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PERFORMANCE AND ECONOMIC ASSESSMENT OF MECHANICALLY INTEGRATED PARALLEL HYBRID AIRCRAFT

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ABSTRACT

In this study, a selection of environmental and economic considerations of mechanically integrated parallel hybrid (MIPH) electric propulsion systems for single-aisle civil transport aircraft are assessed. The environmental assessment focuses on the carbon dioxide and nitrogen oxide emissions with different power management strategies and levels of battery technology. In the economic study, the potential subsidies and tax incentives required to make these aircraft financially viable are determined. To capture the performance results, models of the propulsion systems and airframe were constructed using the Siemens Simcenter Amesim systems modelling software. The operating cost was then computed using adapted direct operating cost estimation methods. Battery replacement was incorporated by using a battery cycle aging model. The results showed that using a battery energy density of 300 Wh/kg will not provide any meaningful benefits. For 600 Wh/kg, fuel savings of up to 3% for missions below 650 nm could be obtained for a PMS where the electrical powertrain operates during takeoff, climb, and cruise. However, the NOx emissions were lowest for the takeoff and climb only PMS, implying a trade-off when selecting a PMS. Based on the cost results, it is determined that taxation on carbon emissions would have to increase at least 50-fold from its current levels for the most optimistic scenarios. Alternatively, considerable subsidies, representing large percentages of the purchase price of the aircraft, will be needed.

Keywords: MIPH, hybrid electric aircraft, performance, CO_2, NOx, operating costs, subsidies.

NOMENCLATURE

BAU	Business as Usual energy scenario
BFH	Block Flying Hours
BPR	Bypass Ratio
CO_2	Carbon Dioxide
DOC	Direct Operating Cost
DoH	Degree of Hybridization in Energy
EGT	Exhaust Gas Temperature
EI	Emission Index
EIS	Entry Into Service
EM	Electric Motor
FAR_{alt}	Altitude Fuel to Air Ratio
FAR_{GL}	Ground Level Fuel to Air Ratio
h_{alt}	Altitude specific humidity
h_{GL}	Ground Level specific humidity
H	Humidity Factor
HEPS	Hybrid Electric Propulsion System
HP	High energy Price scenario
HTC	High Technology Cost scenario
IRR	Internal Rate of Return
LP	Low Pressure
LTC	Low Technology Cost scenario
LTO	Landing and Take-Off cycle
LW	Landing Weight
MIPH	Mechanically Integrated Parallel Hybrid
MLW	Maximum Landing Weight
NOx	Nitrous Oxides
OEW	Operating Empty Weight
OPR	Overall Pressure Ratio
P_{alt}	Altitude Pressure
P_{GL}	Ground Level Pressure
P3	Combustor Inlet Pressure
SMR	Short-Medium Range
T3	Combustor Inlet Temperature
TOW	Take-Off Weight
ZFW	Zero Fuel Weight

1. INTRODUCTION

The electrification of aircraft propulsion has long been considered a promising means of reducing the impact of aviation on the environment. However, with electrification, the energy for propulsion usually needs to be stored in hefty batteries – a factor that can become prohibitive for larger aircraft. Various degrees of hybridization are therefore currently considered, where a portion of the energy is still provided by combustible fuel.

Hybrid electric propulsion systems (HEPS) can be divided into two categories [1]: series and parallel. Series HEPS use a separate propeller/fan, driven by an electrical motor (EM). The location of the EM-driven propeller can be selected to optimize the lift-to-drag characteristics of the aircraft, improving overall efficiency. However, as the EM and the conventional engine are decoupled, a series HEPS require more parts, which raises the complexity of engineering, assembling, and maintaining the propulsion system, as highlighted in [1]. In parallel HEPS, the EM is mechanically connected to the gas turbine engine. The EM can be connected to either the Low-Pressure (LP) or the High-Pressure (HP) shaft of the gas turbine. If it is connected to the HP shaft, the hybrid propulsion system is described as "cycle integrated", while, if it is connected to the LP shaft, it is described as "mechanically integrated" [2].

Cycle integrated hybrid propulsion (CIPH) systems are beneficial to turboshaft engines as they can increase efficiency at part load [3]. However, for the case of turbofans, if no redesign is applied, CIPH performance is worse at engine level, compared with the mechanically integrated configuration [4].

Mechanically integrated propulsion systems increase the overall efficiency of the engine, by lowering the power requirement of the core by supplying power through a more efficient EM. The hybrid architecture chosen for this study is MIPH, as it is recognized as the easiest configuration to implement. The platform is a single-aisle, short-to-medium range aircraft (based on the Airbus A320neo). This aircraft was selected, as the short-medium range market accounts for 67% of the global aviation CO_2 emissions [5].

MIPH propulsion systems have previously been investigated for an A320 based platform by Kang et al. [4] and Ang et al. [6], focusing on fuel and energy consumption and pollutant emissions. Kang et al. [4] assessed a configuration based on an EIS2000 engine and the results indicated that there is potential for fuel reduction from 0.3 to 2.6% for a 1,000 nm mission, with the benefits strongly depending on the power management strategy applied. Ang et al. [6] provided results for an engine based on the CFM LEAP-1A, downsized for cruise, demonstrating a fuel reduction of 7.5% for missions of 1,000km, for the power management strategy assessed.

Albeit these studies provide significant insight into the performance benefits and limitations of hybridization for SMR aircraft, the analysis is limited regarding power management strategies. Economic aspects are also not considered.

Subsequently, it is the aim of this study to quantify a) the fuel and energy consumption and pollutant emissions for different power management strategies, b) the cost of operation for SMR aircraft utilizing MIPH prolusion system considering the effect of battery replacement, c) the economic measures, such as taxation or incentives, that would have to be in place for these aircraft to be feasible. To achieve this, a fully integrated aircraft-propulsion system model, capable of steady state and transient simulation of different power management strategies was developed.

This introduction is followed by Section 2, in which the methodology is described. The results, along with a discussion, are provided in Section 3, whereas the paper is concluded in Section 4.

2. METHODOLOGY

An integrated aircraft-propulsion system model was developed for assessing the overall mission performance and pollutant emissions. The integrated model, developed in Simcenter Amesim, includes the aircraft model, which provides the thrust requirements, the propulsion system model (conventional and hybrid), and correlations for NOx emissions calculations. Additionally, a tool for electric component sizing was used for quantifying the added system weight for hybrid cases, while the Simcenter Amesim design tool was used for scaling the battery and electric motor performance. The economic analysis is based on direct operating cost and includes energy price and battery life.

2.1 Propulsion system

The engine performance was based upon CFM LEAP 1A26, utilizing data available in the open literature [7]. Component efficiencies were based on the technology levels for EIS2015, according to the method described by Sebastian et al. [8] and respecting the technology temperature limits reported in [9] and [10]. The design point is cruise, and the model was adapted to match the sea level performance requirements as well. The thermodynamic cycle design for the powerplant was performed using the Simcenter Amesim gas turbine performance tool. For off-design operation, suitable maps, available in the Simcenter Amesim library were used. For establishing low thrust simulation capability component maps were extended to low rotational speeds, using the extrapolation method proposed by Gaudet and Gauthier [11]. The engine employs a bleed-off valve for low power simulation, based on CFM56-3 engine data published in [12]. The engines provide both thrust and power for subsystems and bleed air for the cabin climate control. The power is extracted from the high-pressure shaft and the air is extracted from the high-pressure compressor. The power and bleed air off takes were taken from Scholz et al. [13] (see Table 1). The engine model was verified against the performance of the LEAP 1A26 engine, reported in the ICAO Engine Emission Databank [7]. The results are presented in Table 2.

The gas turbine performance model includes pollutant emission calculations. CO_2 emissions were directly extracted from the simulation, derived from combustor calculations. The altitude NOx emissions were assessed using the 'P3T3' method. This method is a semi-empirical method, which corrects the ground level NOx emissions for altitude, using Equation (1) [14].

$$EI_{alt} = EI_{GL} \left(\frac{P_{alt}}{P_{GL}}\right)^{n} \left(\frac{FAR_{alt}}{FAR_{GL}}\right)^{m} e^{H} \quad (1)$$

The values of n and m were set at 0.4 and 0 respectively [14]. The humidity factor (H) is computed using Equation (2).

$$H = 19(h_{SL} - h_{alt}) \quad (2)$$

Table 1: Off Takes During Flight [13]

Phase	Power off-take (kW)	Bleed air (kg/s)
Take-off	73.8	0.579
Climb	83.5	0.710
Cruise	79	0.481
Descent	68.6	0.429

Table 2: Engine Model Performance Data

LTO Phase	Fuel flow		
	ICAO	Simulation	difference
Take-off	861	877.8	1.96%
Climb	710	710.7	0.09%
Approach	244	242.1	-0.76%
Idle	91	87.9	-3.37%
Bypass ratio			
Take-off	11.1	10.9	-1.8%
Overall pressure ratio			
Take-off	33.3	34.4	+3.2%

In Equation 2, h_{SL} and h_{alt} are the values for specific humidity at sea level and altitude, respectively. These were computed according to the equation presented by Huang [15]. The ground-level NOx emissions were extracted from the Engine Emissions Data Bank [7]. T3, P3, and FAR values at ground level were obtained from the simulation of the LTO cycle. At altitude, the ground level values of P3, EI, and FAR were derived from T3. The actual EI was then corrected according to Equation (1) and according to the actual values of P3, h, and FAR.

When sizing the electrical propulsion system, the weights of the battery and electric powertrain were taken into consideration following the methodology presented in [16]. The thermal management system chosen was one investigated by Kellermann et al. [17]. That system weighs 120 kg and requires additional power consumption of 2.3 kW. It can extract 125 kW of heat from electric components, which for this study was kept constant for all cases considered. This cooling system was used as a constraint for the sizing of the electrical propulsion system (i.e., the maximum electrical power was based on its cooling capacity, along with the efficiency of the powertrain components). The electric powertrain assumptions are summarized in Table 3.

Considering the safe adoption of hybrid electric propulsion systems, the propulsion system was designed to run with or without the electric motor, meaning that the gas turbine was not redesigned for electrification.

Table 3: Electric Component Specifications

Component	Efficiency	Specific power	Ref
Electric Motor	95 %	6 kW/kg	[18], [19]
Inverter	97 %	50 kW/kg	[18]

The impact of a hybrid electric propulsion system is highly sensitive to the battery energy density. Because the evolution of battery technologies is uncertain, two battery energy density assumptions were considered: 300 and 600 Wh/kg. The 300 Wh/kg battery represents technology that should be available in 2025, while the higher specific energy of 600 Wh/kg represents technologies predicted for 2030 [20]. The motor off-design simulation was done through a map that is scaled for each configuration considered, as discussed in [4]. The battery was simulated using the equivalent circuit model available in Simcenter Amesim [18].

2.2 Aircraft Model

The aircraft was modeled using the Simcenter Amesim point-mass model [18]. This model takes into consideration the aircraft weight, speed, and altitude to compute the aerodynamic forces. The data used for the aircraft are provided in **Table 4**.

Table 4: A320neo Aircraft model parameters [21]

	Value
MTOW	79000 kg
MLW	67400 kg
OEW	45700 kg
Wing area	122 m^2
Wingspan	35.8 m

The angle of attack is controlled using an altitude control loop, whereas the engine fuel flow is controlled using a velocity control loop. Both control loops were tuned to match the flight profile. The flight mission is defined by several phases, namely taxiing, take-off, climb, cruise, descent, and diversion phases, as shown in Figure 1.

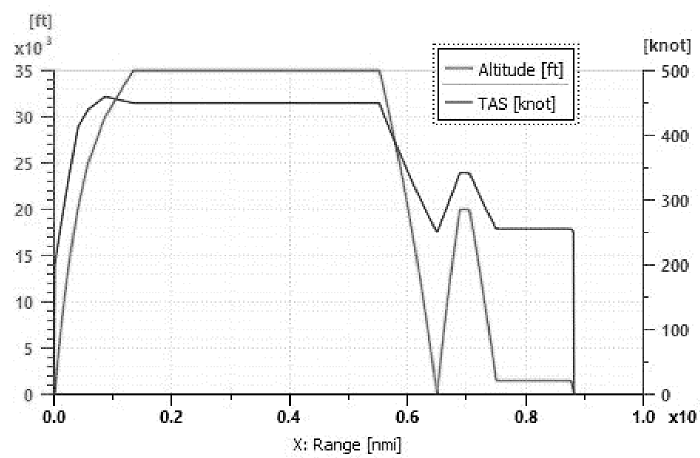

Figure 1: Flight Profile

In the climb phases, the aircraft gradually builds up speed while the climb rate reduces with increasing altitude. The diversion phase allows computing the reserve fuel for each concept. The aircraft-engine model was validated by comparing the simulated payload range diagram to the A320neo payload range diagram [22]. As shown in Figure 2, the integrated model reproduces the expected behavior with acceptable accuracy, with a maximum difference in range reaching 2% at a payload of 15,150 kg.

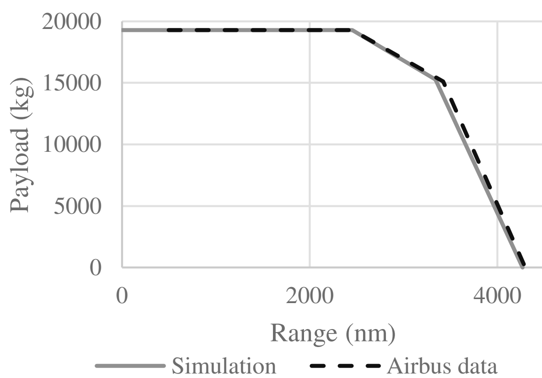

Figure 2: Simulation payload range diagram comparison with published data

2.3 Test Cases

Three mission lengths were investigated: 450 nm, 650 nm, and 1,250 nm. The aircraft must accommodate a payload capacity of at least 18,000 kg (180 pax) [22]. The conventional aircraft has a payload margin of 2,660 kg. This margin is obtained from the cargo capacity and the margin between the zero-fuel-weight (ZFW) and the landing weight (LW). The additional weight will not introduce major structural issues, as it will be stored in the wings and can be accounted for as fuel weight. To accommodate the electric powertrain and cooling system weight, the battery weight was limited to 2,000 kg.

The performance of the hybrid electric propulsion system depends strongly on the power management strategy (PMS) and the battery specific energy [4]. Six PMS (see Table 5) were evaluated, along with the two battery specific energies.

Table 5: Power Management Strategies Definition

PMS	Take-Off	Climb	Cruise	Descent	Landing
TO CLB	Hyb.	Hyb.	Conv.	Conv.	Conv.
CRS	Conv.	Conv.	Hyb.	Conv.	Conv.
DSC LDG	Conv.	Conv.	Conv.	Hyb.	Hyb.
ALL	Hyb.	Hyb.	Hyb.	Hyb.	Hyb.
TO CLB CRS	Hyb.	Hyb.	Hyb.	Conv.	Conv.
TO LDG	Hyb.	Conv.	Conv.	Conv.	Hyb.

Every PMS was constrained by the structure of the aircraft (max battery weight of 2,000 kg to achieve a payload of 18,000 kg) and by the cooling system (max heat extraction of 125 kW). The simulations considered the weights of the battery (max 2,000 kg), cooling system (120 kg), electric motor (EM) and inverter (144 kg), and a payload of 16,000 kg (equivalent to 160 pax or a load factor of 89%). For all cases, the electric powertrain weight was calculated for a 770.83 kW output electric power, which corresponds to the maximum power manageable by the cooling system considered above.

The battery capacity was adapted to each PMS. The maximum battery weight of two tons might not carry enough energy to power the EM at full load for specific PMS. In these cases, the load on the EM was reduced to deplete the battery at a constant pace. This lowers the C-rate of the battery and increases its life, reducing the associated cost.

It should be highlighted that, for MIPH, the booster surge margin is reduced, as discussed by Sahoo et al. [23] and Kang et al. [4]. The degrees of hybridization applied herein are checked to ensure that no operability issues arise for the gas turbine.

2.4 Economic analysis

Direct operating cost (DOC) is frequently used as a measure of the economic viability in a design study. It enables comparing different concepts before development. The following economic analysis is based on the DOC evaluation of each concept (i.e., each combination of power management strategy and battery technology). The DOC is composed of three main costs, according to Jenkinson et al. [24]:

- The cost of ownership, comprised of the depreciation, insurance, and interest costs.
- The maintenance cost is comprised of the airframe and engine maintenance costs.
- The flight operation costs, comprised of crew salary, fuel cost, airport servicing cost, and applicable taxes.

In this study, the cost of ownership is calculated by depreciating the aircraft value linearly and by applying a 15% [12] increase to cover the insurance and interest cost. All inputs for the economic evaluation are shown in Table 6. In reality, these costs would be different for conventional and hybrid aircraft (and among different hybrids). Keeping them the same was therefore a simplifying assumption – an assumption that will need to be relaxed in future work.

Table 6: Inputs for the economic evaluation

Cost	Value	Ref
Acquisition cost	108.4 M$	[25]
Airframe Maintenance Cost	650 $/FH	[26]
Engine Maintenance Cost	350 $/FH	[26]
Crew Salary	1000 $/FH	[27]
Servicing Cost	800 $/Flight	[28]
Battery Price	100 $/kWh	[29]

Two energy price scenarios were evaluated. The Business as Usual (BAU) scenario represents 2019 energy prices, while the High Price (HP) one depicts a hypothetical higher energy price. Furthermore, two technology price scenarios were evaluated. The first represents a low technology cost (LTC), resulting in no increase in acquisition cost, and a battery price of 100 $/kWh. The second represents a high technology cost (HTC), resulting in an acquisition price increase of 10% and a battery price of 150 $/kWh. Both scenarios are hypothetical, as HEPS currently have a low maturity. A CO_2 tax of 50 $/ton was assumed [30]. The scenario parameters are defined in Table 7 and Table 8.

Table 7: Energy price scenario definition

Scenario	Energy	Price	Price ($/MWh)
BAU	Fuel	700 $/ton	57.4
	Elec	0.10 $/kWh	100
HP	Fuel	1400 $/ton	114.8
	Elec	0.15 $/kWh	150

Table 8: Technology price scenarios definition

Scenario	Component	Price
LTC	Battery	100 $/kWh
	Aircraft	108.4 M$
HTC	Battery	150 $/kWh
	Aircraft	119.24 M$

The maintenance cost of the hybrid variants was computed from the change in engine maintenance severity and the battery replacement cost. The electric powertrain maintenance was assumed to be negligible in comparison to the battery replacement cost. The battery maintenance cost was calculated from the battery price and the estimated life of the battery, using the method introduced by Zhang et al. [29]. In that method, the replacement cost of the battery is broken down into each charge-discharge cycle and is calculated with the following equation:

$$C_{bat,c} = \int_t^{t_f} C_{bat} \frac{|I_{bat}|}{3600 Ah_{cyc}} dt \quad (4)$$

where C_{bat} is the total battery replacement cost (see Table 8), I_{bat} is the battery charging or discharging current, and Ah_{cyc} is the total Ah-throughput for the cycle, calculated as follows:

$$Ah_{cyc} = \left[\frac{Q_{cyc,EoL}}{(\alpha SOC + \beta).\exp\left(\frac{-E_a + \eta C_{rate}}{R_{gas} T_K}\right)} \right]^{\frac{1}{z}} \quad (5)$$

$Q_{cyc,EoL}$ is the cycling-induced capacity loss until battery end of life. This is assumed to be 15% [29]. C_{rate} is the battery C-rate and T_k is the operating temperature, which, for the sake of simplicity is assumed to be constant at 298.15 K. Explanations/values for the other parameters in Equation 5 are provided in Table 9.

The engine maintenance cost was assumed proportional to the maintenance severity factor. The change in maintenance cost was therefore extracted from the change in severity factor.

Table 9: Parameters of the battery cycle aging model [31]

Battery parameter	Value
Fitting coefficient α	$\begin{cases} 2896.6, & SOC \leq 0.45 \\ 2694.5, & SOC > 0.45 \end{cases}$
Fitting coefficient β	$\begin{cases} 7411.2, & SOC \leq 0.45 \\ 6022.2, & SOC > 0.45 \end{cases}$
Compensation factor η	152.5
Activation energy E_a [J/mol]	31,500
Gas constant R_{gas} [J/mol.K]	8.314
Power law factor z	0.57

The severity factor was computed for all cases. It varies depending on the engine derate and flight length [32], [33]. As the engine derate is strongly correlated with EGT [32], it was calculated from the average EGT during TO and climb. Table 10 summarizes the severity factor and associated simulated EGT, depending on the derate, for the three mission lengths.

It was assumed that the servicing cost of the hybrid aircraft would increase by 100$/Flight (+12.5%) to account for the added cost of replacing and recharging the batteries and the added complexity of managing the battery fleet. The batteries are

Table 10: Maintenance severity factor for different derate and mission range along with associated EGT

EGT (K)	derate	Severity [34]		
		450nm	650nm	1250nm
1202.52	-5%	2.16	1.83	1.36
1181.85	0%	1.68	1.42	1.07
1160.52	5%	1.25	1.06	0.79
1139.74	10%	1.13	0.96	0.71
1118.81	15%	1.05	0.90	0.67

assumed to be replaced in between each flight and to be recharged at the airport. The airlines would therefore have to manage their battery fleet to ensure that a fully charged battery is ready for each flight.

The DOC variation was computed from the difference in acquisition cost, maintenance cost, servicing cost, and fuel and electricity consumption. The crew salary was assumed to remain unchanged, as the number of employees and their salaries would not necessarily be a function of the propulsion technology.

It is expected that operating hybrid aircraft will be more costly to operate than conventional aircraft. To render the hybrid aircraft financially attractive to airlines, an incentive is required. Two incentives were assessed here. The first takes the shape of a CO_2 tax, increasing the cost of operating a conventional aircraft more than that of a hybrid aircraft. The minimum CO_2 tax required was calculated by dividing the DOC difference by the CO_2 emissions difference. The DOC of operating both the hybrid and conventional variants were then recalculated with this tax to assess the associated increase in DOC.

Another incentive would be to subsidize hybrid aircraft at acquisition. The subsidy value was calculated to lower the operating cost of the hybrid variant down to that of the conventional aircraft. This subsidy would therefore appear in the ownership component of the DOC. As the depreciation of the aircraft was assumed to be linear, the subsidy was calculated using Equation (6).

$$Subsidies = \Delta DOC(\$/BFH)\ BFH(Hr/yr)\ n(yr) \quad (6)$$

The fuel consumption and the C02 and NOx emissions were evaluated for both battery energy densities through performance simulations, for all PMS in Table 5, in Amesim Simcenter. The DOC was then calculated for the energy and technology price scenarios defined in Table 7 and Table 8.

3. RESULTS AND DISCUSSION

3.1 Aircraft capability

Both hybrid concepts show worse payload and range capabilities than the conventionally powered aircraft (Figure 3). The hybrid configurations show very similar payload-range diagrams, as they both incorporate a two-ton battery. The range loss is due to the fuel capacity of the hybrid aircraft being reduced to make space for the batteries. Moreover, the added battery weight causes a higher fuel consumption. However, as this type of aircraft is used 90% of the time for missions shorter than 1,250 nm, this lower fuel efficiency should not be detrimental to its operation.

3.2 PMS influence on fuel savings

As seen in Figure 4, PMS can significantly affect the fuel savings and consequently the CO_2 emissions. For the 450nm mission, the fuel-saving for the case of a 300 Wh/kg battery is marginal at best. Increasing the energy density to 600Wh/kg provides a fuel benefit for all the PMS (up to 2.87% for the case that the EM is activated during the TO, climb, and cruise phases).

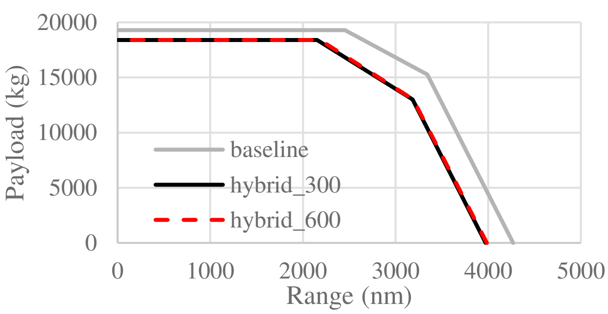

Figure 3: Payload range diagram comparison

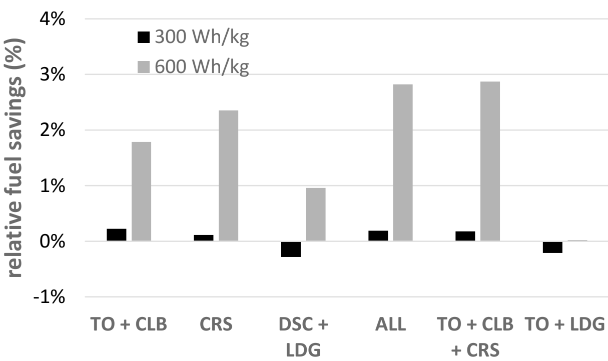

Figure 4: Fuel savings on a 450 nm mission

For the 650 nm case (Figure 5), the 300 Wh/kg battery hybrid concept consumes more fuel than the conventional aircraft for all PMS. The 600 Wh/kg battery hybrid aircraft concept presents a 1.51% reduction in fuel consumption when the EM is utilized for the duration of the whole mission. The fuel benefits drop to 1.47% when it is activated only during the TO, climb and cruise phases and to 1.44% when it is used only during the cruise phase.

Both the 300 and 600 Wh/kg battery hybrid aircraft concepts consume more fuel on a 1250 nm mission as seen in Figure 6.

The PMS analysis for different missions provides the expected results: the shorter the mission, the higher the environmental benefits of a MIPH hybrid electric propulsion system for an A320 sized aircraft. The results indicate that for an energy density of 600 Wh/kg the benefit is up to 3% for shorter missions, even without redesigning the engine. For longer missions, the energy density should further increase for hybridization to provide any fuel and consequently CO_2 benefits.

3.3 PMS influence on NOx

The results for the influence of the PMS on NOx emissions are shown in Figure 7 and Figure 8. Hybrid electric propulsion systems carry both an electric motor, which decreases the load on the core of the engine, and a hefty battery, which increases the thrust requirements. These two components have opposing

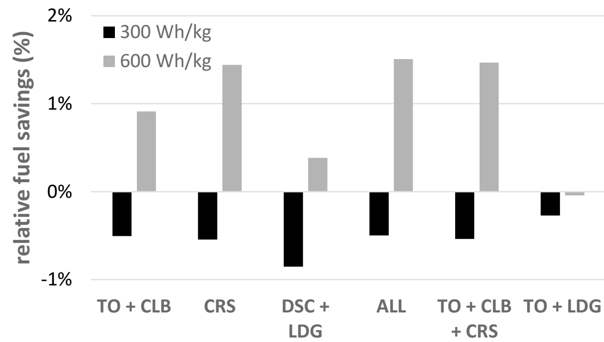

Figure 5: Fuel savings on a 650 nm mission

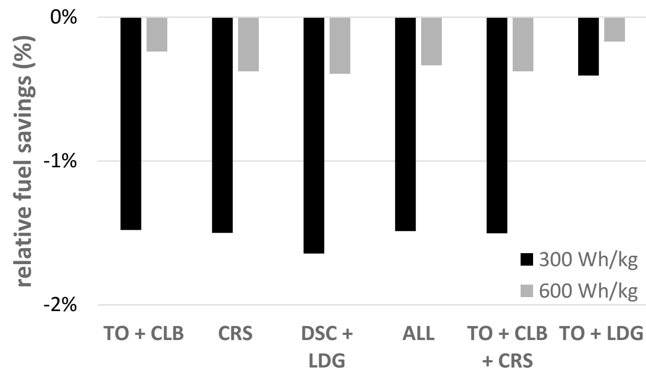

Figure 6: Fuel savings on a 1250 nm mission

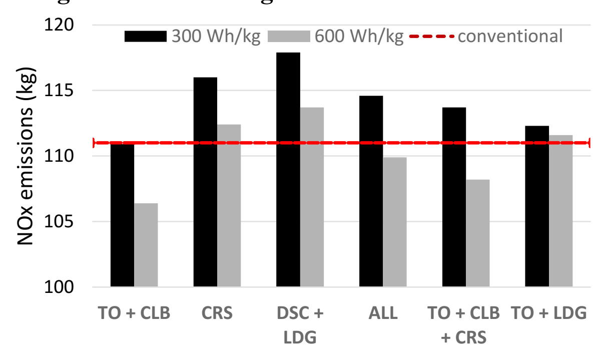

Figure 7: PMS influence on the NOx emissions for a 600 Wh/kg battery on a 450 nm mission

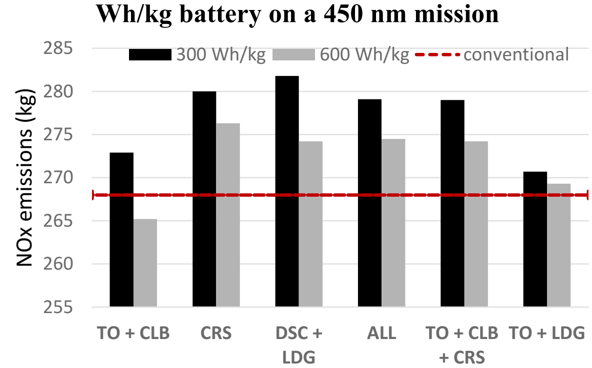

Figure 8: PMS influence on the NOx emissions for a 600 Wh/kg battery on a 1250 nm mission

effects on the NOx being emitted. Decreasing the core load decreases the combustor temperature and the associated NOx emissions. However, increasing the thrust demand requires the engine core to run at a higher temperature, increasing the associated NOx emissions. Depending on the flight phases when the engine is hybridized, the NOx emissions vary. The lower NOx emissions occur when the engine is hybridized during TO and climb. However, when the engine is hybridized during a low thrust phase (i.e., descent), the benefit of using electrical power is outweighed by the battery disadvantage. On longer missions, the hybrid aircraft concepts seem less promising to reduce NOx emissions. To consistently reduce the NOx emissions, the engine should be hybridized during the TO and climb phases of the flight, which will also provide the benefit of reducing NOx at the airport and at low altitudes.

3.4 PMS influence on DOC

As seen, PMS and range have a significant effect on fuel cost and are therefore expected to affect the DOC as well. Additionally, the PMS and range affect the battery utilization and consequently the electricity cost and, more importantly, its expected life. As can be seen in
Figure **9** and Figure 10, the PMS choice has a significant impact on the operating cost. The PMS will determine the current requested from the battery. A higher current will increase the degree of hybridization, resulting in a higher efficiency gain. However, this higher current results in premature degradation of the battery, resulting in a lower life and a higher battery maintenance/replacement cost.

Both concepts are more costly to operate than the conventional kerosene aircraft on all missions and PMS considered. The 600 Wh/kg battery concept is more expensive to operate than the 300 Wh/kg, which comes from the fact that the latter has a higher degree of hybridization. Moreover, a higher capacity battery requires higher electricity consumption. As electricity is more expensive than kerosene, a higher degree of hybridization results in higher DOC. This relation is shown in Figure 11, which demonstrates that a higher DoH has a negative impact on the DOC. The deviation of the data can be attributed to the effect of the PMS and mission length on the operating cost.

3.5 Overall environmental and economic assessment of the most promising PMS

As discussed, the environmental and economic behavior of the hybridized aircraft depends strongly on the PMS and range of interest. The most promising PMS are assessed in this section for the different economic scenarios. The technology cost and energy cost act as variables from which the DOC was calculated. Following the CO_2 tax and subsidies needed to make the hybrid aircraft comparable to the conventional one in terms of economics are calculated. Finally, given that the battery cost is a significant driver for the DOC, its value for making the hybrid aircraft comparable to the conventional one is calculated. The 300 and 450nm missions are considered in this analysis, as the 1250nm case does not provide any fuel or emissions benefits for the technology level considered herein.

The CO_2 emissions of the selected cases are depicted in Figure 12. The 300Wh/kg configuration does not provide any CO_2 benefits – even for the shortest mission. The highest CO_2 reduction is achieved with the 600 Wh/kg battery. It is also noted that HEPS have a greater environmental impact on short range applications, as expected.

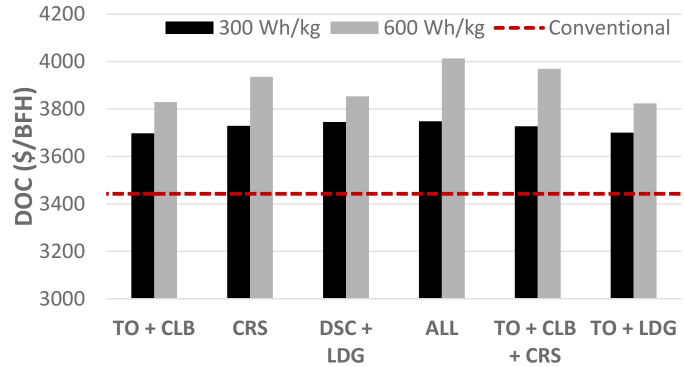

Figure 9: PMS influence on the DOC on a 450 nm mission

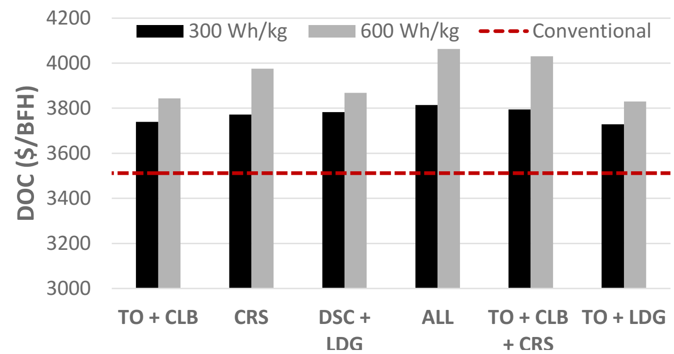

Figure 10: PMS influence on the DOC on a 650 nm mission

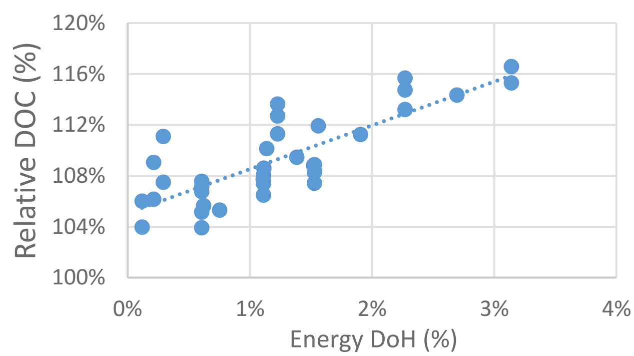

Figure 11: DoH influence on DOC

As mentioned in Section 4.3, the NOx emission savings of integrated HEPS is not trivial. The NOx emissions for the best hybrid PMS are summarized in Figure 13. Again, no NOx benefits are calculated for the 300Wh/kg, while some benefits are calculated for both 450nm and 650nm missions for the 600 Wh/kg battery for specific PMSs.

As the 300 Wh/kg does not provide any benefits in terms of emissions or DOC, it was not assessed further. For the 600 Wh/kg all the PMS are assessed.

As can be seen in Figure 14 and Figure 15, the DOC of both non-hybrid and hybrid aircraft are highly sensitive to the energy price. The hybrid concept's DOC is sensitive to the battery and HEPS price. This sensitivity is heightened for the concepts with the lowest expected battery life.

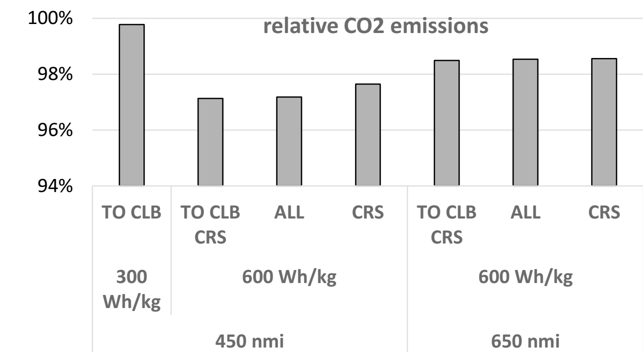

Figure 12: CO_2 emissions

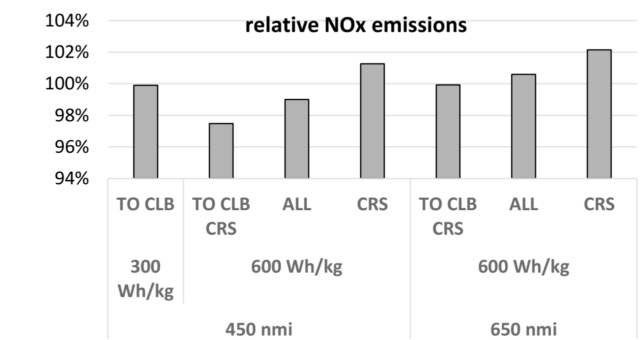

Figure 13: NOx emissions

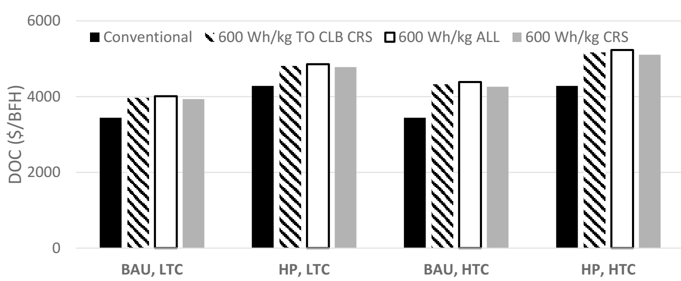

Figure 14: DOC sensitivity to energy and technology price on a 450 nm mission

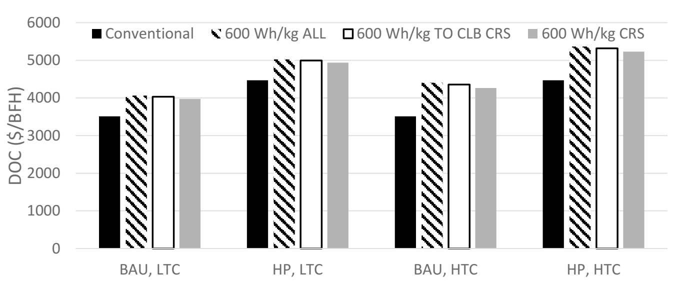

Figure 15: DOC sensitivity to energy and technology price on a 650 nm mission

As a HEPS powered aircraft is found to be more costly to operate than a conventionally powered aircraft, some economic measures would be required to make them attractive to airlines. Two such measures are evaluated in this study: a CO_2 tax, and a subsidy on the acquisition of the aircraft. The incentives were calculated under the low technology price scenario and BAU energy price.

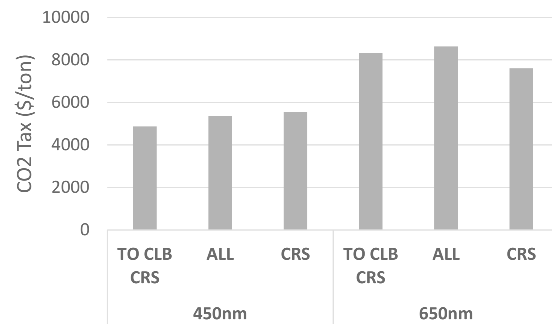

Figure 16: CO2 tax required to render the MIPH concepts competitive

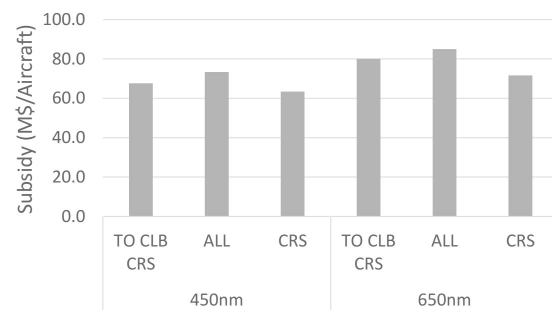

Figure 17: Subsidies required to render the MIPH concepts competitive

Figure 16 shows that the CO_2 tax required to render HEPS financially more attractive than conventional propulsion systems needs to be at least 5000 $/ton. This is much higher than the current CO_2 tax on the EU ETS market, which varied between 40 and 100 $/ton [40]. These high CO_2 tax values are caused by a significant DOC difference and small CO_2 savings.

The subsidy results can be seen in Figure 17. If subsidies were used to incentivize the use of greener HEPS for 180-seater aircraft, they would need to amount to more than half the value of the aircraft with a 600 Wh/kg battery.

These subsidies were computed to equalize the DOC of the aircraft. However, as the subsidy reduces the initial investment, the return on investment and internal rate of return would increase, providing a financial cushion for airlines. In other terms, if the technology is deemed predictable enough, the subsidy could be lowered to equalize the IRR instead of the DOC, further reducing the level of subsidy required. The DOC increase is mainly due to the battery replacement cost.

In Figure 18, it is depicted by how much the battery cost would need to be lowered to make hybrid propulsion financially attractive. the battery prices were reduced by 55%, a MIPH propulsion system would be financially more attractive to operate than a conventional propulsion system, on a 450 nmi mission. If the decrease in battery cost reached 65%, MIPH would be more attractive on 650 and 450 nmi long missions.

The CO_2 tax and subsidy figures presented were calculated separately. However, a mixed scheme taking into consideration both a CO_2 tax and a subsidy for greener aircraft should be investigated. It would permit lowering the value of both the CO_2 tax and the subsidy. The subsidy could be financed by a specific CO_2 tax and new equilibrium values for the CO_2 tax and subsidy could be calculated.

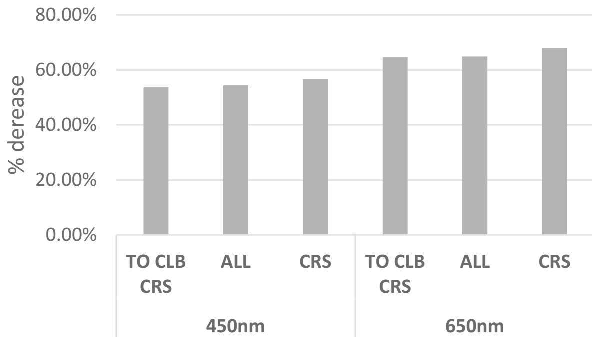

Figure 18: Battery cost reduction required to render the MIPH concepts competitive

4. CONCLUSION

This study compared the environmental and economic impact of a mechanically integrated parallel hybrid electric single-aisle short-medium range aircraft with that of a conventionally powered aircraft.

As indicated by many other studies, the results show that the battery energy density needs to be significantly increased before deriving any environmental benefit for aircraft of this size. Even with a battery energy density of 600 Wh/kg, only about 3% fuel savings were obtained in the most optimistic scenario (short mission length and optimal PMS). For this same scenario, there is no savings in NOx. NOx could, however, be lowered compared with existing aircraft, if using other PMS that are not so conducive to saving on fuel burn. The results show that missions above 650 nm with this MIPH implementation do not provide any benefit.

For an energy density of 300 Wh/kg, the fuel savings was highest for a PMS where the battery is operating only during takeoff and climb. For 600 Wh/kg, it is highest for operation during takeoff, climb, and the whole of cruise. The NOx emissions were lowest for the takeoff and climb only PMS. Comparing the NOx results with that of the fuel burn, there is evidently a tradeoff between fuel burn and NOx emissions when selecting a PMS.

As was expected, the cost results indicate that this MIPH implementation would be significantly more expensive than a conventional aircraft. Much of this is due to the battery replacement cost. The cost will increase with higher battery energy densities.

To make this implementation viable, the taxation on carbon emissions would have to increase at least 50-fold from its current levels for the most optimistic scenario. Otherwise, subsidies of up to half the value of the aircraft would be needed to incentivize an airline to purchase the MIPH aircraft.

There are some limitations to this study that could be addressed with future work. For example, a constant EM power application was employed across the mission for each scenario. This could be varied across the flight in future studies. Also, the maximum power from the motors was limited by the cooling system. For future studies, this could be increased, but the deleterious effects of expanding the cooling system to deal with the excess waste heat would need to be accounted for. In addition, a combination of incentives and carbon taxation could be investigated to expand on the cost study. The effects of differences in the constituent DOC elements between conventional and hybrid electric aircraft should also be investigated in more depth. Finally, the study could be repeated for different fuels, including hydrogen, or other gas turbine implementations, such as open rotor engines.

REFERENCES

[1] Sahoo, S., Zhao, X. and Kyprianidis, K. (2020) “A review of concepts, benefits, and challenges for future electrical propulsion-based aircraft,” Aerospace. MDPI Multidisciplinary Digital Publishing Institute. DOI: 10.3390/aerospace7040044.

[2] Seitz A., Nickl M., Stroh A., and Vratny P. C., (2018), “Conceptual study of a mechanically integrated parallel hybrid electric turbofan,” Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng., vol. 232, no. 14, pp. 2688–2712.

[3] Vratny, P. C., Kaiser, S., Sitz, A. and Donnerhack, S. (2017) “Performance Investigation of Cycle-Integrated Parallel Hybrid Turboshafts,” Journal of Engineering for Gas Turbines and Power, 139(3), pp. 1–9. DOI: 10.1115/1.4034498.

[4] Kang S, Roumeliotis I, Zhang J, Broca O & Pachidis V (2022) Assessment of engine operability and overall performance for parallel hybrid electric propulsion systems for a single-aisle aircraft, Journal of Engineering for Gas Turbines and Power, Volume 144, Issue 4, Article number 041002.

[5] Clean Sky 2 JU and FCH 2 JU “Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050”, May 2020

[6] Ang, A. W. X., Gangoli Rao, A., Kanakis, T. and Lammen, W. (2018) “Performance analysis of an electrically assisted propulsion system for a short-range civil aircraft,” Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. SAGE Publications Ltd, 233(4), pp. 1490–1502. doi: 10.1177/0954410017754146.

[7] ICAO (2020) “Engine Emissions Databank v28.” Available at: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank.

[8] Sebastian S, Kyprianidis G. K., Tomas G. (2015). Consistent conceptual design and performance modelling of aero engines. Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, June 15 - 19, 2015, Montréal, Canada, GT2015-43331, pp.1-10. https://doi.org/10.1115/GT2015-43331.

[9] Larsson, L., Larsson, T, L., Grönstedt, T. and Kyprianidis, K. G. (2011). Conceptual design and mission analysis for a geared turbofan and an open rotor configuration. Proceedings of the ASME Turbo Expo, 1, pp. 359–370. https://doi.org/10.1115/GT2011- 46451

[10] Kyprianidis G. K. (2011). Future Aero Engine Designs: An Evolving Vision, Advances in Gas Turbine Technology, Dr. Ernesto Benini (Ed.), ISBN: 978-953-307-611-9, InTech, Available at: http://www.intechopen.com/books/advances-in-gas-turbine-technology/future-aero-engine-designs-anevolving-vision.

[11] Gaudet S. R., Gauthier J. E. D., (2007), “A simple sub-idle component map extrapolation method,” *ASME Turbo Expo 2007*, GT2007-27193.

[12] Martins D. A. R., (2015), "Off-Design Performance Prediction of the CFM56-3 Aircraft Engine", Tecnico Lisboa MSc Thesis.
[13] Scholz, D., Seresinhe, R., Staack, I. and Lawson, C. (2013) "Fuel Consumption Due To Shaft Power Off-Takes From the Engine," 4th International Workshop on Aircraft System Technologies (AST 2013), 23-24 April 2013, Hamburg, Germany, pp. 169–179. doi: 10.15488/4462.
[14] Norman P.D., Lister D.H., Lecht M., Madden P., Park K., Penanhoat O., Plaisance C., Renger K. Development of the Technical Basis for a New Emissions Parameter Covering the Whole Aircraft Operation: NEPAIR, Final Technical Report NEPAIR/WP4/WPR/01; 2003.
[15] Jianhua Huang (2018) "A Simple Accurate Formula for Calculating Saturation Vapor Pressure of Water and Ice," American Meteorological Society, pp. 1265–1272. doi: 10.1175/JAMC-D-17-0334.1.
[16] Pagonis. M. (2015) 'Electrical Power Aspects of Distributed Propulsion Systems in Turbo-electric Powered Aircraft', PhD thesis, Cranfield University.
[17] Kellermann, H., Habermann, A. L., Vratny, P. C. and Hornung, M. (2020) "Assessment of fuel as alternative heat sink for future aircraft," Applied Thermal Engineering, 170. doi: 10.1016/j.applthermaleng.2020.114985.
[18] Siemens (2018) Siemens eAircraft Presentaion. Available at: https://www.ie-net.be/sites/default/files/Siemens eAircraft - Disrupting Aircraft Propulsion - OO JH THO - 20180427.cleaned.pdf (Accessed: July 6, 2021).
[19] Bolam, R. C., Vagapov, Y. and Anuchin, A. (2020) "A Review of Electrical Motor Topologies for Aircraft Propulsion," UPEC 2020 - 2020 55th International Universities Power Engineering Conference, Proceedings. doi: 10.1109/UPEC49904.2020.9209783.
[20] National Academies of Sciences, Engineering, and Medicine. (2016). Commercial aircraft propulsion and energy systems research: reducing global carbon emissions. National Academies Press.
[21] Lammen, W., & Vankan, J. (2020). Energy optimization of single aisle aircraft with hybrid electric propulsion. In AIAA Scitech 2020 Forum (p. 0505).
[22] Airbus (2020) A320 aircraft characteristics - airport and maintenance planning. Available at: https://www.airbus.com/aircraft/support-services/airport-operations-and-technical-data/aircraft-characteristics.html (Accessed: July 6, 2021).
[23] Sahoo S., Zhao X., Kyprianidis K. G., and Kalfas A., (2019), "Performance Assessment of an Integrated Parallel Hybrid-Electric Propulsion System Aircraft", ASME Turbo Expo 2019, GT2019-91459, pp. 1–17.
[24] Jenkinson, L., Simpkin, P. and Rhodes, D. (1999) "Civil Jet Aircraft Design," Civil Jet Aircraft Design. doi: 10.2514/4.473500.
[25] Airbus (2017) "Airbus Aircraft average list prices." Available at: https://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/Backgrounder-Airbus-Commercial-Aircraf-price-list-EN.pdf.
[26] Aircraft Commerce (2006) "A320 family maintenance analysis and budget," Aircraft Commerce, (44), pp. 18–31.
[27] Olivier Wyman (2019) Reported Operating Cost and Utilization of Narrow-body Jets. Available at: https://www.planestats.com/bhsw_2019sep (Accessed: June 3, 2021).
[28] International Civil Aviation Organization (ICAO) (2017) Airline Operating Costs and Productivity. Available at: https://www.icao.int/MID/Documents/2017/Aviation Data and Analysis Seminar/PPT3 - Airlines Operating costs and productivity.pdf (Accessed: May 20, 2021).
[29] Henze, V. (2020) Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh. Available at: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/ (Accessed: June 1, 2021).
[30] ICE (2021) EUA futures. Available at: https://www.theice.com/products/197/EUA-Futures/data?marketId=6173130&span=2 (Accessed: August 7, 2021).
[31] Zhang, S., Hu, X., Xie, S., Song, Z., Hu, L. and Hou, C. (2019) "Adaptively coordinated optimization of battery aging and energy management in plug-in hybrid electric buses," Applied Energy. Elsevier, 256(September), p. 113891. DOI: 10.1016/j.apenergy.2019.113891.
[32] James, W. and O'Dell, P. (2005) "Derated Climb Performance In Large Civil Aircraft," in Performance and Flight Operations Engineering Conference. Available at: https://www.theairlinepilots.com/forumarchive/quickref/deratedclimbperformance.pdf.
[33] Irsyadi, R. F. and Nirbito, W. (2019) "Derated Thrust: Method Analysis for Optimizing Turbofan Engine Takeoff Performances (SFC, EGT) Due to Lower Maximum Takeoff Weight (MTOW) Requirement," IOP Conference Series: Materials Science and Engineering, 685(1). DOI: 10.1088/1757-899X/685/1/012007.
[34] Hanumanthan, H. (2009) "Severity estimation and shop visit prediction of civil aircraft engines, Ph.D. Thesis." Available at: https://core.ac.uk/download/pdf/9637619.pdf.

Performance and economic assessment of mechanically integrated parallel hybrid aircraft

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