimistic projected 2035 technology model.

Cabling mass per unit length and a thermal management system (TMS) weight factor were kept constant throughout all three models due to their relatively small impact on the overall weight of the aircraft.

Table 2 – Weight sizing & capability values for Hybrid-electric models. [6, 7, 16–19]

	Present SoA	**Cons.Proj 2035**	**Opt.Proj 2035**
Battery Specific Energy Density (Wh/kg)	250	600	800
Motor Efficiency	95.5%	96%	99.9%
Motor Power Density (kW/kg)	5.5	9	13.15
Inverter Efficiency	97%	98%	99.5%
Inverter Power Density (kW/kg)	12	14	16.44
Cabling mass per length	3.9 kg/m [20]		
Thermal Management System	0.68 kW/kg [20]		

The maximum weight available for the ED is determined using the remaining weight available (below Max Landing Weight (MLW): 66,361kg) after operating empty weight (OEW): 41,413kg, [21], reserve fuel weight and payload have been accounted for.

$$W_{ED} = MLW - (OEW + W_{reserve fuel} + Payload) \quad (3)$$

Assuming electrical energy to not contribute to mandated reserve fuels and a payload of 10,000kg based on average payload from real flight mission data, using the relevent manufacturer data [21], it is determined that the electric drivetrain is limited to a mass of 13,129kg.

4.2 Parallel Hybrid-electric: Drivetrain Sizing

The PH propulsion models were applied to a sample of real-world missions of various ranges: Long – 1308nmi, Medium 519nmi and Short – 300nmi.

The PH model is sized separately for each technology level and mission range combination. The ED is designed to provide the maximum permissible percentage (i.e.: DoH) of the average cruise thrust for the entirety of the cruise phase. Enabling electric power during cruise only allows for maximum fuel burn during take-off, resulting in a lighter aircraft during cruise and reduced power requirements. An ED sized for a shorter design mission would therefore be capable of delivering a higher DoH during cruise as it is constrained to the same ED mass (and hence same energy stored) to be deployed over a shorter flight phase. Increasing the DoH is limited to a maximum of 40%, which corresponds to a minimum core engine thrust threshold (MTT).

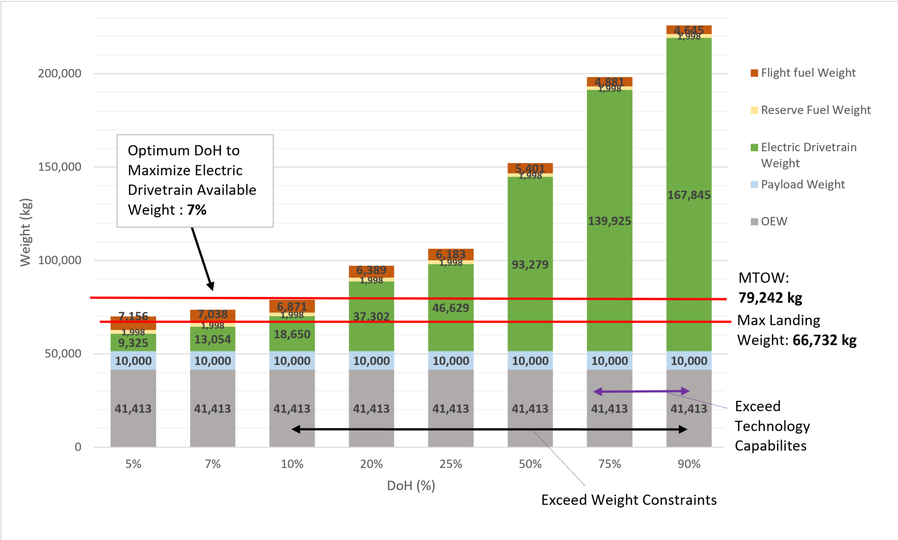

Figure 4 – 1300nmi (Long) - 2023 SoA Technology - Weights vs DoH

Taking the "long" mission as an example (see Figure 4), at current SoA technology levels the ED is limited to providing 7% DoH whilst ensuring sufficient available weight for the electric components. Any DoH above this exceeds the MLW, with hybridization levels above 10% exceeding the maximum take off weight and above 75% exceeding electric technology capabilities (exceeding the motor's power output). Upon increasing to 2035 conservative projected technology (BSED 600 Wh/kg) the maximum DoH achievable under the constraint of MLW is increased to 16.5%. Further increasing to 2035 optimistic projected technology (BSED = 800 Wh/kg), the DoH is limited to 19.5% by MLW.
Table 3 outlines the determined maximum DoH (constrained by MLW and MTT) for each mission length and the corresponding weight of the electric drivetrain.

Table 3 – Summary of Technology level vs Mission Length: Max DoH & Weight details

		Long Mission 1308nmi,160min cruise	Medium mission 519nmi, 50 min cruise	Short mission 300nmi, 15 min cruise
Current SoA Technology [BSED 250 Wh/kg]	**Max DoH:**	7%	21.5%	52% [by MLW] 40% [by MTT]
	Mass:	13,031 kg	13,096 kg	9868.77 kg [DoH 40%]
2035 Conservative [BSED 600 Wh/kg]	**Max DoH:**	16.5%	48.5% [by MLW] 40% [by MTT]	100% [by MLW] 40% [by MTT]
	Mass:	13,036.9 kg	10,759 kg	4713.76 kg [DoH 40%]
2035 Optimistic [BSED 800 Wh/kg]	**Max DoH:**	19.5%	65% [by MLW] 40% [by MTT]	100% [by MLW] 40% [by MTT]
	Mass:	13,155.3 kg	8040.88 kg	3506.32 kg [DoH 40%]

5. Results

5.1 Fuel Consumption

The fuel flow and cumulative fuel burn for each mission have been compared to a baseline mission using the conventional propulsion aircraft model as the reference.

As expected, all PH cases, with the exception of current SoA, present a lower fuel flow and fuel burn savings during the cruise segment as the ED is enabled during this phase only.The magnitude of this fuel burn reduction varies depending on cruise time (i.e.: mission length) and technology level. Current SoA induces higher weight penalties, which out-weigh any benefits gained by the provision of electric power.

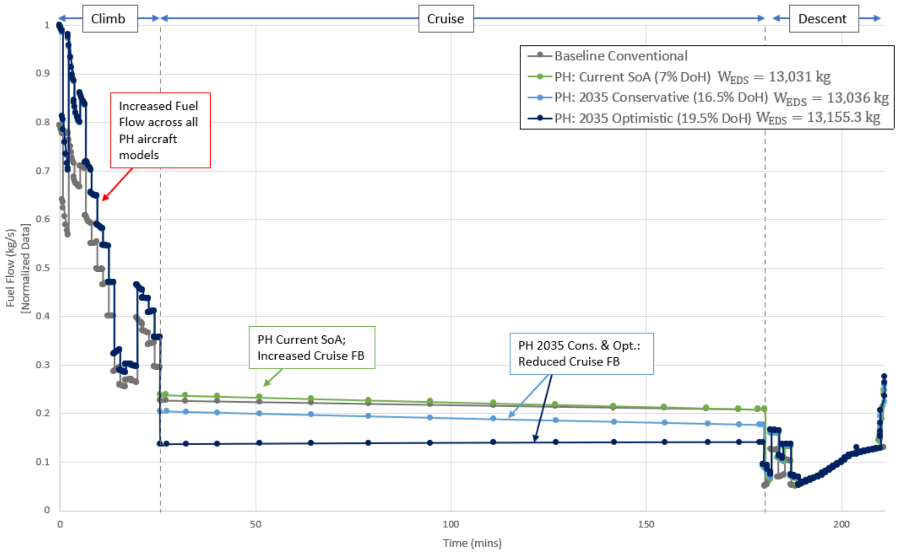

Figure 5 – Long Mission: 1308nmi - Fuel Flow Comparison

Due to additional thrust required during climb for all PH aircraft technology levels and mission lengths, increased fuel flow was observed during this phase. For the long mission, this increase was consistent across technology levels as the additional ED mass is relatively constant, utilising all of the available mass under the constraint of MLW (see Figure 5).
The magnitude of total in-flight fuel burn reductions varied depending on the increased fuel burn during climb and the DoH used. At current SoA technology levels, the increase in mass and relatively low DoH of 7% during the long mission resulted in a cruise fuel flow rate similar to that of the baseline model and a net increase of 7.3% in total mission fuel burn.

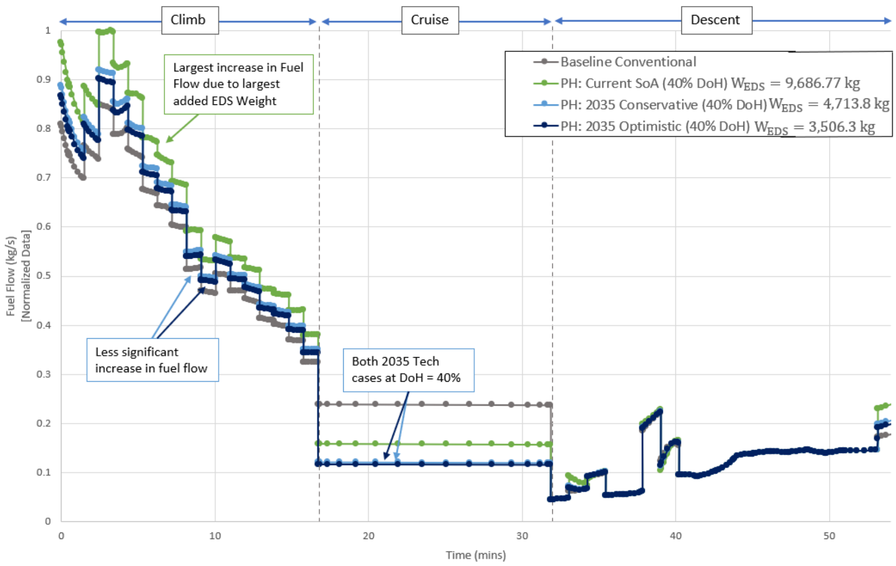

Figure 6 – Short Mission: 300nmi - Fuel Flow Comparison

Reducing the mission length to the medium and short ranges permits higher DoH of 21.5% and 40% respectively. Whilst this does enable reduced fuel flow during cruise, the saving does not exceed the increased fuel consumed during climb and descent due to the high weight penalty of the ED and results in a 0.5% and 2.8% increase in total in-flight fuel burn for the medium and short flights respectively - see Figure 6 and 7.

Both the 2035 conservative and optimistic technology level cases yield fuel savings across all three mission lengths, with both cases returning the highest in-flight fuel burn saving on the medium mission.

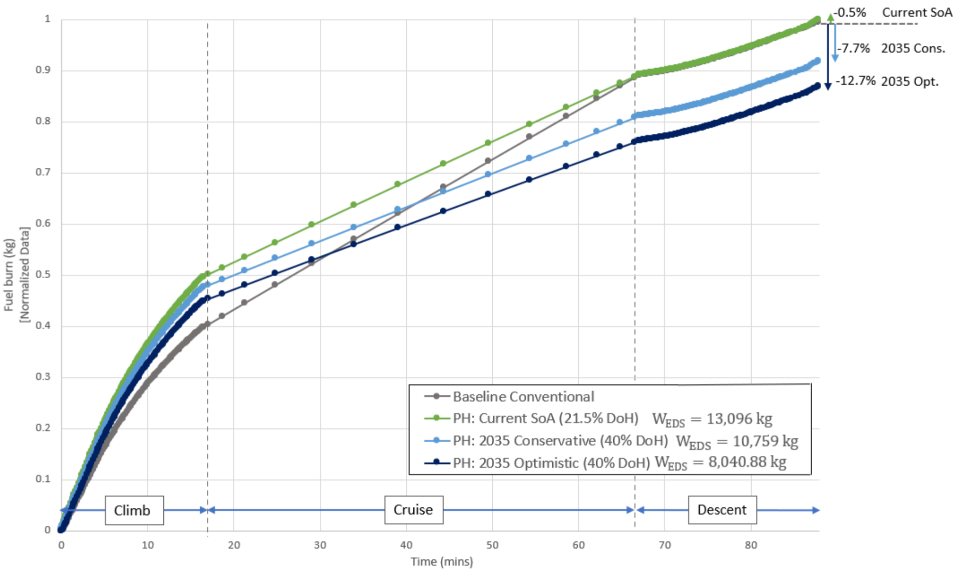

Figure 7 – Medium Mission: 519nmi - Cumulative Fuel Burn Comparison

5.2 Energy Consumption

Full depletion of onboard battery energy is assumed as each model has been sized accordingly and energy consumption due to fuel is determined using fuel energy density (approx. 43.5 MJ/kg for both kerosene and e-SAF [22]). All technology cases across all mission lengths result in an increase in energy consumption with the exception of a 0.7% energy saving on the short mission using 2035 optimistic technology, induced by the high achievable DoH during cruise, increasing the efficiency of the ED relative to the turbofans.

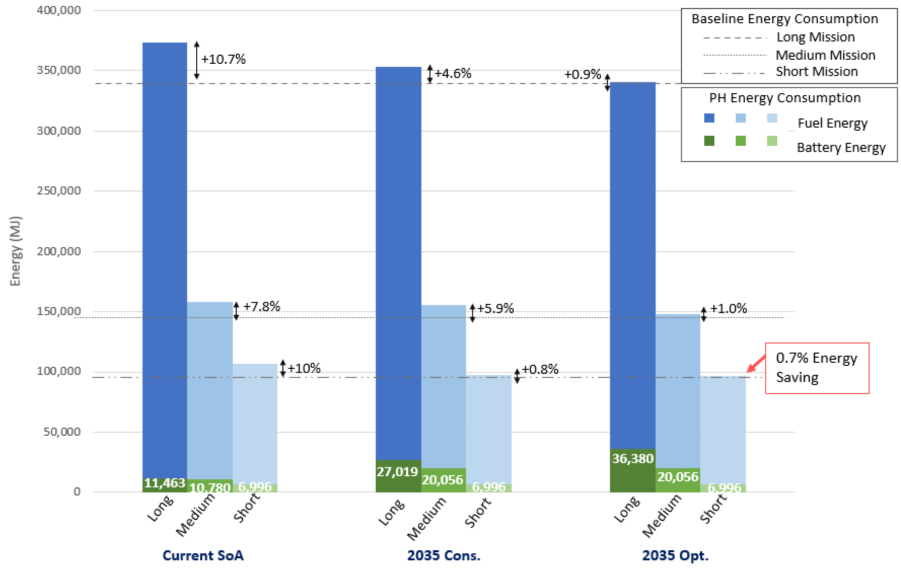

Figure 8 – Combined Fuel & Battery Energy Consumption for PH Aircraft vs Conventional Baseline Model (Mission Length vs Technology level)

Increased energy consumption is observed due to the additional mass derived from the ED. The DoH remains capped at 40% for short missions (Table 3), allowing for reduced weight penalties, leading to lower energy consumption compared to longer missions requiring heavier battery packs, which increase thrust requirements and energy consumption. Higher battery specific energy density at

advanced technology levels results in a lighter aircraft per unit of onboard energy, minimizing weight penalties induced by the ED and reducing energy consumption.
The best case fuel and energy saving mission lengths for each technology level have been highlighted in Table 4. Note that positive values indicate a value increase while negative values indicate savings with respect to the baseline aircraft.

Table 4 – Fuel and Energy consumption with respect to Baseline
(Best Fuel Case & Best Energy Case for each technology level)

Mission		Current SoA	2035 Cons.	2035 Opt.
Long	Fuel	+7.3%	-3.4%	-9.8%
	Energy	+8.2%	+4.6%	+0.9%
Medium	Fuel	+0.5%	-7.7%	-12.7%
	Energy	+10.7%	+5.9%	+1.0%
Short	Fuel	+2.8%	-6.4%	-7.9%
	Energy	+7.8%	+0.8%	-0.7%

5.3 Cost Analysis

Given the low cost of Jet A-1, a conventional aircraft using Jet A-1 fuel will assuredly produce the lowest cost option under current regulatory and policy frameworks. As industry regulators and policies strongly advocate for a net-zero carbon aviation industry, there is considerable drive towards low carbon alternatives. The aviation industry will inevitably have to step away from kerosene and towards alternative fuels such as e-SAF in the near future [23]. Combining e-SAF with the fuel saving benefits of hybrid electric propulsion is a potential solution in alleviating the supply challenges and high costs that surround the uptake of e-SAF. This section details an estimation on the cost savings, if any, associated with implementing a fleet of parallel hybrid electric e-SAF fueled aircraft based on the fuel burn savings attainable on the simulated short, medium and long missions. Assuming an average cost of €0.04 per kWh for green electricity at commercial enterprise rates and $2.85 per kg (derived from $8.80 per gallon) of e-SAF based on cost analysis carried out by the International Council on Clean Transportation [24]. Considering in-flight only fuel burn savings due to the integration of a PH powertrain, Table 5 outlines the cost (to the nearest hundred) increases / saving with respect to a conventional aircraft fuelled by 100% e-SAF for each short,medium and long mission for each technology level.

Table 5 – PH-SAF aircraft cost savings with respect to Conventional e-SAF aircraft

	Long	Medium	Short
Kerosene only	$6,400	$2,800	$1,800
e-SAF only	$22,500	$9,800	$6,400
Current SoA	+7.9%	+1.9%	+4.2%
2035 Conservative	-1.9%	-5.1%	-5.0%
2035 Optimistic	-7.8%	-10.1%	-6.5%

In line with fuel burn saving analysis, the medium mission presents the highest in-flight fuel burn cost savings. However it is only when 2035 projected technology levels are reached that a cost saving is achieved. To highlight the significant cost increase in transferring from Kerosene to zero-carbon propulsion, such as a PH e-SAF fueled aircraft, the cost of each mission carried out in a conventional Kerosene fueled aircraft (based on $2.5 per gallon of kerosene [25]) is highlighted above in Table 5. When compared to the best-case scenario: the Medium mission, a current technology level PH e-SAF fueled aircraft gives rise to a 259% cost increase for in-flight fuel with respect to a today's conventional kerosene aircraft. Upgrading to 2035 conservative and optimistic technology levels would only decrease this cost inflation to 234% and 216% respectively. It is imperative to acknowledge that the shift from kerosene to net-zero carbon propulsion with e-SAF requires a significant increase in in-flight fuel costs, amounting to more than double the conventional expenses regardless of the technology level.
In extending to the full Ryanair missions extract: An extract of Ryanair data available is a representative sample of the daily operations schedule, consisting of 29 missions exhibiting flight ranges between 174nmi and 1308nmi. For the purpose of a wider scale cost saving estimation, these missions

can be categorized into 'short'(< 400nmi), 'medium' (between 400 - 800nmi), and 'long'(> 800nmi) range missions - each of which has an estimated cost saving (or increase) corresponding to the percentage values outlined in Table 5 for each sample length mission. Carrying out all 29 missions (consisting of 12 'short', 7 'medium' and 10 long' missions) using PH aircraft only yields in-flight fuel burn and hence cost savings when 2035 conservative and optimistic technology level are applied (see Table 6 - savings across represented by -% and increases by +%). Current technology levels do not yield any fuel burn savings across any missions, hence a 4.18% cost increase would infact apply across the 29 mission extract.

Table 6 – In-flight Fuel & Cost Saving Estimation: Ryanair Sample Extract of Daily missions

	Fuel Burn		Cost	
	kg	%	$	%
Current SoA	+5,180 kg	+4.9%	+$12,600	+4.2%
2035 Cons.	-5,244 kg	-4.9%	-$15,100	-5.0%
2035 Opt.	-10,557 kg	-10.0%	-$19,900	-6.5%

This can be further scaled to determine an estimation of the potential cost savings returned by the use of PH aircraft across Ryanair's 3,000 daily flights [26] - assuming the 29 mission extract is an accurate representation of the distribution of the complete flight schedule. Whilst current SoA technology does not yield any cost savings, upgrading to 2035 conservative technology levels has the potential to yield a total in-flight daily cost saving (to the nearest thousand) of $1,563,000 USD, with 2035 optimistic technologies further increasing this saving to $2,033,000 USD (with respect to a e-SAF only fueled aircraft) per day across Ryanair's entire average flight schedule.

6. Discussion

Although a higher DoH is possible for shorter range flights, the relative fuel burn savings achieved fall below the fuel burn savings obtained during longer cruise time missions albeit with a lower DoH. When restricting the ED to operate during cruise only, it is preferable to operate on longer missions, increasing the amount of time spent at cruise and sacrificing to drop to a lower DoH as opposed to enabling a higher DoH during shorter missions. Having said that, in order to obtain fuel savings on longer missions which contain long cruise phases, such as the 160 min cruise of the sampled 1300nm 'long' mission, a DoH outside of the scope of the technology levels is required - therefore any fuel savings are not feasible.

The medium mission with a cruise time of 50 minutes is identified as an optimal range with respect to the missions sampled in this research as all technology levels return the highest fuel burn savings / minimal fuel burn increase.

Conversely, energy consumption reduces with shorter mission ranges and lighter aircraft - therefore, the development of PH aircraft in conjunction with technological improvements in battery energy density and electrical components power density can be identified as a potential solution for regional and smaller aircraft classes.

The results suggest that PH propulsion may not be beneficial for longer-range single aisle aircraft such the modelled Boeing 737-800 (which represents current short-haul commercial aircraft). However energy savings are achievable if PH architectures are applied to a re-defined middle-ground range, fitting between short-haul and regional commuter aircraft. It is important to note that this statement is based upon this study's assumption to optimize battery storage for each specific mission, which may present practical difficulties - further analysis may investigate the power management and battery sizing strategies to assist in clarifying this conclusion.

Determining the optimal power management strategy to minimize energy consumption can also contribute additional energy savings. This research employs a hybrid-cruise power management strategy - only enabling the ED under cruise conditions with the aim of maximizing fuel burn savings by burning a larger amount of fuel during climb, obtaining a lighter aircraft for the remaining duration of the flight. However, a mathematical optimization study carried out by Riboldi et al [27] investigating the optimal off-design power management strategy for hybrid-electric aircraft, concluded that maximising energy consumption savings across the entire flight, given the design of aircraft engines being optimised for highest efficiency during cruise, it is preferable to enable electric driven propulsion during phases that core engines are less efficient in, such as climb [27].

7. Conclusions

(1): A conventional propulsion model based on the Boeing 737-800 engine (CFM56 7B-26/3) has been modeled as the foundation of the baseline which PH models are compared to. The NPSS multi-physics propulsion model integrated with component performance maps has been found to be highly accurate with 0.27% and 0.45% errors at 100% and 85% power levels, respectively, upon validation against ICAO SLS engine data. Despite some limitations found in SUAVE, the aircraft mission modelling environment, it is also found to provide sufficiently accurate results with errors ranging from 0.9% to 4.5% upon validation against real-flight data.

(2): Based on the current design of turbofan engines, the model developed in this study presents a minimum thrust threshold limit, restricting the DoH of a PH aircraft to 40% of the design case power (Top of Climb) regardless of the modelled technology level and mission lengths. This could be further increased through the development of advanced air control devices such as variable area fan nozzles and variable bleed valves.

(3): Whilst current SoA technology can deliver sufficient electric power to the turbofan during cruise to reduce cruise fuel burn, the additional weight induces significant increases in climb thrust requirements and no fuel or energy consumption savings are observed for any mission length simulated.

(4): The medium mission with a cruise time of 50 minutes can be identified as an optimal range for fuel burn savings with respect to the missions run in this research as all technology levels return the highest fuel burn savings / minimal fuel increase - the largest being 12.7% using 2035 optimistic technology. Conversely, when seeking to minimizing energy consumption, the reduced mass of the ED required for shorter missions is desirable and it is the short mission (cruise time of 15 minutes) which yields the least significant increase in energy consumption and even a reduction of 0.7% in energy consumption when a 2035 optimistic technology level is applied.

(5); With respect to an e-SAF fuelled conventional aircraft, as per fuel burn savings, cost savings are only applicable from 2035 projected technology on wards - with the medium mission returning cost savings of up to 10% in the case of 2035 optimistic technology. It is important to note that considerable financial investment is required in taking any steps away from kerosene fuel. Transferring to an e-SAF fuelled parallel hybrid aircraft at the highest technology level still requires a 216% cost increase per mission with respect to the current kerosene fuelled conventional aircraft.

(6): The results suggest parallel hybrid electric propulsion may not be beneficial for longer-range aircraft (>1000nmi) such as the Boeing 737-800, which represents current short-haul aircraft. It can instead yield fuel and energy savings (and hence cost savings) if applied to a re-defined middle-ground range, <1000nmi, fitting between short-haul and regional commuter range aircraft.

(7): The extension of the PH propulsion model defined in this research to a smaller regional aircraft and/or the inclusion of advanced airframe technologies is necessary to gain a better understanding of the potential benefits a hybrid electric aircraft can deliver in transitioning to a zero-carbon aviation industry. Advanced airframe technologies permitting higher lift/drag ratios and reduced thrust requirements will be the pivotal in compensating for the weight penalties induced by the addition of an electric drivetrain. Even as limiting electric component technologies (such as battery specific energy) increase, it is necessary to employ additional factors and develop complementary technologies to alleviate the severe weight penalties imposed by the addition of the ED. Additionally, future work will explore alternative power management strategies, utilizing the ED to enhance turbofan power during less efficient operating phases, such as climb, and leveraging the optimized turbofan power output during cruise, investigating potential further energy savings.

8. Contact Author Email Address

Contact author email address: hmurphy5@tcd.ie

9. Acknowledgments

The authors would like to sincerely thank Ryanair for their technical support of this study through the Sustainable Aviation Research Centre at Trinity College Dublin, along with the permission to use their data.

10. Copyright Statement

References

[1] IEA, "Aviation," International Energy Agency, Tech. Rep., 2024, https://www.iea.org/energy-system/transport/aviation.

[2] C. M.K.Bradley, "Subsonic ultra green aircraft research phase ii - volume ii - high electric design exploration," NASA, Boeing Research Technology, Tech. Rep., 2015, https://ntrs.nasa.gov/api/citations/20150017039/downloads/20150017039.pdf.

[3] F. K.Antcliff, "Conceptual design of the parallel electric-gas architecture with synergistic utilization scheme (pegasus) concept," 06 2017.

[4] J. M. Benjamin.J, "Electric, hybrid, and turbo-electric fixed-wing aircraft: A review of concepts, models, and design approaches," *Progress in Aerospace Sciences 104*, 2019.

[5] J. L.Felder, "Nasa electric propulsion system studies, nasa presentation." NASA Glenn Research Center, Tech. Rep., July 2016, https://ntrs.nasa.gov/search.jsp?R=20160009274.

[6] D. S. Wong, K., "Nanotechnology in batteries." *ASME.J.Energy Resour. Technol.*, vol. 138, no. 1, 2017.

[7] X.-G. Yang and C.-Y. Wang, "Understanding the trilemma of fast charging, energy density and cycle life of lithium-ion batteries," *Journal of Power Sources*, vol. 402, pp. 489–498, 2018.

[8] K.P.Duffy and R.H.Jansen, "Turboelectric and hybrid electric aircraft drive key performance parameters," *AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, 2018.

[9] M. A. Gallani, L. C. S. Góes, and L. A. R. Nerosky, "Effects of distributed electric propulsion on the performance of a general aviation aircraft," in *2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, 2020, pp. 1–16.

[10] M. C. Trent W. Lukaczyk, Andrew D. Wendorff, "Suave: An open-source environment for multi-fidelity conceptual vehicle design," *AIAA*, 06 2015.

[11] D. Sziroczak and I. Jankovics, "Conceptual design of small aircraft with hybrid-electric propulsion systems," *Energy*, vol. 204, p. 117937, 2020.

[12] L. R. C. Douglas P. Wells, Bryce L. Horvath, "The flight optimization system weights estimation method," *NASA*, June 2017.

[13] Ryanair, "Our fleet," Tech. Rep., accessed May 2024, https://corporate.ryanair.com/about-us/our-fleet/.

[14] . Conor Gallagher, Charles Stuart and S. Spence, "Validation and calibration of conceptual design tool suave," June 2023, https://doi.org/10.2514/6.2023-3225.

[15] M. T. T. Scott M. Jones, William J. Haller, "An n+3 technology level reference propulsion system," *NASA*, 2017, https://ntrs.nasa.gov/api/citations/20170005426/downloads/20170005426.pdf.

[16] E. Alibeik, M. dos Santos, "High-torque electric machines: State of the art and comparison," 2022.

[17] T. S. S. P. Wheeler, "Electric/hybrid-electric aircraft propulsion systems," vol. 109.6, June 2021, pp. 1115–1127.

[18] "Annual report," National Academy of engineering (NAE), Tech. Rep., 2016, https://www.nae.edu/File.aspx?id=174321&v=9579eb7d.

[19] "Electrical and electronics technical team roadmap," US Department of Energy, USDRIVE, Tech. Rep., October 2017.

[20] J. F. J.R Welstead, "Conceptual design of a single-aisle turboelectric commercial transport with fuselage boundary layer ingestion," *Scitech Conference*, 2016, https://ntrs.nasa.gov/api/citations/20160007674/downloads/20160007674.pdf.

[21] B. Commercial, "737 airplane characteristics for airport planning," Tech. Rep., October 2021.

[22] J Holladay, US Department of Energy. "Sustainable Aviation Fuel Review of Technical Pathways". https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuel-review-technical-pathways-report.

[23] M. M.Shehab, K.Moshammer, “Analysis of the potential of meeting the eu’s sustainable aviation fuel targets in 2030 and 2050,” *Sustainability*, 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/12/9266

[24] Yuanrong Zhou, INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION. "Working Paper: Current and future cost of e-kerosene in the United States and Europe". https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuel-review-technical-pathways-report.

[25] ICAO: International Civil Aviation Organization. "Jet Fuel Monitor". https://www.iata.org/en/publications/economics/fuel-monitor/.

[26] Ryanair Group. "Annual Investor Report 2022". https://investor.ryanair.com/wp-content/uploads/2022/07/Ryanair-2022-Annual-Report.pdf.

[27] C. E. Riboldi, “Energy-optimal off-design power management for hybrid-electric aircraft,” *Aerospace Science and Technology*, vol. 95, p. 105507, 2019.