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Hybrid Power System Topology and Energy Management Scheme Design for Hydrogen-Powered Aircraft

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***Abstract*—The electrification of the aviation industry is a major challenge to realizing net-zero in the global energy sector. Fuel cell (FC) hybrid electric aircraft (FCHEV) demonstrate remarkable competitiveness in terms of cruise range and total economy. However, the process of simply hybridizing different power supplies together does not lead to an improvement in the aircraft economy, since a carefully designed power system topology and energy management scheme are also necessary to realize the full benefit of FCHEV. This paper provides a new approach towards the configuration of the optimal power system and proposes a novel energy management scheme for FCHEA. Firstly, four different topologies of aircraft power systems are designed to facilitate flexible power flow control and energy management. Then, an equivalent model of aircraft hydrogen consumption is formulated by analyzing the FC efficiency, FC aging, and BESS aging. Using the newly established model, the performance of aircraft can be quantitatively evaluated in detail to guide FCHEA design. The optimal aircraft energy management is realized by establishing a mathematical optimization model with the reduction of hydrogen consumption and aging costs as objectives. An experimental aircraft, NASA X-57 Maxwell, is used to provide a detailed performance evaluation of different power system topologies and validate the effectiveness of the energy management scheme. The new approach represents a guide for future power system design and energy management of electric aircraft.**

***Index Terms*—Transportation electrification; electric aircraft; hybrid energy storage system; power system topology; energy management strategy.**

Abbreviations

FC	Fuel cell.
FCHEV	Fuel cell hybrid electric aircraft.
BEA	Battery electric aircraft.
BESS	Battery energy storage system.
MEA	More electric aircraft.
HESS	Hybrid energy storage system.
FP	Full passive.
BA	Battery active.
FCA	Fuel cell active.
FA	Full active.
Crate	Charging and discharging rate.
DoD	Depth of discharge.
DP	Dynamic programming.

Nomenclature

P_{fc}	Working power of FC stack [kW].
η_{fc}	Efficiency function of FC stack [%].
E_{low,H_2}	Low enthalpy of hydrogen [MJ/kg].
Δt	Length of the energy management interval [s].
$P_{fc,rat}$	Rated power of FC stack [kW].
$k_{fc}^{\max}$	Maximum FC load variation rate [kW/s].
φ_h , φ_l , φ_v	FC aging quantification functions.
ΔL_{fc} ΔL_{bat}	Quantified FC and battery life loss [%].
Pr_{fc}^{unit}	Unit price of FC stack [$/kW].
C_{H_2}	Weight price of hydrogen [$/kg].
Q_{bat}	Rated capacity of the battery [kWh].
Q_{loss}	Cycle life loss of the battery [%].
N_{cycle}	Rated cycle life of the battery.
C_{rate}	Working Crate of aircraft BESS.
Pr_{bat}^{unit}	Unit price of the battery [$/kWh].
$\mathbf{S}_k$, $\mathbf{u}_k$	State and control variables.
SoC_k	Battery energy state at k [%].
$P_{fc,k}$	Fuel cell output power state at k [kW].
$P_{d,k}$	Aircraft power requirement at k [kW].

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η_{pmsm}	Efficiency of motor DC/AC converter [%].
η_{bat} , η_{fc}	Efficiency of battery and FC converters [%].
L , J_k	Instantaneous and accumulative cost functions.
P_{bat}^{ch}	Maximum battery charging power [kW].
P_{bat}^{ds}	Maximum battery discharging power [kW].
$SoC_{\min}$	Minimum SoC state of the battery pack [%].
$SoC_{\max}$	Maximum SoC state of the battery pack [%].

I. Introduction

ELECTRIFICATION of the transportation sector is of great significance to realizing the net-zero target in the global energy sector [1]. In recent years, the adoption of electric vehicles has been proven effective in reducing hydrocarbon fuel consumption and greenhouse gas emissions [2, 3]. Similar to the vehicle transportation sector, aviation is also responsible for more than 2.4% of all greenhouse gas emissions [4]. Therefore, an increasingly strong appeal appears in recent years for aviation electrification. According to [5], the UK government has carried out many strategies and policies to realize the net-zero target in the aviation industry by 2050. All-electric aircraft and more electric aircraft, which use an electric motor to replace traditional gas turbine engines, have been recognized as a cost-effective way to create a sustainable and low-carbon aviation industry [6, 7]. However, a reliable and efficient power supply system and energy management scheme are indispensable for aircraft to realize this target.

In recent years, battery electric aircraft (BEA), which uses battery energy storage systems (BESS) as the only power source has aroused extensive attention in aviation electrification [8-10]. Alpha Electro [11] is the world's first 2-seater commercial electric airplane, whose energy storage system consists of a 21-kWh battery pack. Compared with its gasoline version, the aircraft achieves better dynamic load-following performance due to the high responding speed [12] and power density [13] of lithium batteries. BESS is also used as a single power source in E-Fan [14], a two-seater electric aircraft developed by Airbus company. The adoption of electric propulsion systems reduces around 90% of aircraft operating costs. However, the energy density of lithium batteries limits the commercial application of BEA. According to [15], the energy density of lithium batteries is only about 5% ~ 8% of aviation kerosene, which indicates that the cruising range of BEA can only reach 10% of conventional aircraft using fossil kerosene. The cruising range of both Alpha Electro and Airbus E-Fan fails to reach 90 nautical miles because of the limitation of battery capacity. For this reason, Rolls-Royce and Airbus cancelled the E-Fan X project in 2020 and turned to a more economic aircraft electric propulsion solution: hydrogen and fuel cell (FC).

Compared to BEA, the energy density of hydrogen is much higher than conventional lithium batteries and can provide enough energy for extending aircraft cruising range. In recent years, many studies have been carried out to study electric aircraft with the FC and hydrogen energy storage system [16]. An FC-based power unit was developed in [17] to provide auxiliary power in more electric aircraft (MEA). Simulation results indicate that the FC stack can provide stable power for the aircraft for emergency use. Similarly, FC was also used in [18] as an emergency power system for more-electric aircraft. Furthermore, FC has also been used as the main propulsion energy resource in light unmanned aerial vehicles. In [19], FC was used to supply power to aircraft motors directly. Simulation results validate that the FC system and the corresponding power distribution strategy can meet optimal aircraft control and operational modes.

FC and hydrogen energy storage have a bright future in MEA applications because of their high energy density in extending aircraft cruising range. However, the commercialization of FC aircraft is challenging at present because of high aging costs and narrow working zone [20, 21]. The power requirement of aircraft shows different characteristics in different flight segments. Aircraft power demand is relatively high during taking off and climbing, but its value dramatically decreases when cruising, descending, and landing. In satisfying aircraft power requirements under different stages, aircraft with FC stack as the single power source is always concerned with low efficiency and high aging cost. Recently, the development of the hybrid energy storage system (HESS) brings a bright prospect to improve the efficiency and economy of electric aircraft [22-24]. The concept of fuel cell hybrid electric aircraft (FCHEA), whose power system consists of FC and battery HESS has been regarded as a promising pathway in realizing aviation electrification targets by many countries. In 2020, the UK government set a £54M collaborative H2GEAR Programme [25] to push hydrogen technology and accelerate aerospace decarbonization to zero emissions. The project mainly focuses on improving aircraft hydrogen-powered performance through FC and battery hybrid energy storage systems (HESS), in turn enabling applications on larger aircraft and longer journeys. The European Union also issued an urgent call for a green air travel and put forward an aggressive timeline pushing hydrogen-powered aviation as a commercial product for the commuter, regional, and short-range segments before 2035. Accordingly, Airbus also carried out a program called ASCEND to promote aviation electrification by utilizing hybrid electric propulsion and liquid hydrogen technologies. Further, the literature [26] further points out that hydrogen and FC-battery hybrid drive systems will be a disruptive technological path to clean up the aviation sector.

Compared with aircraft using FC stack and battery as the single power source, FCHEA can improve the competitiveness of electric aircraft on both cruising range and total economy. Nevertheless, simply hybridizing different power supplies together is not equal to aircraft performance improvement. Due to the heterogeneity of components, the energy management strategy of FCHEA is much more complicated than aircraft with a single energy storage unit. On the one hand, FC should be scheduled to operate more in high-efficiency zone with battery assistance for improving hydrogen economy. Meanwhile, FC and battery degradation should also be actively mitigated by coordinating HESS operation to improve aircraft longevity and in turn, reduce operating costs. Aircraft power system topology and the corresponding energy management algorithm should be reasonably designed to realize the above targets. However, the full passive structure [27] with no energy management unit is still the most commonly used aircraft power system configuration in the existing literature, which undermines the benefit of FC-battery HESS in the aviation industry.

Based on the above discussion, this paper investigates the optimal hybrid power system configuration and proposes an energy management method for FCHEA. Firstly, four different power system topologies are designed for aircraft with FC-battery hybrid energy storage systems. Then, an integrated equivalent hydrogen consumption model is built to analyze FC stack energy consumption, aging cost, and BESS aging cost in aircraft operation. The optimal aircraft energy management is realized by a dynamic programming model with the improvement of hydrogen efficiency and the reduction of aging costs as optimization objectives. Performances of different aircraft power system topologies and the effectiveness of the established energy management model are evaluated with an experimental airplane: NASA X-57 Maxwell.

The contributions of the paper can be summarized as follows:

(1) This paper provides the first attempt to investigate integrated power system topology and energy management scheme design for aircraft with FC and battery hybrid energy storage devices. Compared to existing passive structures, the designed active power system schemes realize flexible aircraft power flow control and facilitate economic aircraft energy management.

(2) It establishes an equivalent hydrogen consumption model by comprehensively analyzing aircraft FC output efficiency, stack aging, and BESS aging. With the newly established model, the performance of aircraft can be quantitatively evaluated for optimizing power system topology and energy management scheme design.

(3) It establishes a novel multi-objective energy management optimization model for realizing economic and flexible power distribution for electric aircraft with FC and battery hybrid propulsion systems. By solving the established mathematical model with dynamic programming, the reduction of aircraft hydrogen consumption and power system aging costs can be simultaneously realized for improving the total economy.

Furthermore, the theoretical and practical significance of the developed methodology can be summarized as follows:

(1) It qualitatively and quantitatively analyzes and compares the performance and economy of different power system topologies, which provide solutions for the design of large commercial electric aircraft with FC and battery hybrid energy storage systems.

(2) By solving the established multi-objective optimization model with a dynamic programming method, the derived optimal power distribution results serve as a reference and criterion for guiding real-time aircraft energy management and performance evaluation.

The rest of the paper is organized as follows: Section II presents the designed aircraft hybrid power system configurations and the established equivalent hydrogen consumption model. Section III introduces the developed multi-objective aircraft power system energy management scheme. Section IV demonstrates and discusses the results derived in this paper. Finally, Section VI concludes this article.

II. Aircraft Power System Topology and Equivalent Hydrogen Consumption Model

This section configures aircraft power system topology and establishes an equivalent hydrogen consumption model. Firstly, the parameters and simulation of the studied electric aircraft are presented. Then, four different aircraft power system topologies are designed. At last, an aircraft hybrid power system mathematical model is established, where driving system energy consumption, FC stack aging cost, and BESS aging cost are converted to equivalent hydrogen consumption.

A. Aircraft hybrid power system configuration

This section presents four different aircraft power system topologies: full passive (FP), battery active (BA), FC active (FCA), and full active (FA), as shown in Fig. 1. In the FP topology (a), FC and battery are designed to connect to the DC bus directly without any converter, which has been widely used in hybrid electric vehicles for its low cost and compactness. In this topology, the power outputs of aircraft energy storage components are not controllable. Therefore, the energy management system (EMS) controller is unnecessary, the working states of the FC stack and BESS are determined by bus line voltage directly.

Different from full passive topology, DC/DC converter is used in BA, FCA, and FA configurations to adjust the working state of the FC stack and BESS. Based on the state information of FC stack, battery pack, and aircraft power requirement, aircraft EMS controller formulates the optimal operation schedule for different power system sectors. In BA topology, BESS is connected to the DC bus via a DC/DC converter, while the FC stack is connected directly. BA topology facilitates the independent power-split control of BESS, and the corresponding energy management strategy is conducted by the converter between the battery pack and the DC bus. Fig. 1 (c) illustrates the FCA topology, whereas the battery system is directly connected to the DC bus. In this topology, power flow between the FC stack and DC bus can be flexibly controlled by the energy management unit. Battery energy storage capacity is used as a passive device to provide auxiliary power and recover excess power generation from the FC stack. The FA topology is shown in (d). With FC stack and battery pack converters, aircraft power system operation can be fully scheduled by deploying power distribution strategies. In this topology, both the FC and battery working state can be flexibly controlled, while the system is bulkier and with lower efficiency because of the use of two DC/DC converters.

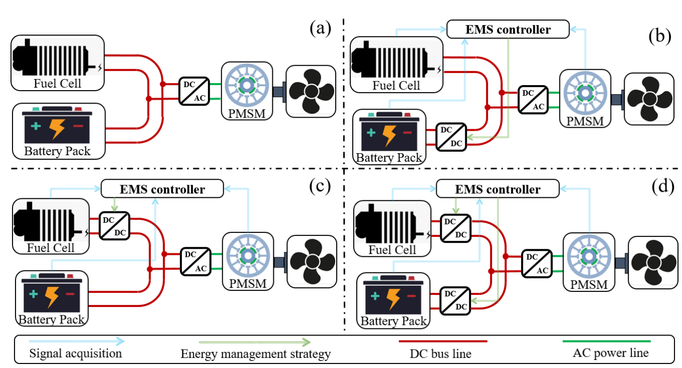


Fig. 1. The studied four different aircraft power system topologies. (a) full passive; (b) battery active; (c) FC active; (d) full active.

In most existing converters, the high-gain PID algorithm is used to control the converter to track the reference output current [28, 29]. The transient frequency of the converter is much shorter than the control frequency of the power distribution algorithm in electric aircraft [30]. Thus, the converters between the bus line, HESS, and PMSM are regarded as ideal controllers in this study.

B. Fuel cell hydrogen consumption model

This part establishes a mathematical model for quantifying FC stack hydrogen consumption in the studied electric aircraft. According to [31], assuming that the temperature and humidity of the FC stack can be well controlled, the hydrogen efficiency of the fuel cell can be simplified to a function of its output power. Compared with the theoretical polarization voltage model, the static efficiency model can be well applied to energy management scenarios for its better computational efficiency. Therefore, this study uses the empirical model [32] obtained from experimental data to characterize the FC hydrogen efficiency under different output power levels.

Fig. 2 shows FC working efficiency under different output power levels. According to hydrogen efficiency, FC operation can be divided into three areas: light load area (0~120 kW), economic operation area (20~70 kW), and heavy load area (70~100 kW). FC efficiency is very low when it works under light load conditions because the ancillary systems consume the most electricity. The FC stack reaches the highest efficiency at medium load, but its efficiency dramatically decreases with the improvement of output power states. The reason is that the power consumption of air and hydrogen compressors greatly increases under heavy load conditions. Therefore, different from combustion engines, the peak efficiency of FC stack appears at medium and low power levels, which highlights the necessity of using HESS in electric aircraft.

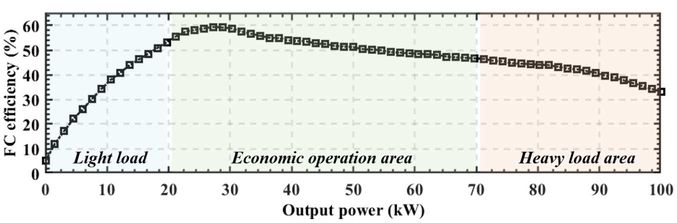


Fig. 2. Aircraft FC hydrogen efficiency profile under different output power levels.

Based on the presented efficiency profile, FC hydrogen consumption at t_0 can be calculated by the following formula:

$$M_{H_2} = \frac{1}{E_{low,H_2}} \int_{t_0}^{t_0+\Delta T} \frac{P_{fc}}{\eta_{fc}\left(P_{fc}\right)} \mathrm{d}t \tag{1}$$

where: P_{fc} and η_{fc} are the output power and efficiency function of the FC stack, respectively. E_{low,H_2} is the low enthalpy of hydrogen. Δt is the length of an energy management interval.

C. Fuel cell aging model

This part establishes an FC aging model to represent aircraft FC degradation cost in energy management. According to [33], there is still no consensus on the best mathematical model for FC system degradation. Since the output power is the only variable that can be manipulated in the aircraft energy management optimization, an empirical formula or semi-rational formula of FCS degradation is acceptable. It has been suggested in [34] that FC life loss is mainly contributed by the following three operations: heavy load, light load, and high load variation rate:

- ➢ Under heavy load conditions, the high current density blocks the reaction material transport on electrodes. The reduction of reactants concentration in the FC stack further results in voltage dropping and will dramatically accelerate its aging.
- ➢ In idle working conditions, according to FC voltammetry characteristics, cell voltage rises because of the low working current. The FC stack cathode potential is usually as high as 0.85 V to 0.9 V, which can lead to accelerated decay of the catalyst and carbon carrier.
- ➢ The load fluctuation directly influences the transport speed of reactants, which can result in uneven distribution of reactants and poison the healthy state of the FC stack.

Based on FC aging experiment data in [33], FC aging in the studied FCHEA is characterized under the above three working conditions. Aircraft power requirement is relatively high during taking off and climbing, the following equation is used to quantify the FC life loss contributed by heavy load conditions:

$$\varphi_h(P_{fc}) = 4.12\times10^{-7} \cdot \Delta t \cdot \frac{P_{fc}}{P_{fc,rat}} \tag{2}$$

where: $P_{fc,rat}$ is the rated discharging power of FC stack. The higher the working power, the more the FC longevity will be depleted.

Aircraft power requirement becomes relatively low during cruising, descent, and landing. The following equation is designed to quantify the FC life loss under low load and idle working conditions:

$$\varphi_l(P_{fc}) = 3.53\times10^{-7} \cdot \Delta t \cdot \frac{P_{fc,rat} - P_{fc}}{P_{fc,rat}} \tag{3}$$

Aircraft power requirements frequently change while taking off, landing, and under complex environments. In this study, the roughness of the FC output power profile is used to evaluate the stability of FC working conditions:

$$\varphi_v(P_{fc}) = 3.51\times10^{-7} \cdot \Delta t \cdot \frac{\int_{t_0}^{t_0+\Delta T} \left|\frac{\mathrm{d}P_{fc}}{\mathrm{d}t}\right| \mathrm{d}t}{\int_{t_0}^{t_0+\Delta T} k_{fc}^{\max} \mathrm{d}t} \tag{4}$$

where: $k_{fc}^{\max}$ is the maximum FC output power changing rate. The smoother the FC output power profile, the less the FC life is depleted.

Based on the above analysis, FC life loss during aircraft operation can be quantified by the following equation:

$$\Delta L_{fc}(P_{fc}) = \frac{\varphi_h(P_{fc}) + \varphi_l(P_{fc}) + \varphi_v(P_{fc})}{10\%} \tag{5}$$

It should be figured out that the FC life span ends when its voltage decline reaches 10%. In this study, the FC life loss is finally converted to aircraft hydrogen cost to enable the active aging mitigation in energy management:

$$\Delta M_{H_2}^{fc,ag} = \frac{\Delta L_{fc}\, \mathrm{Pr}_{fc}^{unit} \cdot P_{fc,rat}}{C_{\mathrm{H}_2}} \tag{6}$$

here, the price of the FC stack is simplified to be related to its rated power. $\Pr_{fc}^{unit}$ is the unit price of the FC stack, C_{H_2} is the hydrogen weight price.

D. Aircraft battery energy storage system aging model

The aging of BESS is quantified in this part to realize optimal aircraft power management. According to previous literature [35-37], DoD and Crate are the common degradation parameters that characterize battery aging. In qualitative analysis, the higher the value of DoD and Crate, the more the battery life will be depleted. The empirical cycle depth stress model that models battery life loss by quantifying the impact of DoD and Crate has been widely adopted and well recognized by the academic [38, 39] and industrial [40] sectors. It has been proven effective in inferring the aging characteristics of BESS in energy bidding [41], renewable energy systems [42, 43], and electric vehicles [44] under different working conditions. Therefore, both the influences of charging/discharging rate (Crate) and depth of discharge (DoD) are considered to model aircraft battery aging. The empirical equivalent battery degradation model in [45] is used to characterize the impact of DoD on aircraft battery aging under different working conditions. The total cycle life of the aircraft battery is assumed to be a constant, and the influence of DoD is quantified by the following equation:

$$Q_{loss} = \frac{\int_{t_0}^{t_0+\Delta T} P_{bat}\,\mathrm{d}t}{3600 \cdot N_{cycle} \cdot Q_{\mathrm{bat}}} \quad (7)$$

where: Q_{bat} and Q_{loss} are the rated capacity and the quantified cycle life loss of the battery. N_{cycle} is the rated cycle life of the battery under 1C discharging current. Meanwhile, based on the battery aging experiment carried out in [45], the influence of Crate on battery life is quantified by the following function:

$$\hbar(C_{rate}) = \varepsilon_1 C_{rate}^3 + \varepsilon_2 C_{rate}^2 + \varepsilon_3 C_{rate} + \varepsilon_4 \quad (8)$$

where: $\varepsilon_1 = 0.001442$, $\varepsilon_2 = 0.003205$, $\varepsilon_3 = 0.1009$, and $\varepsilon_4 = 0.8907$ are four Curve fitting coefficients, which are used to approximate experiment points. C_{rate} is the working Crate of aircraft BESS. Battery life loss in aircraft energy management strategies is quantified by factoring the impact of DoD and Crate together, which can be represented by the following equation:

$$\Delta L_{bat} = \frac{\int_{t_0}^{t_0+\Delta T} P_{bat} \cdot \hbar(P_{bat})\,\mathrm{d}t}{3600 \cdot N_{cycle} \cdot Q_{\mathrm{bat}}} \quad (9)$$

In this study, BESS aging cost is also converted to aircraft hydrogen consumption to facilitate anti-aging energy management. The following equation is used to calculate aircraft equivalent hydrogen consumption cost by battery aging:

$$\Delta M_{H_2}^{bat,ag} = \frac{\Delta L_{bat} \Pr_{bat}^{unit} \cdot Q_{bat}}{C_{\mathrm{H}_2}} \quad (10)$$

where: $\Pr_{bat}^{unit}$ represents the unit price of the battery.

III. Multi-objective aircraft energy management scheme

With the power system topology in Section II, aircraft power requirements can be co-satisfied by FC stack and BESS to improve efficiency and economy. However, a properly designed power distribution algorithm is also indispensable to enable this benefit. This section develops a multi-objective aircraft energy management scheme.

The established multi-objective aircraft energy management optimization model is presented in Fig. 3. Firstly, the flight path and cycle condition are predefined before taking off, and the generated aircraft power requirement profile is used as the input of the aircraft energy management model to derive the optimal energy storage system operation schedule. Then, based on the established equivalent hydrogen consumption models, aircraft power system state and operation cost in different energy management strategies are estimated. On the basis of the calculated aircraft power requirement and the estimated power system states, optimal aircraft energy management is modeled as a multi-objective optimization problem. Dynamic Programming (DP) [46] is one of the most commonly used mathematical methods for solving multi-stage decision problems in complex nonlinear systems. Therefore, this section establishes an optimal hybrid fuel cell aircraft power management model based on the DP algorithm.

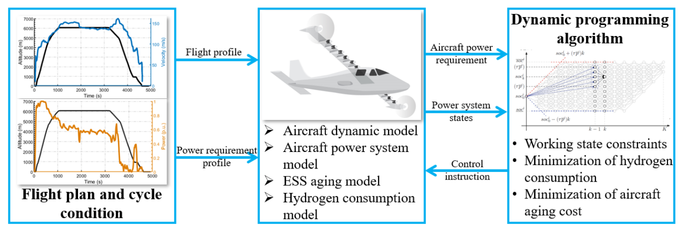


Fig. 3. The developed dynamic programming algorithm-based multi-objective aircraft energy management method.

In this paper, optimal aircraft power management is regarded as a multi-stage decision problem, and the state variable $\mathbf{S}_k$ is designed as battery energy state SoC_k and fuel cell output power state $P_{fc,k}$ at each interval:

$$\mathbf{S}_k = \left[SoC_k, P_{fc,k} \right] \quad (11)$$

For a predefined flight cycle, the energy demand at any time is a known quantity. Aircraft power system state changes from the initial state $S_0 = \left[SoC_0, P_{fc,0} \right]$ during taking off to the final state $S_N = \left[SoC_N, P_{fc,N} \right]$ after landing. The length of the decision step in aircraft management is designed as 1 s, and time is discretized as {0 s, 1 s, …, k s, …}.

The decision variables in aircraft power system topology shown in Fig. 1 (b) and (c) are selected as the change of battery output power and FC output power, respectively, as described in Eq. (12) and (13). While as for aircraft power system topology in Fig. 1 (d), the control variables are designed as both the change of FC output power and battery output power to enable flexible power flow control between different energy storage sectors, as described in Eq. (14):

$$\mathbf{u}_k = \left\{ \Delta P_{fc,k} \right\}, k = 0,1,2,\cdots,N \quad (12)$$

$$\mathbf{u}_k = \left\{ \Delta P_{bat,k} \right\}, k = 0,1,2,\cdots,N \quad (13)$$

$$\mathbf{u}_k = \left\{ \Delta P_{fc,k}, \Delta P_{bat,k} \right\}, k = 0,1,2,\cdots,N \quad (14)$$

The output power of FC and battery are calculated by the following equations:

$$P_{fc,k} = P_{fc,k-1} + \Delta P_{fc,k} \quad (15)$$

$$P_{bat,k} = P_{bat,k-1} + \Delta P_{bat,k} \tag{16}$$

Aircraft power requirements should be strictly satisfied by the FC stack and battery pack dynamically. The power balancing state of aircraft hybrid power systems with BA, FCA, and FA topologies are represented in Eq. (17), (18), and (19), respectively:

$$P_{d,k} = \eta_{pmsm} \cdot (P_{fc,k} + \eta_{bat} \cdot P_{bat,k}) \tag{17}$$

$$P_{d,k} = \eta_{pmsm} \cdot (\eta_{fc} \cdot P_{fc,k} + P_{bat,k}) \tag{18}$$

$$P_{d,k} = \eta_{pmsm} \cdot (\eta_{fc} \cdot P_{fc,k} + \eta_{bat} \cdot P_{bat,k}) \tag{19}$$

where: P_d is the power requirement of the aircraft engine. η_{pmsm}, η_{bat}, and η_{fc} are the efficiency of the converters of the PMSM motor, battery, and FC stack. Meanwhile, based on the characteristics of the FC stack, the following constraints are used to limit its maximum output power and load variation rate:

$$0 \le P_{fc,k} \le P_{fc,rat} \tag{20}$$

$$-k_{fc}^{\max} \le \Delta P_{fc,k} \le k_{fc}^{\max} \tag{21}$$

Similarly, battery output power and SoC state are limited by the following constraints in the established energy management model:

$$-P_{bat}^{ch} \le P_{bat,k} \le P_{bat}^{ds} \tag{22}$$

$$SoC_{\min} \le SoC_k \le SoC_{\max} \tag{23}$$

where: P_{bat}^{ch} and P_{bat}^{ds} are the maximum charging and discharging power of the battery; $SoC_{\min}$ and $SoC_{\max}$ are the permitted minimum and maximum SoC state.

The relation between FC output power and battery SoC is determined by the following equation:

$$\mathrm{SoC}_k = \mathrm{SoC}_{k-1} - \frac{P_{bat,k} \cdot \Delta t}{Q_{bat}} \tag{24}$$

where: $P_{bat,k}$ is calculated based on the (17) ~ (19) according to different aircraft power system configurations.

The established energy management model considers the improvement of aircraft hydrogen efficiency, the protection of FC longevity, and the mitigation of battery life loss to improve the total economy. Therefore, the equivalent hydrogen consumption of the aircraft hybrid power system is designed as the instantaneous cost function, which can be expressed as the sum of the FC direct hydrogen consumption and the aircraft equivalent hydrogen consumption cost by system aging:

$$L = \Delta M_{H_2}^{fc} + \Delta M_{H_2}^{fc,ag} + \Delta M_{H_2}^{bat,ag} \tag{25}$$

where: $\Delta M_{H_2}^{fc}$ is the FC stack instantaneous hydrogen consumption, which can be calculated according to (1); $\Delta M_{H_2}^{fc,ag}$ and $\Delta M_{H_2}^{bat,ag}$ are the equivalent hydrogen consumption caused by FC and BESS aging. The optimal energy management strategy is derived by minimizing cost function in a multi-time step decision process, which can be represented as:

$$J_k(\mathbf{S}_k) = \min_{u_k}\left[L(\mathbf{S}_k, \mathbf{u}_k) + J_{k+1}^{*}(\mathbf{S}_{k+1}) \right] \tag{26}$$

where: J_k is the multi-step cost function from k to the last decision step.

IV. Results and Discussions

In this section, qualitative, quantitative, and sensitivity analyses are carried out to compare the performance of different aircraft power system topologies and validate the effectiveness of the developed aircraft energy management method.

A. *The studied electric aircraft with HESS*

An experimental electric aircraft, NASA X-57 Maxwell, is selected as the research objective of this study. As shown in Fig. 4, X-57 Maxwell is an all-electric aircraft powered by 14 distributed propellers on wing leading edges. The detailed parameters of the studied electric aircraft are summarized in Table I. In this study, aircraft operation is co-simulated based on flight conditions, aircraft aerodynamics, and a hybrid power system model. Firstly, the COESA atmosphere simulation model in [47] is used to simulate aircraft aerodynamic characteristics in the flight mission profile, such as airflow velocity, air density, air viscosity, and air compressibility. The power requirement of the studied aircraft under different working conditions is further simulated based on the open-access aircraft dynamic simulation model established in [48]. At last, aircraft power requirements are distributed between the FC stack and BESS according to power system topologies and energy management strategies. Based on the above experimental platform, qualitative and quantitative analyses are carried out in this section to analyze the performance of different aircraft power system topologies and validate the developed energy management scheme.

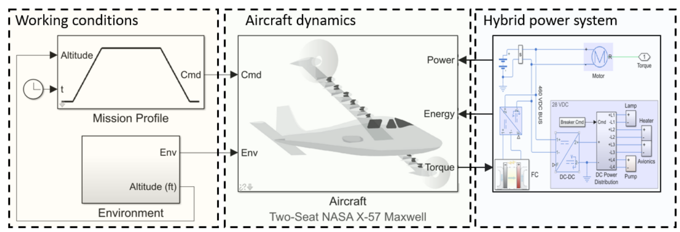


Fig. 4. The power requirement simulation of the studied NASA X-57 Maxwell electric aircraft [49].

Table I. Parameters of aircraft propulsion and hybrid energy storage system.

Category	Parameters	Value	Parameters	Value
Aircraft	Aircraft mass/kg	770	Wing area/m^2	6.15
	Climb speed/m/s	43	Coefficient of drag	0.05
	Cruise speed/m/s	70	Coefficient of lift	0.6
Engine	Main engine power/kW	2×48.1	Auxiliary engine power/kW	12×14.4
	Engine efficiency	0.95		
	Thrust Time Constant/s	0.01	Thrust Efficiency/%	92
HESS	FC rated power/kW	100	Energy density/kWh/kg	2.3
	Battery capacity/kWh	25	Energy density/kWh/kg	0.12

B. *Aircraft power system working state analysis*

In this study, the statistical aircraft operation simulation model in [50], which is generated by analyzing 6000 more regional flights is used to simulate the operation of the studied FCHEA. Based on flight altitude and velocity profiles, aircraft power requirements are simulated based on the dynamic simulation model in [48], which is built with the Simscape toolbox. Fig. 5 shows aircraft altitude, velocity, and power requirement profiles in a typical flight mission, which is used to evaluate the performances of FCHEA with different power system topologies. On the basis of the established aircraft power system mathematical model and energy management scheme, aircraft power requirements are distributed between the FC stack and BESS.

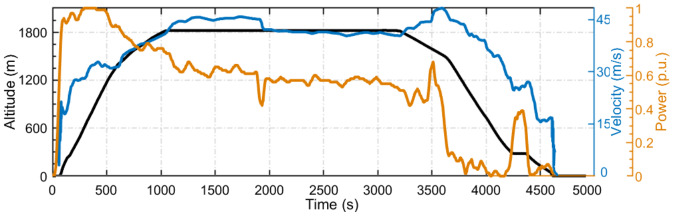


Fig. 5. Altitude, velocity, and power requirement profiles of the studied aircraft in a typical flight mission.

The working state of aircraft FC stack and BESS in the studied typical flight mission is shown in Fig. 6. Performances of five different aircraft power system configurations, including FC aircraft (Case 0), hybrid full passive topology (Case 1), hybrid battery active topology (Case 2), hybrid FC active topology (Case 3), and hybrid full active topology (Case 4), are compared in this section. The distribution of FC output levels and load variation rates in the flight under different aircraft power system configurations are compared in (a) and (b). Without ancillary power provided by BESS, the FC stack needs to fully cover aircraft power requirements. In Case 0, the FC stack works under low-efficiency states (light and heavy load area) for more than 45% of the entire flight, which indicates the low hydrogen efficiency of the aircraft. The deployment of HESS significantly improves the energy management flexibility of aircraft power systems. In Cases 1 and 2, 8.7% and 25.3% more FC working point under uneconomic area can be moved to the high-efficiency area by utilizing the power ancillary services provided by aircraft BESS. Meanwhile, compared to Case 0 which uses the FC as the only power supply device, FC average load variations are also reduced by 7.4% and 25.3%, which indicates that FC is effectively protected. However, FC output is not actively controlled in FN and BA power system topologies, which limits the efficiency of FC operation management. In Cases 3 and 4, FC's working points in low-efficiency areas are further reduced by 13.7% and 16.5% by actively regulating its output power. As a result, the aircraft FC stack can efficiently work for 90% more time in the whole flight, which validates the effectiveness of the studied FCA and FA power system topologies and the proposed energy management scheme. Meanwhile, FC stack load variation rates are also reduced by 7.2% and 8.1% in Cases 3 and 4, validating that the FC is also effectively protected.

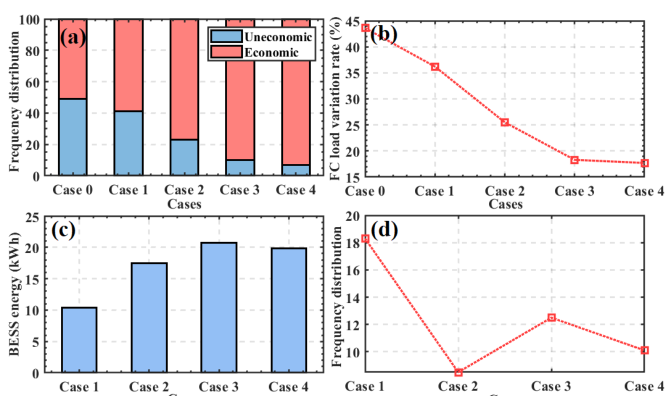


Fig. 6. Aircraft energy storage system working states in the studied typical flight mission. (a) FC stack hydrogen efficiency; (b) FC average load variation rate; (c) BESS throughout energy output; (d) BESS working states under high Crate (>3C) conditions.

Fig. 6 (c) and (d) compare BESS working states in the flight under different aircraft hybrid power system configurations. In this study, BESS is proposed to provide ancillary power for the aircraft hybrid power system to improve the operation economy of the FC stack. In Case 1, only 10.7 kWh of ancillary power can be provided, which indicates that BESS energy storage can hardly be reasonably utilized in aircraft with FN topology. In BA, FCA, and FA topologies, the battery output power can be actively regulated. Accordingly, the provided ancillary power is improved by 40.6%, 49.7%, and 47.5% respectively, which validates the effectiveness of active power system topologies and the proposed energy management scheme in scheduling aircraft BESS operation. Meanwhile, the active power system topologies also show great effectiveness in protecting BESS from the impact of high Crate working conditions. As shown in (d), compared to Case 1, battery working points under high Crate conditions are reduced by 51.6%, 33.5%, and 43.4%, which indicates that battery aging can be mitigated in Cases 2, 3, and 4. In summary, the FCA topology greatly outperforms FP and BA configurations in improving aircraft hydrogen economy and mitigating energy storage system aging. It realizes flexible aircraft energy management and achieves around 95% overall performance compared to the FA topology with a simplified power system structure.

C. Quantitative performance analysis

Aircraft aging cost and hydrogen efficiency with the developed energy management method are further quantitatively compared in Table II. The H_2 efficiency of FC aircraft is only 14.05 kWh/kg because the FC stack works in uneconomic areas (light and heavy loads) most of the time in the flight mission. Meanwhile, the high load variation rate also results in accelerated FC aging, and more than 1.891×10^{-2}% of FC life is depleted. The use of BESS devices can significantly improve aircraft hydrogen efficiency and mitigate aging costs. In full passive topology, aircraft hydrogen efficiency can be improved by 12.9%. Furthermore, the life loss of the FC stack average is reduced by also reduced by 41.1%, which validates the necessity of using BESS in FCHEA.

TABLE II. PERFORMANCE COMPARISON OF DIFFERENT AIRCRAFT POWER SYSTEM TOPOLOGIES.

Topology	FC load variation rate	Battery Crate	Hydrogen Efficiency (kWh/kg)	FC aging $\times10^{-2}$ (%)	Battery aging $\times10^{-2}$ (%)
FC aircraft	43.6	---	14.05	1.891	---
Full passive	36.2	2.13	15.86	1.115	2.895
Battery active	25.5	1.21	16.43	0.833	2.217
FC active	18.3	1.84	17.15	0.651	2.651

With the developed energy management strategy, the total economy of aircraft power systems is further improved. Compared to passive topology, aircraft hydrogen efficiency and FC protective performance can be improved by 3.6% and 25.3% in BA topology. Furthermore, BESS life loss is also reduced by 23.4%, which indicates that battery aging can be significantly mitigated by active power system topology. In FC active topology, aircraft FC stack working condition is further optimized, and its load variation rate and aging cost are reduced by 28.2% and 21.8% compared to BA topology. However, because the battery working state cannot be actively controlled in FCA topology, aircraft BESS aging cost is evaluated by 19.6% in the flight mission. The full active topology realizes both the best operation scheduling of FC stack and BESS compared with BA and FCA topologies. As shown in Table II, aircraft H_2 efficiency reaches 17.28 kWh/kg, which indicates that the FC stack can always work under economic area. Meanwhile, FC and BESS life losses are also reduced to 0.642×10^{-2}% and 2.154×10^{-2}%, respectively, which validate the effectiveness of the developed aircraft power system scheme.

D. Sensitivity analysis

The sensitivity analysis is further carried out in this study to validate the generalization performance of the proposed energy management scheme facing different power requirements. According to previous literature [51-54], the flight range, cruising velocity, and cruising altitude are the three most significant parameters that impact the performance of aircraft power systems. Therefore, three independent scenarios are further carried out by changing the flight range, cruising velocity, and cruising altitude to 7 different levels. In Scenario 1 in Table III, the flight range is shortened and extended from -45% to 45% in cases 1 to 7 to validate the effectiveness of the proposed energy management scheme in reasonably utilizing BESS energy storage capacity. Aircraft hydrogen economy can be greatly impacted by the peak power requirement that appears in the climbing stage of the flight. Therefore, the flight altitude is also changed from -45% to 45% in 7 different cases in Scenario 2 to validate the effectiveness of the proposed energy management scheme in facing different aircraft peak power requirements. The preset simulation parameters in different cases are presented in Table IV. Further, the cruising velocity influences the aircraft's average power requirement level in the whole flight. To validate the performance of the developed method under different power requirement levels, aircraft cruising velocity is also changed in 7 different cases in Scenario 3 according to Table V.

TABLE III. THE CHANGE OF FLIGHT RANGE IN SCENARIO 1.

Test Scenario 1	Case 1: -45%	Case 2: -30%	Case 3: -15%	Case 4: 0%	Case 5: 15%	Case 6: 30%	Case 7: 45%
Flight range (km)	88	112	136	160	184	208	232

Cruising velocity=40 m/s, Cruising altitude=1800 m.

TABLE IV. THE CHANGE OF CRUISING ALTITUDE IN SCENARIO 2.

Test Scenario 2	Case 1: -45%	Case 2: -30%	Case 3: -15%	Case 4: 0%	Case 5: 15%	Case 6: 30%	Case 7: 45%
Cruising altitude (m)	990	1260	1530	1800	2070	2340	2610

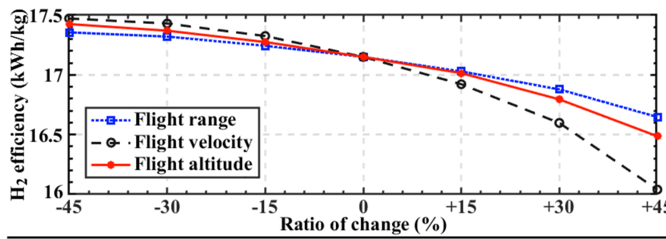
Flight range=160 km, Cruising velocity=40 m/s.

TABLE V. THE CHANGE OF CRUISING VELOCITY IN SCENARIO 3.

Test Scenario 3	Case 1: -45%	Case 2: -30%	Case 3: -15%	Case 4: 0%	Case 5: 15%	Case 6: 30%	Case 7: 45%
Cruising velocity (m/s)	22	28	34	40	46	52	58

Flight range=160 km, Cruising altitude=1800 m.

Fig. 7 shows the change in aircraft hydrogen efficiency in the studied 21 cases in 3 scenarios. The increase in flight range and velocity elevates aircraft power requirements during cruising, where FC can work under the high-efficiency area even without ancillary power provided by BESS. Therefore, the decrease in aircraft hydrogen efficiency can still be limited to 2.93% and 3.87% when the extension of flight range and velocity reaches 45% in Scenarios 1 and 3. By contrast, the change of flight altitude increases the power requirement peak period during climbing, where the battery is required to provide power ancillary service frequently. With limited energy storage capacity in BESS, the FC stack needs to work under the heavy load low-efficiency area independently. In Scenario 2, the aircraft hydrogen efficiency drop reaches 6.48% with the increasing flight altitude. Limited by the energy storage capacity of BESS, aircraft hydrogen efficiency decreases as flight power requirement improves. It should be noted that aircraft hydrogen efficiency steadily changes in all three scenarios, which validates that the energy management algorithm can keep stable operation under the variation of aircraft working conditions.



Ratio of change in hydrogen efficiency (%)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Scenario 1: Range	1.20	0.99	0.55	0.00	-0.71	-1.58	-2.93
Scenario 2: Altitude	1.88	1.63	1.02	0.00	-1.33	-2.64	-6.48
Scenario 3: Velocity	1.60	1.28	0.73	0.00	-0.79	-2.07	-3.87

Fig. 7. The change of aircraft hydrogen efficiency under different flight ranges, velocities, and altitudes.

With the reduction of aircraft power requirement, more energy storage capacity in BESS can be utilized to reduce the working pressure of the FC stack. As a result, aircraft hydrogen efficiency increases with the reduction of flight range, velocity, and altitude. When the ratio of change reaches 45% in Scenario 1, 2, and 3, aircraft hydrogen efficiency can be improved by 1.20%, 1.88%, and 1.60%, which indicates that the proposed energy management scheme can flexibly schedule the operation of aircraft BESS under different working conditions.

In this study, we mainly focus on the aircraft design and planning stage rather than the operation control stage. Future work can be conducted on deploying the off-line strategy in real-time aircraft energy management through model-predictive control, artificial intelligence, and rule extraction methods.

V. CONCLUSION

This paper provides a new approach to configure the optimal hybrid power system, which is combined with a novel energy management scheme to optimize hybrid power systems for FC-battery hybrid electric aircraft. Four different aircraft power system topologies are designed to facilitate the flexible power flow control and energy management strategies deployment. The optimal aircraft energy management is realized by a dynamic programming model with the improvement of aircraft efficiency and the reduction of aging costs as optimization objectives. The performance of different aircraft power system topologies and the effectiveness of the established energy management model are evaluated in detail for a NASA X-57

Maxwell. Key findings and outcomes are:

(1) The active power system topologies demonstrated significant improvements in hybrid aircraft performance compared to passive structures. These topologies allowed for the flexible distribution of power requirements among different sectors, enabling economical aircraft energy management.

(2) The established equivalent hydrogen consumption model and the proposed multi-objective aircraft energy management scheme were proven to be highly effective in optimizing the operation of FCHEA (Fuel Cell Hybrid Electric Aircraft). By minimizing aircraft equivalent hydrogen consumption through energy management, aircraft driving system energy consumption, FC aging cost, and BESS aging cost could be effectively reduced.

(3) The proposed active power system topology and energy management scheme facilitated the efficient operation of the aircraft FC stack under varying power requirements. Through the appropriate distribution of power requirements between the FC stack and battery throughout the flight mission, aircraft hydrogen consumption was significantly reduced.

Our results provide a new approach to developing practical solutions for aircraft power system design and serve as a reference for real-time aircraft energy management in real-world applications. The findings highlight the strengths of active power system topologies and the effectiveness of the energy management strategies proposed, contributing to the advancement of hybrid aircraft technology. These insights can guide future aircraft designers and operators in optimizing their systems for improved performance and cost efficiency.

In conclusion, this study has shed new light on the optimization of hybrid power systems for FC-battery hybrid electric aircraft. The findings contribute to the field and are expected to inspire the development of more efficient and sustainable aircraft power systems in the future.

APPENDIX

This Appendix details the model-solving method for deriving the optimal aircraft energy strategies.

The dynamic programming method is adopted in this paper to derive the optimal aircraft energy management strategy by solving the established mathematical optimization model in (26). Compared to advanced optimization methods, such as heuristic algorithms, artificial intelligence algorithms, and gradient optimization schemes, dynamic programming is a more mature and stable method for achieving optimal solutions [55, 56]. Further, dynamic programming has also been integrated into an open-access toolbox: Generic Dynamic Programming Matlab Function [60], which enhances the repeatability of the optimization model. For the above reasons, it has been commonly used in verifying BESS energy management optimization schemes in electric vehicles [57], grid energy storage systems [58], and intelligent transportation systems [59].

Based on the above discussion, the Generic Dynamic Programming MATLAB Function in [60], which is specially designed for solving nonlinear BESS operation optimization problems, is employed in this study to solve the established aircraft power system energy management model. As shown in Fig. 8, the optimization is decomposed into several subproblems to derive the optimal aircraft energy management strategy. In model solving, the global optimization problem in aircraft energy management is transformed into an N-level dynamic decision-making process. From the final state $\mathbf{S}_N$ to the initial state $\mathbf{S}_0$, the optimal decision variable trajectories are solved recursively by minimizing the value of the cost function $J_k(\mathbf{S}_k)$ step by step. In each stage, the system state variable is updated from $\mathbf{S}_{k-1}$ to $\mathbf{S}_k$ based on the decision variable $\mathbf{u}_k$. The combination of decisions in each sub-stage is the formulated dynamic programming strategy, which can be applied to the controlled object to achieve the optimal result in the scheduling period.

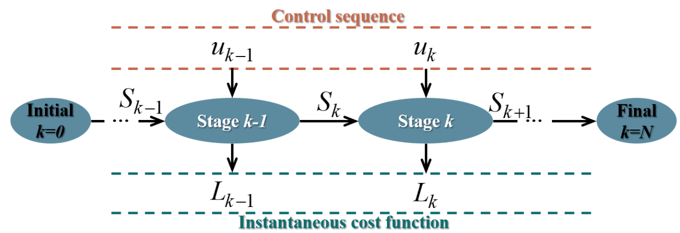


Fig. 8. The solving of the established aircraft power system energy management model based on dynamic programming.

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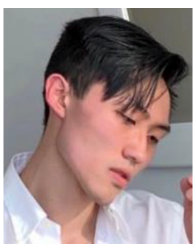

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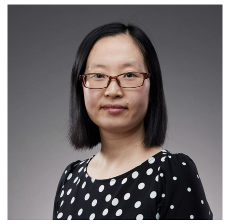

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