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SERIES OR PARALLEL HYBRID-ELECTRIC AIRCRAFT PROPULSION SYSTEMS? CASE STUDIES OF THE ATR42 AND ATR72

Aman Batra[1]*, Reiko Raute[2], Robert Camilleri[1]
[1]Institute of Aerospace Technologies, University of Malta, MSD2050
[2]Dept. Ind. Elec. Power Conv., University of Malta, MSD2050
* aman.batra@um.edu.mt

Abstract

With the ever-increasing pressure on the environment, there is the political will to achieve air travel in a sustainable manner, while continuing to offer economic growth and serve society's needs. In the European Union, this is driven by its ambitious strategy Flightpath 2050. More recently this has been renewed through the Green Deal which also includes sustainable aviation. This has promoted a substantial research effort into long-term goals such as the development of hydrogen powered aircraft. However, this paper argues that through careful design and optimisation, hybrid-electric propulsion systems (gas turbine with electric drives) can fill a gap in the short-to-medium term. This is particularly true for the short haul, regional aircraft. Such aircraft perform over 40% of all commercial flights and thus small fuel savings can immediately account to a significant impact on the environment. Although hybrid-electric aircraft would still produce some emissions, such propulsion systems could be effective to reduce emissions. The paper considers a case study of the ATR 42 and ATR 72 models (ATR - Avions de Transport Regional) and investigate their hybridization potential with increasing passenger capacity and expected improvement in battery energy density over the coming decades. The paper computes the in-flight CO_2 emissions for the various degree of hybridization. The results show that parallel hybrid electric provides a slight edge in emission savings than series hybrid architecture. Due to the limitations in battery energy density, this potential decreases as the passenger carrying capacity increases, but improves as the energy density of batteries increases. Surprisingly, the results show that the assumption that smaller aircraft are easier to hybridize is often not fully true and requires careful consideration on a number of variables.

Keywords: Series hybrid-electric, parallel hybrid-electric, regional aircraft

1. Introduction

Aviation is vital to global economic competitiveness and cohesion. It supports 87.7M jobs [1] around the world and contributes over 991billion Euro [2] to the economy. Aviation brings citizens closer together, enabling commercial and cultural exchanges. In the past two decades, air transportation experienced a yearly growth of 5% [3]. While this was beneficial from a socio-economic perspective, it had a significant environmental impact. Pre-Covid, aviation accounted for 2% of the global greenhouse gas (or CO_2) emissions [3]. Aviation energy usage in 2018 was equivalent to about 14% of the world's annual electricity demand. Yet it is estimated that only 10% of the global population account for 80% of all passenger-kilometers [4]. As poor countries are pulled out of poverty, their population will also travel and the negative environmental impact of aviation will grow. Over the past two decades, there was a continuous effort by the industry to make incremental improvements in the airframe design and the traditional powerplant. In the European Union, this is driven by its ambitious strategy Flightpath 2050 [5] which aims to achieve air travel in a sustainable manner while continuing to serve society's demands. This strategy sets aggressive targets to reduce in flight CO_2 emissions by 70% and NOx emissions by 90% and a reduction of noise when compared to the year 2000.

The discourse on the urgent need for environmental action has been somewhat eclipsed by the COVID-19 pandemic. The pandemic has left devastating effects on the aviation industry. However, this has time and again demonstrated to be a resilient economy sector and it is forecasted to bounce back and experience regrowth by 2050 [6]. It is therefore important now to revisit the opportunities for a better balance between social, economic and environmental impact of the sector. There is currently a strong belief that the ability to electrify the propulsion system will decouple CO_2 emissions from aviation growth [7]. However, this is heavily dependent on the technological advances in battery energy density. It is estimated that a battery energy density in the range of 800 kWh/kg is required to satisfy an aircraft range of 1000 km [8]. With current battery energy densities of around 250 kWhr/kg and expected energy density doubling every 23 years [9], it is estimated that the battery powered aircraft dream will take considerably long to materialize. Furthermore, aviation operates at particular environmental conditions in high altitude – low pressure and low temperatures. Therefore, progress in battery technology driven by the automotive world might not automatically be reflected in aerospace [9].

While there is substantial research effort into long-term goals such as the development of hydrogen powered aircraft, in the medium-term hybrid-electric propulsion systems can fill the gap. This is particularly true for the short haul, regional aircraft. Hybrid-electric propulsion combines fueled engines with electric drives powered by battery packs. Although hybrid-electric aircraft would still produce combustion emissions during flight, such propulsion systems could be effective to reduce emissions. However, the technological route is still unclear, which means the choice of current and future state-of-the-art components needed for a successful hybrid-electric aircraft is still imprecise. Unless hybrid aircraft are carefully designed, the aircraft frame becomes very heavy. A careful balance needs to be reached the reduced emissions from battery powered drivetrain, charged through a greener source and the economic feasibility of the passenger carrying aircraft.

This paper addresses this gap by providing two case scenarios based on the regional aircraft ATR 42 and ATR 72. These are used as a baseline as these types of regional aircraft perform over 40% of all commercial flights and their operations is projected to increase manifold in the future. The next step in the process is to compare series and parallel versions with different degrees of hybridization. This process is repeated with advances in energy density of battery technology, thus providing an insight into how advances in energy storage technology is expected to impact the aircraft design. To achieve this the paper is organized in the following manner:

Section 2 provides an overview of the ATR 42 and ATR 72 aircraft which are used as a test case study. Section 3 describes the methodology adopted for "converting" the powertrain into series-hybrid and parallel-hybrid versions. The results are demonstrated in Section 4 hybrid aircraft are compared across the passenger carrying capacity. The implications of these results are discussed in Section 5 which also draws conclusions on the topic.

2. The ATR short haul regional aircraft: A test case study

The ATR 42 and the ATR 72 are twin-engine turboprop short-haul regional airliner. The aircraft are straight, high-wings and T-tail configuration. The ATR 72 was directly developed from the ATR 42 and therefore the aircraft share a high degree of commonality. The while the ATR 42 has maximum seating capacity of 48, the seating capacity of the ATR 72 was increased to 70 by stretching the fuselage, along with an increase in wingspan, and more powerful engines. Figure 1 shows a schematic of the fuselage for the two aircraft. The purpose of this schematic is to visualize the future hybrid-electric aircraft with variation of this architecture due to additional components (such as motors, generators and batteries) and a sized gas turbine which keeping the fundamental structure same. Table 1 shows a number of parameters for the two aircraft, which were used as the input for the computation carried out further in the paper.

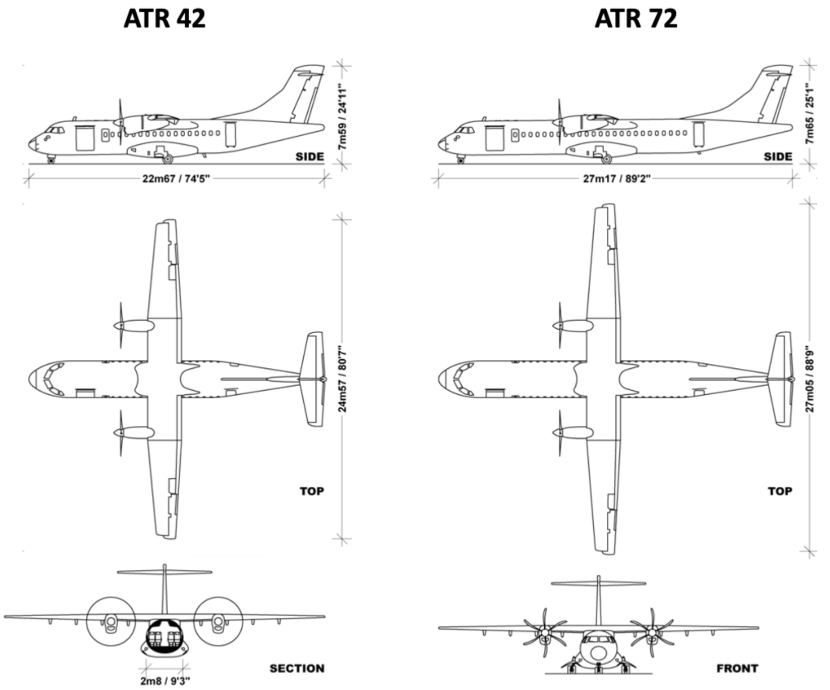


Figure 1. Schematic of the ATR 42 and ATR 72 respectively [12]

Table 1: Data for ATR 42 and ATR 72

Parameter	ATR 42-600	ATR 72-600	Units
Maximum passengers	48	70	
Length	22.67	27.17	m
Wingspan	24.57	27.05	m
Height	7.59	7.65	m
Wing Area	54.5	61	m^2
Empty weight	11,700	13,500	kg
Max. Take-off Weight (MTOW)	18,600	23,000	kg
Max. Payload	5,300	7,500	kg
Engine Power	1,611	1,846	kW
Cruise Speed	556	510	km/h
Max pax range	1,326	1,528	km

Having described the aircraft models that will be used as a test case study, the following section describes the methodology for defining and modelling the powertrain.

3. Methodology

This section is divided into three parts. The first part provides an overview of the series and parallel hybrid electric powertrains with the aim to explain the main characteristics and differences. Following this, a general overview of the model is provided. Finally, a definition of each of the components, and how these feed into the model is provided.

3.1 Definition of the Series and Parallel hybrid-electric powertrains.

Different configurations of hybrid-electric propulsion systems exist with the most common being series hybrid and parallel hybrid [10] [27] [28]. The basis of classification is on the mode of power delivery to the propeller. In a series hybrid powertrain, the propeller is always driven by an electrical motor. This can then be supplied by a battery or electrically fed by a generator which is in turn driven by a fuel powered gas turbine. In this case the gas turbine can be optimized to run at a single speed [10] [11]. While sometimes, series hybrid-electric architectures are depicted without a battery source, in that case there would considerable emissions as the gas turbine would be running for the entire operation. Therefore, in this paper a series hybrid-electric architecture is designed to contain a battery pack. The series hybrid-electric powerplant is depicted in Figure 2.

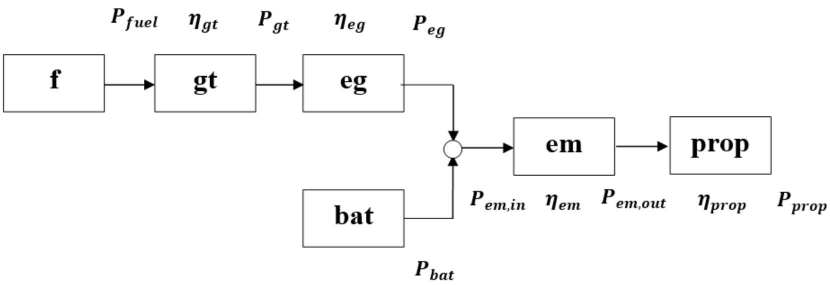


Figure 2: Schematic of the series hybrid-electric powerplant.

The symbols in the figure are defined as follows: *gt* is the gas turbine, *eg* is the electric generator, *bat* is the battery, *em* is the electric motor, *prop* is the aircraft propeller, *f* stands for the fuel, *P* denotes power and *η* is the efficiency.

Conversely, in a parallel-hybrid powertrain the propeller is connected to a power management device such as a gear box which is fed either by the gas turbine, or the electric motor powered by a battery, or a combination of both [10]. The parallel hybrid-electric powerplant is depicted in Figure 3.

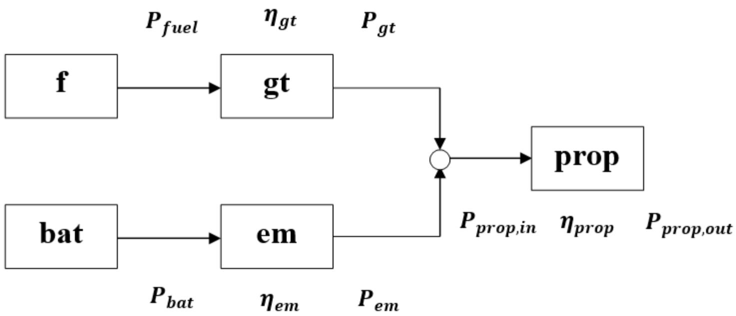


Figure 3: Schematic of the parallel hybrid-electric powerplant.

The symbols in the figure are defined as follows: *f* stands for the fuel, *gt* is the gas turbine, *bat* is the battery, *em* is the electric motor, *prop* is the aircraft propeller, *P* denotes power and *η* is the efficiency.

In both series and parallel hybrid-electric architectures, the efficiency $\boldsymbol{\eta}$ of each device can be generally written as a ratio of power output from the device $\boldsymbol{P_{output}}$ to the power input $\boldsymbol{P_{input}}$ [13]:

$$\eta = \frac{P_{output}}{P_{input}} \tag{1}$$

This paper [14] adopts the concept of setting a degree of hybridization φ. which defines as the power split between the two energy sources (aviation fuel P_f and batteries P_{bat}) as follows:

$$\varphi = \frac{P_{bat}}{P_{bat}+P_f} \quad (2)$$

This is useful as it allows to assess how technological progress (for example in battery energy density) can be reflected into a higher degree of hybridization and in turn lower emissions.

3.2 Definition of the model

To perform the analysis, an iteration loop was created. A schematic is shown in the Figure 4 below. The maximum take-off weight (MTOW) of the aircraft was set as a fixed constraint so that the overall aircraft weight including the hybrid powerplant, fuel and batteries do not exceed the MTOW. The MTOW is defined by the aircraft manufacturer and is dependent on the structural properties of the aircraft [15] and altering the MTOW would lead to redesigning the entire aircraft.

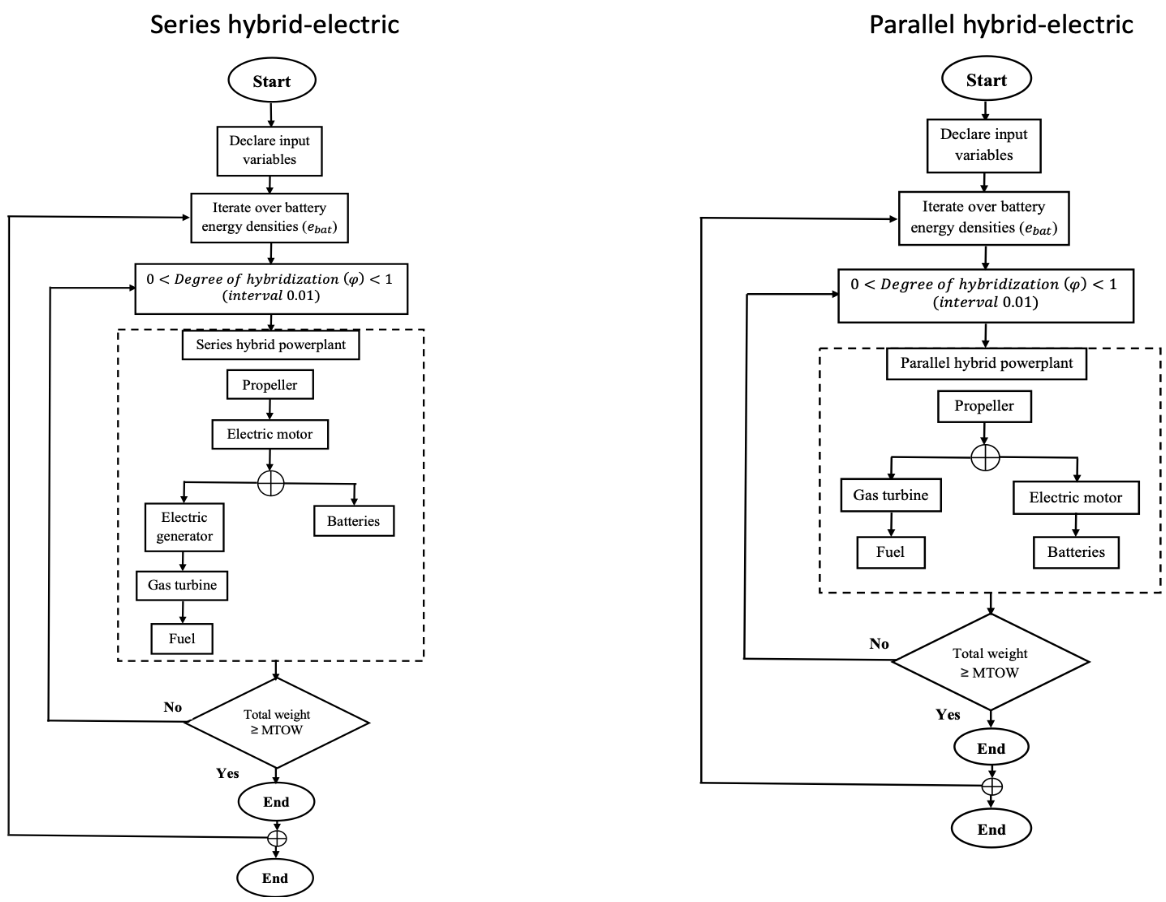


Figure 4: Schematic of the iterative model for the series hybrid-electric (left) and parallel hybrid-electric (right)

The analysis process is described as follows. The input parameters are taken from Table 1. As the analysis begins, it iterates over (0,1) degree of hybridization values with 0.01 interval. Following which the loop enters the hybrid powertrain and with degree of hybridization and engine power as the input, it computed the associated power and weights of individual components. The total weight of all the components of the hybrid powerplant is computed at the end of each iteration loop. During the analysis, the battery energy density was a varying variable. The choice of values is indicated in Section 3.3.6. The iteration loop ends at the required degree of hybridization (with the constraint of the MTOW as explained before). The difference between the series and parallel hybrid-electric is the hybrid powertrain architectures and the sizing of components. The weight of energy sources such as aviation fuel and batteries needed for each cycle of analysis is found at the end of the loop. The overall fuel consumption for the specific degree of hybridization was then converted into the emissions. This is done using the conversion factors available for various pollutants (such as HC, NOx, CO and CO_2).

3.3 Definition of the components

To model the powertrain accurately, the efficiency and power requirement for each component of the respective series and parallel-hybrid chains should be defined. This is shown in the following sub-sections where the equations used for the models are explained.

3.3.1 Modelling the propeller

The efficiency of the propeller η_{prop} can be defined in terms of total propulsive power of the powerplant P_{prop} and the input power to the propeller or output power of the electric motor $P_{em,out}$ as:

$$\boldsymbol{\eta_{prop}} = \frac{\boldsymbol{P_{prop}}}{\boldsymbol{P_{em,out}}} \qquad (3)$$

In this research, η_{prop} is taken as 0.75 [16].

The weight of the propeller W_{prop} is found using the following equation originally described in [16]:

$$\boldsymbol{W_{prop} = 40 * d_{prop} = 40 * 3.93 = 157.2\ kg} \qquad (4)$$

Where, d_{prop} is the diameter of the propeller at 3.93 m [12].

While in series-hybrid architectures, the propeller is fully powered by an electric motor, in parallel-hybrid architectures, the propeller can be fed by two sources: the gas turbine or the electrical motor, or both. The power transfer is managed by a gearbox connected to the propeller. The contribution of individual sources depends on the degree of hybridization. The power output of the sources is summed and acts as an input to the propellers. This is defined by the following equation:

$$\boldsymbol{P_{prop,in} = P_{gt} + \varphi * P_{em,out}} \qquad (5)$$

Where $P_{prop,in}$ is the power input into the propeller, P_{gt} is the power output from the gas turbine and φ is the degree of hybridization.

3.3.2 Modelling the electric motor.

The efficiency of the electric motor η_{em} can be expressed in terms of total output power of the electric motor $P_{em,out}$ and the input power to the electric motor $P_{em,in}$ as follows:

$$\boldsymbol{\eta_{em}} = \frac{\boldsymbol{P_{em,out}}}{\boldsymbol{P_{em,in}}} \qquad (6)$$

In this research this was considered to be 0.95 [17].

The weight of the electric motor W_{em} is found using the power density of the electric motor as follows:

$$\boldsymbol{W_{em}} = \frac{\boldsymbol{P_{em,out}}}{\left(\frac{\boldsymbol{Power}}{\boldsymbol{Wt.}}\right)_{\boldsymbol{ratio,em}}} \qquad (7)$$

Where $\left(\frac{Power}{Wt.}\right)_{ratio,em}$ is the power to weight ratio of the electric motor. In this research, a state-of-the-art value of 47.84 kW/kg [18] was considered.

The series architecture gets divided into two arms subsequently. One arm is composed of the electric generator, the gas turbine and the aviation fuel energy source while the other arm is made up of the batteries energy source. Contribution of individual arms depends on the degree of hybridization. The power output of the arms is summed and acts as an input to the electric motor. This is defined by the following equation:

$$\boldsymbol{P_{em,in}} = \boldsymbol{P_{eg}} + \boldsymbol{\varphi} * \boldsymbol{P_{bat}} \qquad (8)$$

Where P_{eg} is the power output by the electrical generator and P_{bat} is the power output of the battery.

3.3.3 Modelling the electric generator and the gas turbine.

The efficiency of the electric generator η_{eg} and its weight W_{eg} can be expressed as:

$$\boldsymbol{\eta_{eg}} = \frac{\boldsymbol{P_{eg}}}{\boldsymbol{P_{gt}}} \qquad (9)$$

$$\boldsymbol{W_{em}} = \frac{\boldsymbol{P_{eg}}}{\left(\frac{\boldsymbol{Power}}{\boldsymbol{Wt.}}\right)_{\boldsymbol{ratio,eg}}} \qquad (10)$$

Where P_{gt} is output power of gas turbine , $\left(\frac{Power}{Wt.}\right)_{ratio,eg}$ is power to weight ratio of the electric generator and a state-of-the-art value of 8 kW/kg [18] is considered for the same. In this research η_{eg} is considered to be 0.98 [19].

Similarly, the efficiency of gas turbine η_{gt} and its weight W_{gt} can be found using the following expression:

$$\boldsymbol{\eta_{gt}} = \frac{\boldsymbol{P_{gt}}}{\boldsymbol{P_{fuel}}} \qquad (11)$$

$$\boldsymbol{W_{gt}} = \frac{\boldsymbol{P_{gt}}}{\left(\frac{\boldsymbol{Power}}{\boldsymbol{Wt.}}\right)_{\boldsymbol{ratio,gt}}} \qquad (12)$$

Where P_{fuel} is the power yielded from fuel energy source, $\left(\frac{Power}{Wt.}\right)_{ratio,gt}$ is the power to weight ratio of the gas turbine with a value of 4.27 kW/kg [21]. The value of η_{gt} is taken to be 0.35 [20].

3.3.4 Modelling the fuel energy source and the battery pack

The weight of aviation fuel W_f consumed is found using P_{fuel} and the fuel energy density e_f. The power needed is converted to energy by multiplying it with the duration of flight (one hour) as follows:

$$\boldsymbol{W_f} = \frac{\boldsymbol{P_{fuel}} * \boldsymbol{3600}}{\boldsymbol{e_f} * \boldsymbol{1000}} \qquad (13)$$

The energy density of kerosene fuel is taken as 43 MJ/kg [22].

To model the electric-hybrid powerplant, the weight of batteries W_{bat} is found using P_{bat} and is converted into energy requirement by multiplying it with the duration of flight (one hour), and the energy density of the battery e_{bat} as follows:

$$W_{bat} = \frac{P_{bat} * 3600}{e_{bat}} \qquad (14)$$

Another aim of the paper is to model the powertrain with the current battery technology and provide an insight into how this can change over the coming decades. To achieve this, the historical trend of battery energy density was used. It can be shown that over the last 7 decades, battery energy density improved at an exponential rate of 3% per year [23]. This is in agreement with [9] which highlights that the energy density of batteries doubles every 23 years. This data was used to project the energy density of batteries into the next 3 decades as shown in Figure 5, which is a plot between battery energy density and the respective year. The curve equation was found using the historical data for the battery energy densities. The curve starts from 1950 and is projected upto the year 2050. It is an exponential curve as stated before with a 3% increase per year. The fit helped in computing the projected values for decades 2030, 2040 and 2050. The battery energy density values used for modelling the hybrid powertrain are 228 Wh/kg, 310 Wh/kg, 420 Wh/kg and 570 Wh/kg respectively.

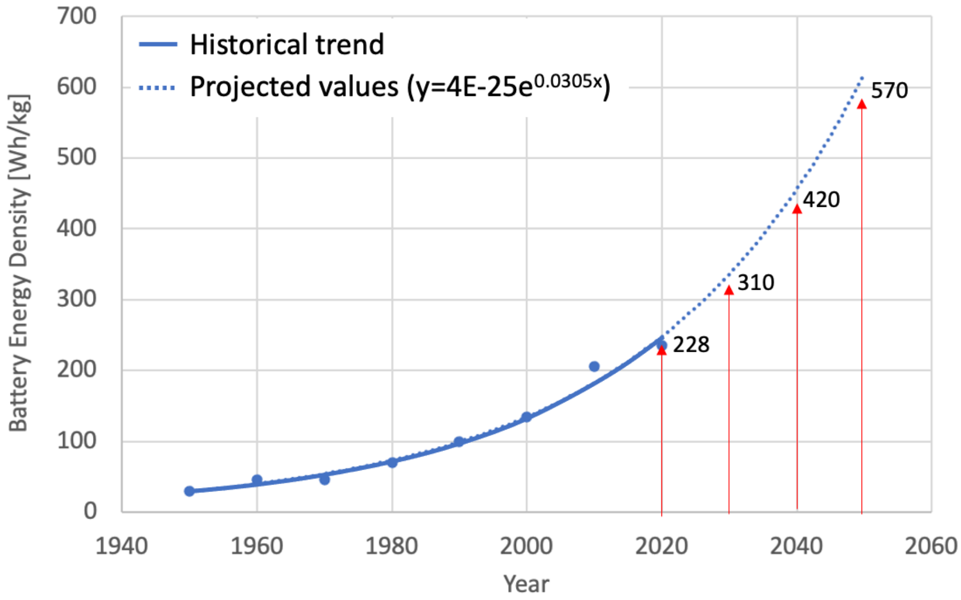


Figure 5: Energy density improvement in battery technology. Data extracted from [23]

3.3.5 Power requirement and time duration for different stages of flight

The general phases of flight are take-off, climb, cruise, descent, landing and taxiing. These phases of flight have varying power requirements according to their functions and flight characteristics. The take-off phase consumes most power and is for a very short duration. While in the cruise phase, the aircraft requires a continuous supply of power (78%) and is also the longest phase of the flight. The descent phase requires only 30% and is one of the least efficient phases. The climb phase requires more power than cruise but is for a short duration comparatively. The power requirement values for ATR 42 & 72 are mentioned in Table 2. The values for the ATR 72 were taken from the source [21], while for the ATR 42, the values were computed using the associated power percentages. For the initial preliminary calculations, climb, cruise and descent phases were considered for computation, which occupy the maximum time duration of flight.

Table 2: Power requirements for ATR 42 & 72 during various phases of flight

Modes (power %)	Power requirement ATR 72 (kW)	Power requirement ATR 42 (kW)
Descent (30%)	615	537
Climb (80%)	1635	1432
Cruise (78%)	1590	1396.2
Take-off (100%)	2050	1790

The time duration of various phases of flight is mentioned in table 3. The time to climb (t_{climb}) to FL170 for ATR 42 & 72 is taken from sources [24] and [25] respectively. The total duration of the flight is considered to be one hour. The $t_{descent}$ for ATR 42 & 72 is computed as follows:

$$T_{descent} = \left(\frac{1}{descent\ rate}\right) * altitute\ (in\ feets)$$

Where, the descent rate is taken to be 1500 feet/min [26] and altitude to be FL170.

Table 1: Time duration of various phases of flight for ATR 42 & 72 aircrafts

Time (sec)	For ATR 72	For ATR 42
$T_{descent}$	11.34	11.34
T_{climb}	17.5	12.7
T_{cruise}	31.16	35.96

Having provided a comprehensive description of the architectures, model and components, the following section presents the results of this study.

4 Results

4.1.1 A comparison of hybrid-electric powertrain

This section focuses on the degree of hybridization for the ATR 42 and ATR 72 with variation in passenger carrying capacity. Figure 6 compares the series hybrid-electric and the parallel hybrid-electric architectures for the ATR 42 with passengers between 10 and 40 in steps of 10. Likewise, Figure 7 compares the series hybrid-electric and parallel hybrid-electric architectures for the ATR 72 with passengers between 20 and 70 in steps of 20, with the last one being the current total number of passengers. Figures 6 & 7 display the results obtained after the iteration loop described in the previous section. The plots show the variation of degree of hybridization with the total aircraft weight, the horizontal line in the middle is the threshold MTOW and results for various battery energy densities is shown in different colors. The following general observations can be made:

- At maximum capacity, the aircraft has very little payload to “sacrifice” for the battery. Therefore, in both ATR 42 and ATR 72 operating at maximum capacity, the degree of hybridization is low. This can be observed from the last rows of the Figures 6 & 7.

- However, as the number of passengers decrease, the degree of hybridization increases. This is largely due to the weight of the batteries dictated by the low energy density of batteries when compared to fuel. This trend can be noticed as one moves from the last to the first row of Figures 6 & 7.

- For a constant passenger load, the parallel hybrid architecture is always more effective than the series hybrid configuration and as the energy density improves, the degree of hybridization also increases. This is largely due to the added components in the series hybrid configuration which gives rise to added weight compounded efficiency values of the drive train. This can be seen as one moves from the left to the right column of Figures 6 & 7.

- Surprisingly, the notion that smaller passenger aircraft are easier to hybridize is not always true. It can be seen that at maximum capacity, and with current battery technology, the ATR 42 can be hybridized to 26% (shown in Figure 6 parallel-hybrid with 40 PAX). Conversely, the ATR 72 at maximum capacity can only be hybridized to around 17% (depicted in Figure 7 parallel-hybrid with 70 PAX).

  However, as the passenger capacity is brought down, the ATR 72 becomes more favorable. When both aircraft are operated at half capacity, the ATR 72 has a slight edge in hybridization over the ATR 42 (observed from the middle rows of Figures 6 & 7). Furthermore, when operated at very low capacity the ATR 72 is hybridized up to 73% compared to 64% of the ATR 42 (noticed from the first rows of Figures 6 & 7). The more obvious reason for this is that the bigger aircraft can store a large battery with reduced capacity. However, the requirement for a hybridized (or even fully electric aircraft) might require aircraft designers to depart from the historical notion of the aircraft size. Aircraft may have to become bigger (for the same passenger capacity of today's aircraft) if indeed they are required to become greener.

4.1.2 Fuel Consumption and inflight-Emissions reduction

Having discussed the potential for hybridization for the ATR 42 and ATR 72 case studies, this section shows the resulting reduction in fuel consumption and emissions as a result of the hybridization process. Figure 8 shows fuel consumption and the in-flight CO_2, CO & NOx emissions for the conventional ATR 42 & 72 baseline and hybrid aircraft. The hybridization level for the aircraft at maximum take-off weight is considered. It can be observed from Figure 8 that at high battery energy density (570 Wh/kg) 100% hybridization (or fully-electric configuration) is achieved for the 10, 20, & 30 PAX cases (for ATR 42) and 20, 40, & 60 PAX cases (for ATR 72). However, as the battery energy density decreases, the weight of battery pack increases and it leads to decrease in hybridization. This results in increase in fuel consumption and thus in-flight emissions. The values being maximum for the conventional case (or 0% hybridization). The CO_2, CO & NOx emissions have similar trend as the fuel consumption and it was observed that with the decrease in hybridization as the weight of batteries increase, it leads to more in-flight emissions. Henceforth, both case scenarios show that fuel consumption and consequently emissions reduces drastically as a larger degree of hybridization is permitted due to less passengers and more payload weight available (can be noticed when one moves from right to left on the Figure 8 plots). It can also be seen that even a small implementation of hybridization (due to reduction in the passenger carrying capacity) causes an effective reduction in fuel consumption and respective in-flight emissions (can again be noticed when one moves from right to left on the Figure 8 plots).

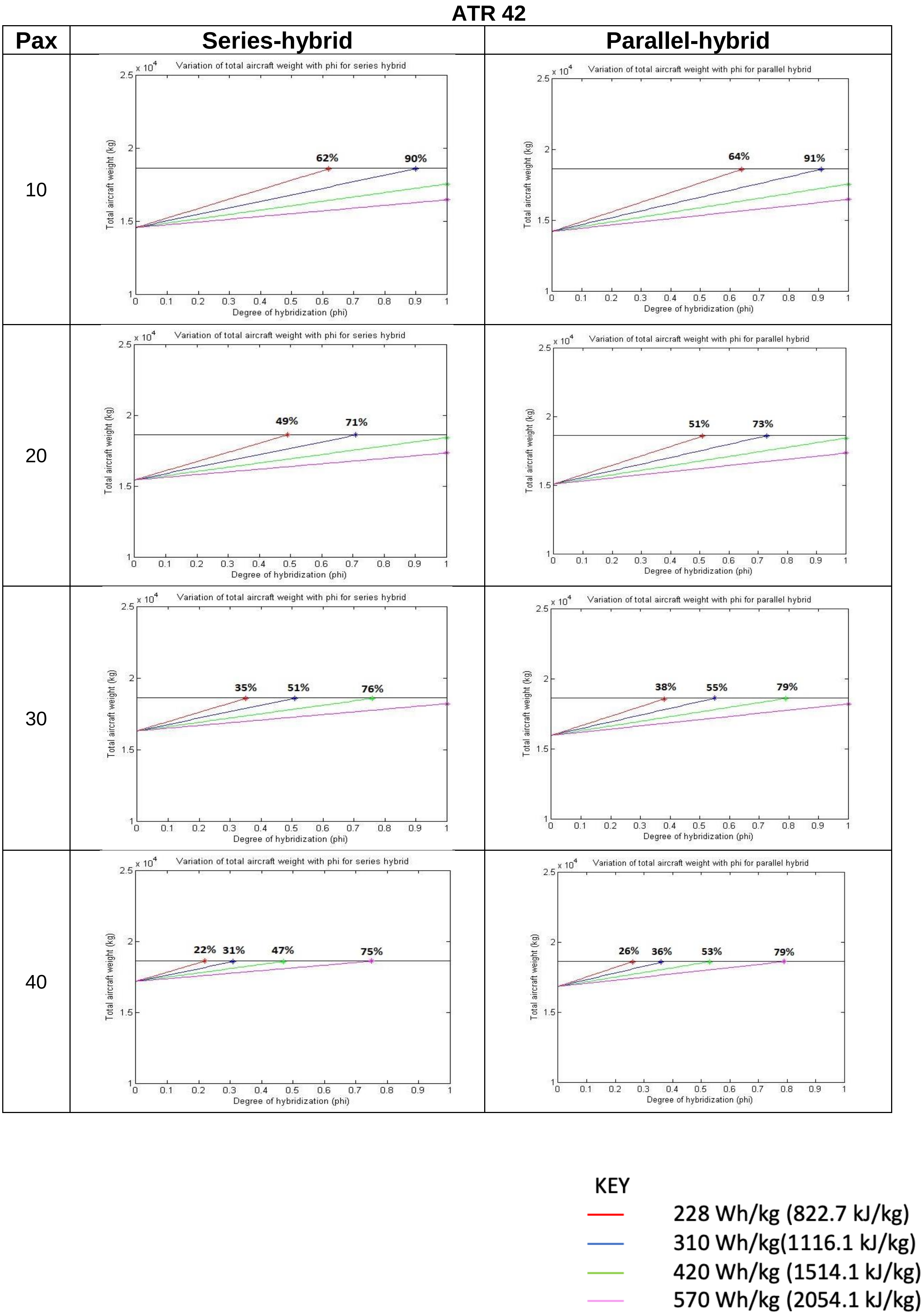
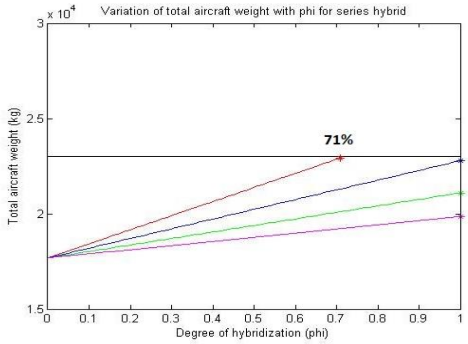
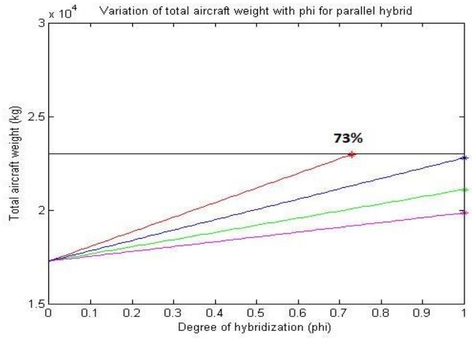
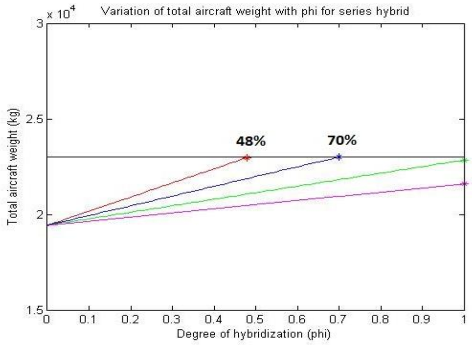
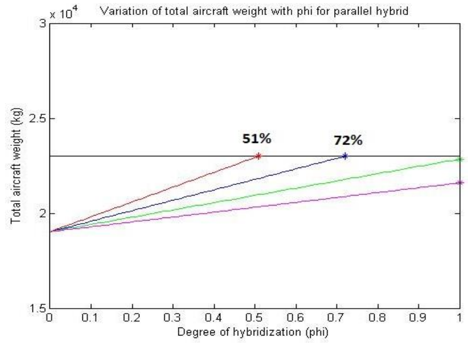
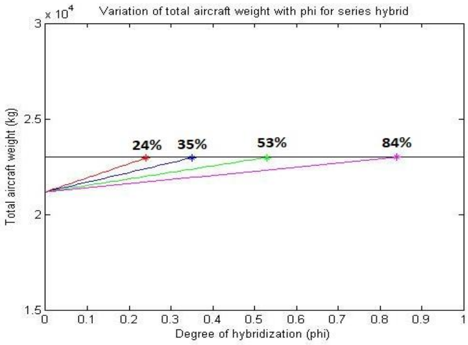
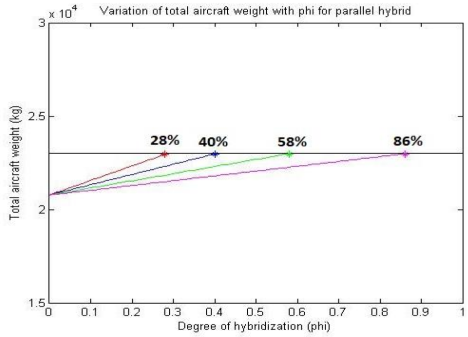
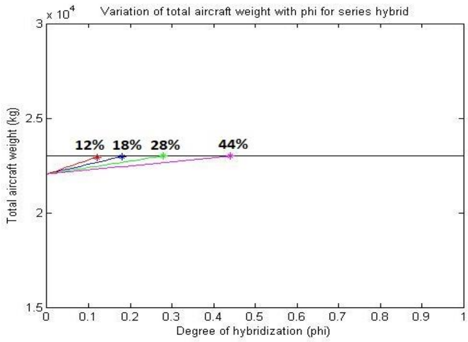
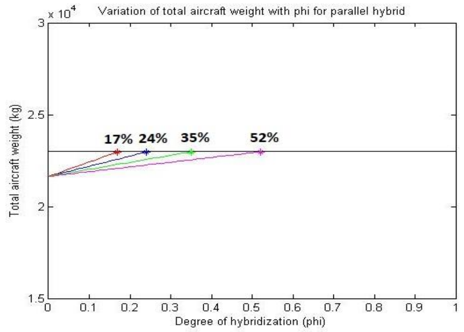


Figure 6: Results for the ATR 42 with Series (left) and Parallel (right) hybrid-electric propulsion.

ATR 72

Pax	Series-hybrid	Parallel-hybrid
20		
40		
60		
70		

KEY

- 228 Wh/kg (822.7 kJ/kg)
- 310 Wh/kg(1116.1 kJ/kg)
- 420 Wh/kg (1514.1 kJ/kg)
- 570 Wh/kg (2054.1 kJ/kg)

Figure 7: Results for the ATR 72 with Series (left) and Parallel (right) hybrid-electric propulsion.

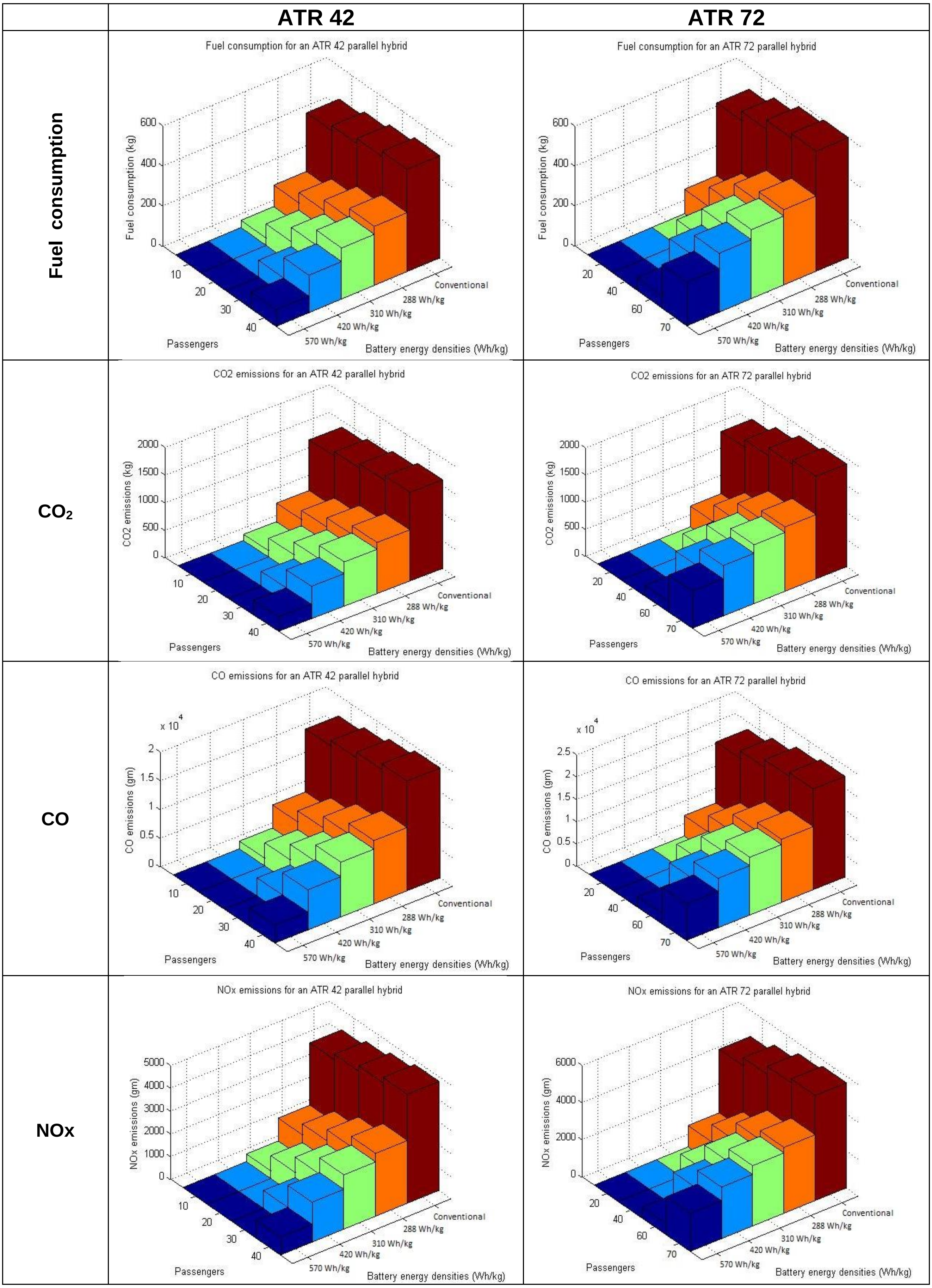


Figure 8: Fuel consumption, in-flight CO, NOx and CO_2 emissions for the ATR 42 and ATR 72 aircrafts with parallel hybrid-electric powertrain

5 Discussion and Conclusion

With the ever-increasing pressure on the environment, new solutions for a sustainable aviation is sought. While there is a big effort for a long-term solution such as hydrogen powered aircraft, the technology requires a drastic investment and technical solutions. The paper proposes hybrid-electric propulsion to fill the gap, particularly for the short haul, regional aircraft which is a short-to-medium term solution. The paper adopts ATR 42 and the ATR 72 aircrafts as case study, and develops a model which allows to establish the potential of hybridization of these aircraft with varying passenger capacity. The paper also shows how this picture will change in the next three decades during which battery technology is expected to improve.

The paper finds that with current battery technology, a high degree of hybridization is possible if the payload (number of passengers) decrease, thus utilizing the aircraft carrying capacity battery packs (as seen from Figures 6 & 7). However, the paper shows that improves as the battery energy density continue to improve over the coming decades. The parallel hybrid-electric configurations provide a slight edge in the degree of hybridization and therefore savings in fuel consumption and in-flight emissions with a constant passenger load. The paper also finds that the notion that smaller planes are easier to hybridize is not always accurate. With the current battery technology and maximum capacity, ATR 42 & 72 can only be hybridized to 26% & 17% respectively. However, when the passenger capacity decreases the ATR 72 becomes more favorable than ATR 42. The former can be hybridized to 73% while the latter to only 64% (also observed from Figures 6 & 7).

Additionally, as the battery energy density increase, weight of battery packs decrease, leading to a higher degree of electrification and a decrease in fuel consumption and the in-flight emissions (from Figure 8). It was also observed that even a small implementation of hybridization (due to reduction in the passenger carrying capacity) causes an effective reduction in fuel consumption and respective in-flight emissions (also from Figure 8). The current model also incorporates power requirements and time duration of various stages of flight. This helps in obtaining a better degree of hybridization and higher fuel savings and emission reduction. Therefore, this keeps hybrid-electric aircraft attractive as an effective means to combat climate change while maintaining sensible economic models.

The hybrid-electric technology applied to aircrafts has huge scope of research. The paper has a few limitations too which will also be the subject of future work. For instance the model focuses on climb, cruise and descent. The power requirement for take-off and landing phases are currently missing from the model. It would be interesting to establish how the hybrid strategy could be operated during takeoff to minimize emissions around the airport. The paper currently also considers in-flight emissions. In future this would be extended to include emissions due to the electrical charging of batteries by introducing the energy mix of the country in which the aircraft is operated. These limitations will be dealt with in a separate publication.

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