A Method to Predict Propulsion Architecture for Future Jetliners

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***Abstract*—The electrification of propulsion technologies in aerospace engineering has been considered as the future-vision for aviation industries. The Selection of electrified propulsion architecture for a particular mission-flight has become a new challenge. In this paper, a method to study different propulsion architectures and battery sizing for jetliners using multi-physics modeling is presented. The designed approach is then carried out to investigate conventional and hybrid/electric propulsion architectures of a commercial jetliner (Avro RJ-85). Based on the comparative study, an effective propulsion architecture is also suggested. The designed method is expected to help predict effective propulsion architecture for future aviation.**

Keywords—Hybrid-Electric-Propulsion, Co-Simulation, Aircraft, Propulsion-Architecture.

NOTATIONS

Aspect Ratio	AR
Thrust at altitude 'h'	$T(h)$
Mass	m
Wing Area	S
Speed	V
Acceleration	a
Air density at altitude 'h'	$\rho(h)$
Generator On/Off	β
Flight path angle	γ

SUBSCRIPTS DEFINITIONS

Maximum	max
Minimum	min
Electric Fan	EF
Jet Engine	jet
Required	Req
True Air Speed of aircraft	TAS
Aircraft	ac

I. INTRODUCTION

The term 'electrification' has two major applications in aviation sector: non-propulsive (NP) electrification and propulsive electrification. For many years, aviation industries have been enjoying the benefits of non-propulsive electrification of the auxiliary systems and introduced more-electric commercial aircraft which offer benefits in terms of reliability, operation cost and environmental considerations. Research suggested that, NP devices such as: high pressure air-bled, fuel pumps, hydraulic driven actuators etc. consume over 4.3% of the engine output power [1]. Thus, by introducing effective electrification, the overall efficiency improved dramatically.

In Electric propulsion, the electric energy is utilized to develop propulsive thrust to propel an aircraft. This thrust can be generated either by electric motor and fan combination or by charged ion [2]. By combining both conventional jet and the electric propulsion, hybrid-electric propulsion is realized. Although, the electrification in propulsion is not historically unprecedented, it now has much more significance. It is predicted that the increment of energy consumption in the aviation sector will be amplified by 11% over the subsequent decades. Now, the objective of the aviation industries is to step up from more-electric-aircraft to all-electric aircraft ensuring low-operation cost, zero-emission, system reliability and affordability [3].

Meanwhile, many companies and research institutes broaden their interests towards electric propulsion. As a result, recent full-electric (FE) aircrafts such as: eGenius in 2011[4], Airbus E-Fan [5] in 2014, NASA X-57 Maxwell-IV in 2018 [6] showed the potentiality for electric propulsion in the aviation sector. It is obvious that, conventional propulsion has a high energy-density where the FE propulsion performs with significantly higher efficiency. By taking advantages of both technologies hybrid architecture such as: i) series-hybrid-electric (SHE), ii) parallel-hybrid-electric (PHE), iii) Turboelectric or their combinations are realized and studied by different researchers; Table-I summarizes some of the recent outcomes. It can be observed that the research-trends are converging towards the business/commercial jet-liners (regional to long-range versions with >50 passengers) with two different directions: i) by developing new aircrafts ii) transforming existing aircraft to include a hybrid architecture. Generally speaking, the jet-liners would find the second method practical to step-out from the proven jet-technology and implement a new hybrid concept in their aviation. Recent programmes like 'Airbus EFAN-X', 'Project 804', 'Hybrid-Electric Cessna 337' are the on-going illustrations to that statement. In order to introduce hybridization into existing aircraft, comparative studies of propulsion-configurations are essential. For example, Richard and Danielle performed a comparative study of the existing characteristics of all-electric aircraft [7]. Their research was bounded by only full electric case only. Moreover, the effects of electrification for a particular aircraft were not studied technically due to the absence of generic framework. Hybrid aircraft propulsion system for skydiving mission was carried by Glassock and Galea [8]. They used a commercial simulator so called 'X-Plane' from Microsoft and developed the hybrid rendered

TABLE I. ARCHITECTURE SELECTION PARAMETERS

Aircraft [reference] (Order by year→)	**Study/ Lunch-year**	**Arch**	**PAX**	**Max. Pwr** (kW)	**Range** (km)
eGenius [4]	2011	FE	2	60*	450
Airbus –E Fan [5]	2014	FE	1	60*	160
E-Fusion [9]	2018	SHE	2	60*	1100
ATR-72-Hybrid [10]	2018	PHE	70	3820	1528
Hybrid Cessna [11]	2019	SHE	6	330	600
Project 804 [12]	2020	PHE	50	1000*	1080
Airbus E-Fan X [5]	2021	SHE	70	2000*	
STARC-ABL [13]	2035	TE	154	2600*	6300
NASA N3-X [5]	2045	TE	300	50000	7500

*Electric Power

model to study the architectures. However, internal structures and characteristics such as: motor power consumption, battery state of charge (SOC), etc. could not be observed because the simulation programs were black-box. Other problems of using such tools have been highlighted in [14]. Incorporation of numerical and high-fidelity physics-based models can be a potential solution to study various architectures.

Broadly speaking, in order to realize the applicability hybrid/electric propulsion for any jetliner other factors such as: real-world mission- profile, battery-cell selection etc must be taken into consideration. Furthermore, a generic framework with multi-physics model is required to overcome above mentioned flaws. In this paper, a method to study different propulsion-architectures and battery-sizing are presented for jetliners which helps to identify the challenges of transitioning research-aircraft to commercial aviation. Given the mission profile, the thrust requirement is firstly calculated. Next, both numerical and physics-based propulsor models are developed for different propulsion architectures with simplified aircraft-dynamics. The well-known Matlab/Simulink and AMESim software are used for this purpose. A model-in-loop (MIL) simulation is then carried out with adaptive thrust-tracking control of the propulsors. Next, electrical and mechanical characteristics are observed and a comparative study is performed for different combinations of hybrid/electric propulsion-architecture. Finally, by utilizing the simulated data, battery-sizing with different battery-cell technologies are carried out. A commercial flight SCW9031 of Braathens Regional Airlines flown by an Avro RJ-85 is considered as a case study. An effective architecture is suggested for the specified flight by considering the minimum battery-pack mass of the comparative cell-technologies.

II. Simulation Method

In this section, the designed methodology of the aircraft propulsion simulation is described. The design steps are: i) define initial parameters and mission profile ii) calculate the thrust-requirement iii) develop physics-based electric and jet propulsor model iv) develop thrust controller, v) simulation and obtain energy requirement iv) perform battery-pack sizing and generate report. In this study, the parameters associated with the degree of hybridization of propulsion architecture are considered. For the sake of simplicity, power-split factor was selected automatically based on the maximum capacity of the powertrain and hence energy-managements were neglected. Other influence factors for instance: thermal effects, electro-magnetic interferences are not taken under consideration.

A mission profile, segmented by different time variances (mission index) with associated parameters such as: altitude, ground speed (Mach number), coefficient of drag (C_d) and coefficient of lift (C_L) is provided in the Simulink Model. Indeed, the two coefficients C_d and C_L are completely depend on the aerodynamic shape and the flying style in each mission index. However, a way to calculate these two parameters can be found in [15]. The initial parameters corresponding to the aircraft configuration such as: aircraft mass, aspect-ratio, wing-area, jet and/or initial battery size, generator size, zero-lift drag (C_{d0}) etc, should be defined with the corresponding mission profile. The required thrust T_{req} is then calculated based on a simplified 3DOF aircraft dynamics [16]:

$$T_{req} = m_{ac}a_{ac} + \mu m_{ac}g + 0.5\rho(h)V_{TAS}S(C_D - \mu C_L) + m_{ac}g\sin(\gamma) \quad (1)$$

here, μ and g are the runway friction coefficient and gravitational acceleration. Once the plane takes off runway $\mu = 0$ can be considered. Next, physics-based propulsor models: jet engine and electric-fan with electro-mechanical characteristics are developed in AMESim (See the next subsections). The thrust outputs: T_{jet} and T_{EF} for jet engine and electric propulsor respectively, are fed back to the Simulink environment. By defining the number of electric propulsor n_{EF}, and jet engines n_{jet} the total thrust $T_{tot} = n_{EF}T_{EF} + n_{jet}T_{jet}$ is calculated. The proposed approach is graphically represented in Fig 1. In order to simulate T_{req} with the developed thrust T_{tot}, controllers are necessary. Hence, two individual controllers: EPC and JPC are developed for electric fan and jet engines respectively by utilizing neuro-adaptive proportional-integral-derivative (NAPID) controller as derived in [17]. The two controllers share the same error $e = T_{req} - T_{tot}$ and generate control signals individually by minimizing the objective functions $\frac{x_1 e^2}{2}$ and $\frac{x_2 e^2}{2}$. The scaling factors x_1 and x_2 can be selected as:

$$x_1 = \begin{cases} \frac{1}{n_{EF}} & if\ n_{EF} > 0 \\ 0 & Otherwise \end{cases}; x_2 = \begin{cases} \frac{1}{n_{jet}} & if\ n_{jet} > 0 \\ 0 & Otherwise \end{cases} \quad (2)$$

The design procedures of physics-based propulsor models briefly described in the next sub-sections.

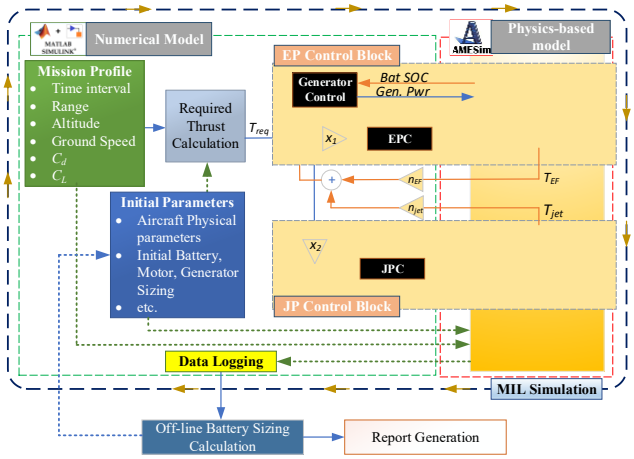

Fig. 1 Aircraft propulsion simulation methodology

A. Jet Propulsor Model

A conventional jet model is designed using the default model of AMESim aerospace toolbox (Fig. 2). Based on the throttle command received by the JPC controller, the thrust T_{jet} is generated. Here, T_{jet} depends on the total-air-temperature (TAT), total-air-pressure (TAP), total-air-speed

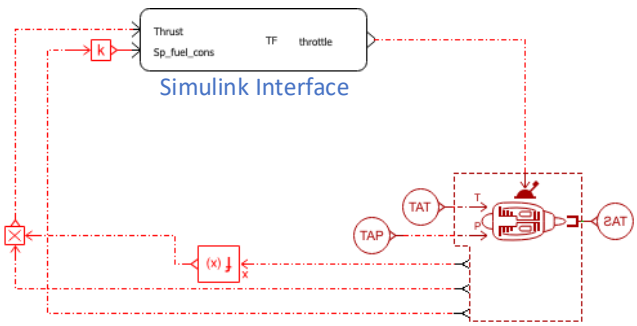

Fig. 2 Jet propulsor model

(TAS) and other thermodynamic parameters which need to be defined. Next, T_{jet} and the specific fuel consumption are fed back to the Simulink through the interface block.

B. Electric Propulsor Model

The architecture of EP is depicted in Fig 3. A field-oriented controller takes the torque command as input, drives a star-connected permanent-magnet-synchronous-motor (PMSM) through an inverter. This torque command is given by the EPC through Simulink-interface block. The DC/AC converter is connected to the DC bus where a generator and a battery models are attached in parallel. When needed, the generator can supply a certain level of power to the DC-bus which can be used to charge the batteries or to drive the motor directly. A simple technique so-called 'thermostat control'[18] is used to regulate the amount of generated power

$$Generator\ Power = \frac{\beta(SOC_{max} - SOC(t))}{SOC_{max} - SOC_{min}} \tag{3}$$

Here, $SOC(t)$ denotes the current state-of-charge of battery and SOC_{max} andSOC_{min} are in turn the maximum and the minimum SOC thresholds. $\beta \in \{0,1\}$ is a parameter which suggests the availability of the generator. When a torque command is provided, the motor draws power from the power sources and rotates a ducted fan connected to its mechanical shaft. The fan model is developed using 'AMESim Gas Turbine library'. Once the fan starts rotating, the air is passed from its intake to exit nozzle. Finally, the thrust output from the ducted fan is calculated as:

$$T_{EF} = \dot{m}_{air}(V_{air,exit} - V_{TAS}) \tag{4}$$

Where, $\dot{m}_{air}$ is the mass flow rate of air passing through the duct. Including this generated thrust value other signals such as battery SOC, bus voltage, power, etc are transmitted to the Simulink by the interface block for further operations. This finalize the design process and simulation can be performed.

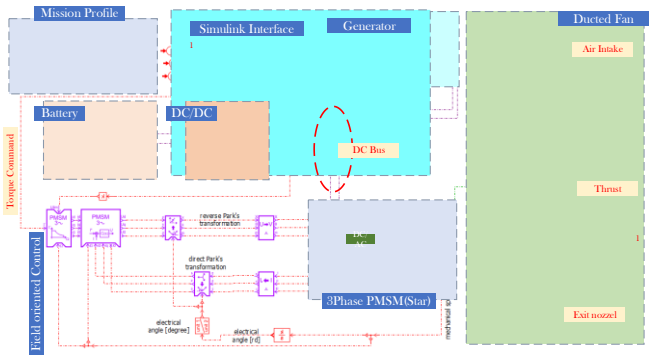

Fig 3. Electric propulsor model

It is important to note that, by controlling the parameters β, n_{EF}, and n_{jet} the following architectures can be simulated:

TABLE II. ARCHITECTURE SELECTION PARAMETERS

n_{EF}	n_{jet}	β	Architecture
0	> 0	0	Conventional Jet
> 0	0	0	FE
> 0	0	1	SHE
> 0	> 0	0	PHE (distributed propulsion)
> 0	> 0	1	Partial Series-PHE

III. BATTERY SIZING

After the simulation process, the used electrical and fuel energy, peak power consumption, current, voltages can be found. The battery sizing is then performed as follows:

Let Q_{bat},$P_{bat,max}$,η_{bat},V_{bat}, I_{bat} be the capacity, power, efficiency, nominal voltage and current of a battery respectively. The number of required cells in series and parallel are denoted by N_s and N_p respectively. C_{max}, Q_{cell} and V_{cel} are in turn the maximum 'C-rate', the capacity, and the nominal voltage of a cell. Therefore, N_s and N_p are calculated as:

$$N_s = \frac{V_{bat}}{V_{cell}} \qquad N_p = \frac{Q_{bat}}{Q_{cell}} \tag{5}$$

Where, $I_{bat} = C_{max}Q_{bat}$. And $Q_{bat} = \frac{P_{bat}}{V_{bat}C_{max}}$. The total number of cells are then simply calculated as:

$$N_T = N_p \times N_s \tag{6}$$

Once the total cell number is found, the approximate pack size can be found by $m_{cell}N_T$.

IV. CASE STUDY

This section deals with a case study for the proposed methodology. A commercial jetliner Braathens Regional Airline's flight SCW9031 is considered here. SCW9031 was approximately 2.5h of flight between Stockholm-Arlanda, Sweden and London Southend UK, operated by a well-known Avro RJ-85 category aircraft. The Avro RJ-85 was an improved version of its predecessor BAE-146 having four LF 507 engines capable to produce total 124KN of thrust at sea level and static condition and can carry 85-112 passengers. The operation empty weight of this aircraft is 24600kg. Here the associated aircraft parameters are considered as: $m_{ac} = 33500kg$, $AR = 8.98$ and $S = 77.3m^2$. The mission profile dated 1st March, 2020 of the selected flight was derived from https://www.flightradar24.com/ which is further considered in this paper (Fig. 4). It was obvious that, only two parameters: ground speed and altitude with respect to time were found from the profile. However, other parameters such as wind speed, flaps setting that represents the lift (C_L) and drag (C_D) coefficients were unknown to the developers. Thus, for the sake of simplicity, wind speed was neglected and the value of C_L and C_D were tuned based on [19].The extracted mission parameters were further summarised in Table III.

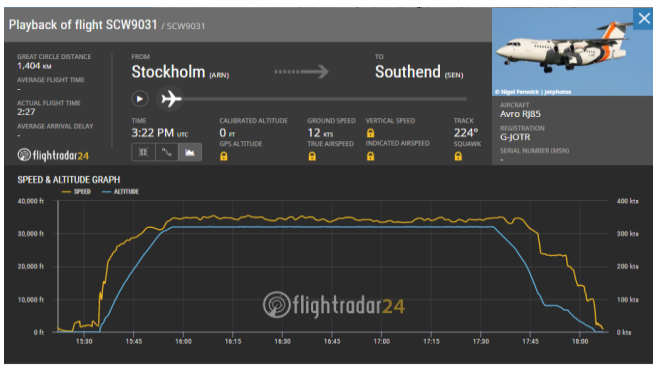

Fig 4. Mission profile of SCW9031 dated 1st Mar. 2020 from flightradar24.com

TABLE III. MISSION PROFILE TABLE

Mission Index	Time	Altitude (ft)	TAS (Mach)	C_D	C_L
0	03:26:00	0	0	0.15	1.2
1	03:26:32	0	0.00302	0.15	1.2
2	03:31:00	0	0.03023	0.15	1.2
3	03:34:21	0	0.02720	0.15	1.2
4	03:35:30	1125	0.18421	0.02	1.2
5	03:37:00	3125	0.23474	0.02	0.5
6	03:54:55	30975	0.57583	0.02	0.5
7	03:58:00	31975	0.59979	0.02	0.5
8	05:33:44	31975	0.59976	0.02	0.5
9	05:40:00	25625	0.57785	0.02	0.5
10	05:56:22	6550	0.31123	0.02	0.5
11	06:03:51	1025	0.15195	0.02	1.3
12	06:04:42	0	0.07769	0.1	1.3
13	06:07:00	0	0.01360	0.15	1.3
14	06:07:30	0	0	0.15	1.2

Next, the T_{req} was calculated with eq. (1). The associated model-parameters were set in a way that the total thrust and thrust-specific-fuel consumption were matched with LF 507 engine at sea-level. The simulations were then carried out for four different propulsion architectures: 'Conventional JP', 'FE', 'SHE' and 'Partial Series-PHE'; realized by setting of the combinations: ($n_{EF} = 0$, $n_{jet} = 4$, $\beta = 0$); ($n_{EF} = 4$, $n_{jet} = 0$, $\beta = 0$); ($n_{EF} = 4$, $n_{jet} = 0$, $\beta = 1$) and ($n_{EF} = 2$, $n_{jet} = 2$, $\beta = 1$) respectively (see Table-II). The initial battery configurations were sized as 20000Ah for FE and SHE and 360Ah for 'Partial Series-PHE' architecture. Furthermore, the nominal voltage and bus voltage were selected as 1000V and 3000V respectively. The generator used for SHE and Partial Series-PHE was assumed to be a 5.6MW, driven by T408 engine with 80% conversion efficiency. The simulation then started and results were obtained.

V. SIMULATION RESULT

The calculated minimum thrust requirement for the aircraft is shown in Fig. 5a. As seen, the thrust-tracking objective was effectively performed by the two controllers for all architectures. It was observed that, in case of conventional architecture the total energy consumption was 31.6MWh (Fig. 5b). For Partial-Series PHE and SHE, the energy consumptions were 28.04MWh and 16.64MWh respectively (see Fig 5b). Due to high efficiency the FE finished the mission with only 10.1MWh of energy. The equivalent fuel consumptions are figured in Fig 5c. The simulated fuel

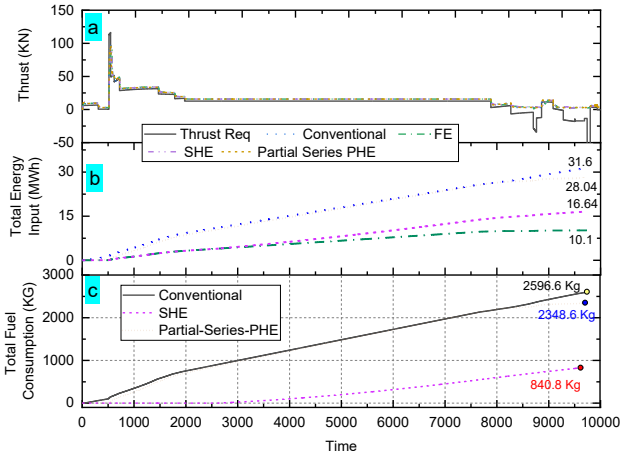

Fig 5. Comparison of thrust, total energy and total fuel-consumption for flight SCW9031 for different configurations.

consumption for conventional configuration was 2596kg. Compare to conventional jet propulsion, Partial-Series PHE architecture consumed 248kg of less fuel. In addition, the SHE architecture could save more than 1750kg of fuel. The reasons of such high fuel efficiencies for hybrid configurations can be explained with Fig 6 which illustrates the electrical characteristics of the designed configurations. As depicted, approximately 20MW of power was required for both SHE and FE where the Partial-Series PHE drawn approximately 8MW of power during take-off phase. From Fig. 6b, the generator of hybrid architectures: SHE and Partial-Series PHE, started after dropping the SOC below the threshold (80%) and fed the necessary power to the DC-bus. This explains why the SOC varies compared to the FE-continuously charge depleting (Fig. 6c). Due to integration of generator, SHE and Partial Series-PHE finished the mission with SOC 68%, 83% respectively where about 50% remained for FE. Clearly, reliance of battery power was the key to high fuel efficiency. Fig. 6d shows the final energy consumptions for SHE and Partial-Series PHE and FE were in turn 6535.4 kWh, 51.6 kWh and 10182 kWh. It is important to note that, given more thrust delivery by the conventional engines, the battery power consumption (see Fig 6a) and the energy consumption (see Fig 6d) of Partial-Series PHE were significantly lower than FE and SHE architectures. Apparently, due to low energy consumption, FE can be considered appropriate. However, other factors such as battery-capability also need to be studied before confirming the applicability which is studied next.

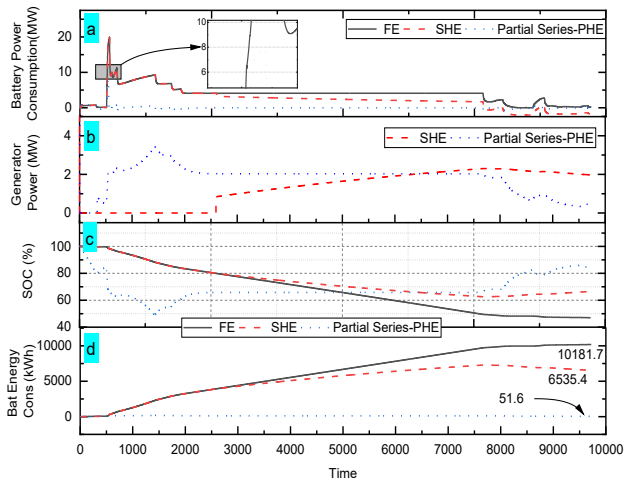

Fig 6. Illustrations of battery-electric properties for FE, SHE and Partial Series -PHE in flight SCW9031.

A. Battery-Pack Sizing

It is always required to achieve the highest level of electrification by the lowest possible battery energy requirement. However, capacity is not the only parameter in battery sizing but the discharge C-rate as well. For example, meeting high power demand (e .g 20MW for FE during take-off) at a high current rate may not be possible for such a battery pack using the existing cell technologies. Thus, it was necessary to re-size the battery by taking both capacity and the discharge rate of the existing cells. In this paper, three different kinds of typical commercially available cells 'Kokam 11.6Ah', 'Panasonic CGR26650A' and 'Panasonic NCRBD' were taken for sizing study (Table IV) using the method described in Section III. Each cell's short

TABLE IV. BATTERY PACK SIZING WITH EXISTING CELLS

Arch. ↓	Cell Name →		Kokam 11.6Ah	Panasonic CGR26650A	Panasonic NCRBD
	Requirement	Cell Spec → ($V_{cell} = 3.6V$)	11.6Ah, DCR: 2.0 Unit mass: 0.175kg	2.65Ah, DCR: 15.1 Unit Mass: 0.09kg	3 Ah, DCR 3.3 Unit mass: 0.049kg
FE	P_{peak}=20MW $E_{bat} = 10.1MWh$	Total Cell No	244084	1067520	942976
		Pack mass (kg)	42715	96077	46206
		Resized pack energy (kWh)	10193	10184	10184
SHE	P_{peak}=20MW $E_{bat} = 6.53MWh$	Total Cell No	156514	685270	605206
		Pack mass (kg)	27390	61674	29655
		Resized pack energy (kWh)	6536	6537.5	6536.2
Partial-Series PHE	P_{peak}=8MW $E_{bat} = 51.6kWh$	Total Cell No	95632	55600	221566
		Pack mass (kg)	16736	**5004**	10857
		Resized pack energy (kWh)	3993.6	530.42	2392.9

specification such as capacity, discharge C-rate (DCR) and unit mass were provided as well. As observed, for FE and SHE cases, the calculated pack-masses were too high to be carried by the aircraft and therefore, impractical to implement. However, a 5004kg of battery pack, developed by 'Panasonic CGR26650A' cell showed promises to implement with Partial-Series PHE architecture.

From the above case study, it can be summarized that, if flight SCW9031 is transformed from a conventional jet into Partial-Series PHE, a 5004kg of battery pack and 2348.6kg of fuel (See Fig 5c and Table IV) are required. Given the current mass (i. e 33500kg), theoretically, the aircraft could carry 1547 Kg of payload. It is worth to mention that, the maximum take of mass of this class of aircraft is 44000kg and thus by tuning the climb-rate, more payload can be carried.

VI. CONCLUSION

Hybridization can be the first step to enter into the electrified propulsion for aviation industries. In this paper, a methodology to study different types of electric/hybrid propulsion architectures is presented and carried out for a commercial flight SCW9031 using multi-physics-based software. Using the simulated energy and power information, battery-pack sizing is carried out with different battery cells. Though total electrification of propulsion promotes sustainable aviation, it is still far from reality because of the limitation of current battery technologies. Proper selection of hybrid/electric architecture with high 'C-rate' and high energy battery-cells have a bright future for next-generation aviation propulsion. Future research will be carried out to study more commercial flights with proper energy management control and experimental validation.

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