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Optimal sizing of a passive hybridization fuel cell – battery

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Abstract — In order to size the elements of a storage system for an aeronautical application, a simplified model of a High Temperature Proton Exchange Membrane Fuel cell (HT-PEMFC) - Battery passive hybridization has been developed. It is compared to a dynamic model for validation. Sizing, done by a combinatorial algorithm, must meet a dual objective: on the one hand, satisfy the mission profile, and on the other hand, minimize the mass of the system. Several battery technologies, NiCd or lithium-ion, are studied in order to analyze the advantages and disadvantages of each in such hybridization. The characteristics of the battery appear to be decisive in the sizing of the system. The fuel cell preheating, provided by the battery, also constrains its size.

Keywords — Hydrogen, Fuel cells, High Temperature PEMFC, Battery storage, More electric aircraft, Passive hybridization

I. INTRODUCTION

The need to sharply reduce greenhouse gas emissions to minimize the global warming on the one hand, and the dependence on limited fossil fuel reserves on the other hand, drives the need to develop carbon-free energy systems. This is particularly the case in the aeronautic sector, which has historically been growing strongly, and is considered to be responsible for around 2.4 % of the global CO₂ emission in 2018 [1].

The fuel cell makes it possible to produce electricity, heat and water from hydrogen and oxygen. Quiet, capable of using hydrogen or other compatible fuels produced from renewable sources, it appears to be a promising solution. Among the fuel cell technologies, the High Temperature Proton Exchange Membrane fuel cell (HT-PEMFC) technology, operating at 160 °C, has great advantages: the heat produced is more easily recoverable and the cooling system is more compact than the Low Temperature PEMFC. The HT-PEMFC also presents a good tolerance to impurities, in particular those present in the hydrogen obtained by reforming, such as carbon monoxide [2]. The use of a polymer membrane containing phosphoric acid used as an electrolyte eliminates the need for a gas

humidification system. An energy system using a HT-PEMFC is particularly interesting for on-board applications by reducing the size of the auxiliaries, by facilitating the use of reformed hydrogen and finally by allowing on-board multi-generation: electricity, heat, water and inert gas [3]. However, this technology still presents low specific power and too rapid aging [2], two limiting obstacles in the context of on-board applications.

One possible solution of these two limitations consists in hybridizing the fuel cell with a battery to take advantage of its high specific power. The battery provides a degree of freedom in the system sizing, allowing to reduce the fuel cell size, and improves its lifetime. In addition, in an on-board system, the energy required for the fuel cell start and stop phases can be supplied by the battery. If the battery is only used as a power source component, and not as an energy source, its initial state of charge (SoC) must be equal to the final one. However, it may be used in some cases as an energy source, for example in the case of a fuel cell failure, adding some redundancy in the system.

Hybridization is most often done through static converters providing a DC current bus (Fig. 1 a), which makes it possible to regulate the operating point of each component independently and therefore to avoid degrading operating conditions for the fuel cell, for example long operation at high cell voltage. The battery also protects the fuel cell by providing rapid variations of power to the load, which damage the fuel cell if its auxiliaries are too slow to respond. It is especially the case with a H₂/Air fuel cell for which the inertia of the air compressor must be taken into account. However, the operation of power converters causes energy losses and requires the implementation of complex

control strategies. The operation of power converters also results in current harmonics which may accelerate the fuel cell aging [4]. Finally, power converters are additional components that increase the mass of the system and which may fail.

The direct electrical connection of the fuel cell and the battery, in parallel, called passive hybridization (Fig. 1 b), eliminates at least one converter. Passive hybridization therefore may reduce energy losses, mass and the complexity of the system. No control strategies are needed as the system is self-managed. In addition, the ripple currents created by the remaining converters are supplied by the fuel cell - battery assembly and no longer by the fuel cell alone. The feasibility of passive hybridization has been shown for HT-PEMFC and LT-PEMFC, both in an automotive and aeronautical context [5, 6].

Other types of hybridization use only one converter between the fuel cell and the battery (Fig. 1 c) to regain some control over the power sharing between the two components. However, as in the indirect hybridization topology, these architectures require the implementation of a converter control strategy to ensure that the components provide the power needed and stay into their operating limits. This strategy must include a regulation of the battery SoC to compensate its losses.

The main problem associated with passive hybridization is the loss of control over the system during in operation. Indeed, the absence of a converter between the fuel cell and the battery removes a degree of freedom in operation. It is not possible to control the operating point of the components by this means. The sizing of the system is therefore crucial in order to ensure that the system can safely satisfy the intended mission. The sizing is more complex because the parallel fuel cell - battery association is a new physical object whose electrical behaviour and operating limits depend on the electrical characteristics of the components. The variation of these electrical characteristics caused by aging phenomena or operating variations, and the inevitable uncertainties about the real mission, must be taken into account during the design phase to ensure the robustness of the system. Modeling of the hybrid system therefore appears as an essential step for the design phase and for studying its performances.

This paper presents the sizing of a passive hybridization with a HT-PEM fuel cell and a battery. An algorithm is used in order to obtain the optimal sizing of the hybridized system according to a load profile. To limit the computation time, the electrical models of the fuel cell and the battery are based on simplified models developed on Matlab-Simulink software. To validate this simplification, an analysis is carried out to compare the accuracy of the simplified models with dynamic models developed on Simulink. In section III, the proposed sizing method is presented. The results for different battery technologies are compared taking into account several criteria such as mass and system performance.

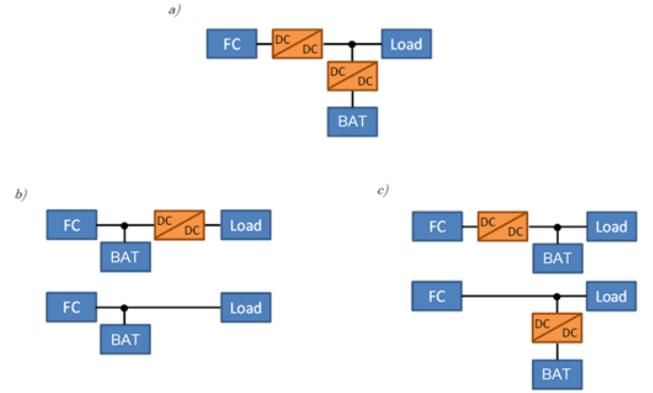


Fig. 1. Types of connection of a fuel cell - battery hybridization.

II. SYSTEM MODELING

A. Topology

The hybrid system studied is composed of a HT-PEMFC H₂/Air directly connected to a battery through two contactors K_1 and K_2 .

Each component is connected to the load through a power cable. The characteristic of the cable has a prime importance for the current sharing between the components in passive hybridization mode as recalled in [7]. However, to simplify the analytical resolution of the hybridized system, the cable is modelled by a constant resistance R_{cable} (the contact resistance of the contactor is included in R_{cable}). In this study, R_{cable} is fixed at 0.03 mΩ.

B. Mission

The hybridized system has to supply an electrical load without regenerative phases, in an aeronautical environment, for 5 hours. The average and maximum power are respectively 0.8 kW and maximum power 1.9 kW (without consumption of fuel cell auxiliaries). The maximum power variation ramp is 1.5 kW/s.

The battery is alone when starting up the fuel cell preheating phase, which represents a significant amount of energy, as well as when stopping in order to interrupt it. At the end of the mission, before stopping and inverting the fuel cell, the two components are left connected together so that the fuel cell can charge the battery up to its initial SoC, in order to retain the "source of power" behaviour of the battery. To charge the battery, the OCV of the fuel cell must be greater than the OCV of the battery with the charging speed depending on the gap between the OCVs. The contactors are not used at any other time during the mission.

The required power for the fuel cell auxiliaries $P_{fc_{aux}}$ is considered as a linear function of the fuel cell power P_{fc} as mentioned in (1) where $P_{fc_{max}}$ refers to the maximum power of the fuel cell stack. Note that the maximum cell power density considered in this study is equal to 0.45 W/cm².

$$P_{fc_{aux}} = 0.02 * P_{fc_{max}} + 0.13 * P_{fc} \quad (1)$$

C. Dynamic model

A dynamic model of a HT-PEM fuel cell - LiFePO₄/graphite battery passive hybridization (Fig. 2) has been developed, using close equivalent electrical models for the fuel cell [8] and the battery [9]. As the resolution time of this model is about 10 times higher than the simplified model detailed in the next section, the sizing results of this dynamic model are only used in this paper to validate the sizing obtained with the simplified model.

This dynamic model allows to observe the current dynamic sharing between the fuel cell and the battery during a rapid variation in the power required by the load, or when these two components are connected with the closing of K_1 . Each cable is modeled by an R_{cable} resistor, but it would be possible to add an equivalent inductance in series as done in [8] in order to be able to represent the inductive effect of the cable on the dynamic sharing of currents between fuel cell and battery. An equivalent cabling capacity C_{cable} , in the order of 1 nF [10], has been added to enable numerical resolution. The dynamic model simulates the internal currents' evolution, in particular the faradic current i_f which corresponds to the main reaction current in each component. This model also allows observing the filtering effect of the electrochemical double-layer phenomena, represented here by an equivalent capacity C_{dc} . The SoC is calculated by integrating the faradic current of the battery i_{fbatt} over time. A rapid change of the faradic current of the fuel cell i_{ffc} risks degrading the fuel cell due to starvation phenomena specially happening when the air compressor is not responsive enough and does not provide the necessary amount of oxygen. Diffusive phenomena are represented by an equivalent capacity C_{diff} .

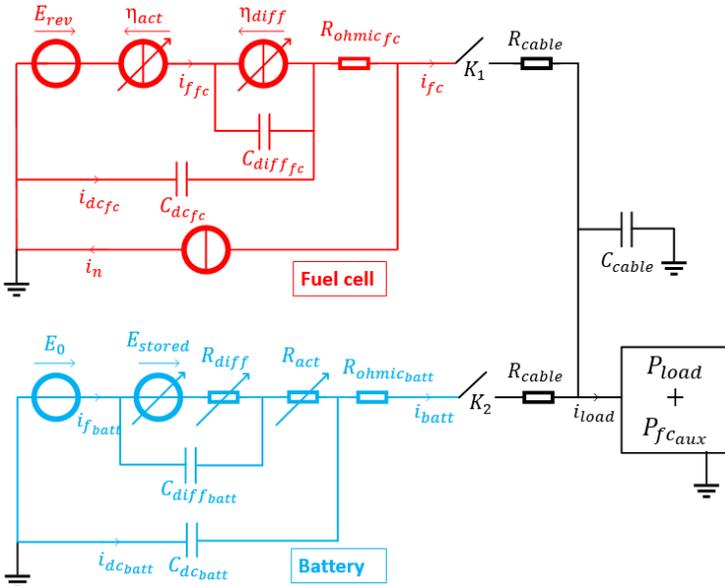


Fig. 2. Equivalent electrical circuit of the dynamic model of a fuel cell - battery passive hybridization.

The parameterization of the fuel cell and the battery dynamic models was carried out from test data. For the fuel cell it consists in quasi-static polarization curve, electrochemical impedance spectroscopy and current sweeping of the operating range at different frequencies in order to identify the values of the equivalent capacities. For the battery, a current profile containing static and dynamic solicitations, at different SoCs, is used: the hybrid pulse power characterization profile (HPPC) [11].

D. Simplified model

The dynamic model was simplified in order, on the one hand, to solve the system analytically, and, on the other hand, to have a fast numerical resolution easily integrated into an optimization sizing process. The equivalent electrical circuit is shown in Fig. 3.

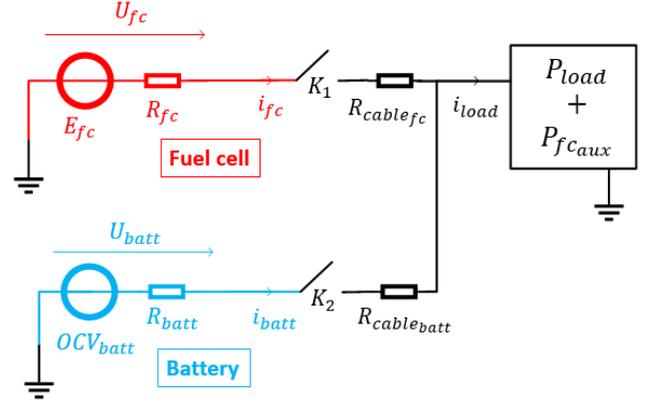


Fig. 3. Equivalent electrical circuit of the simplified model of a fuel cell - battery passive hybridization.

1) Fuel cell model

The fuel cell stack voltage E_{fc} and internal resistance R_{fc} depends on the number of cells in series $Nb_{fcseries}$.

$$E_{fc} = Nb_{fcseries} * E_{fc_{cell}} \quad (2)$$

$$R_{fc} = Nb_{fcseries} * R_{fc_{cell}} \quad (3)$$

The voltage $E_{fc_{cell}}$ of the HT-PEMFC H₂/Air is governed by its polarization curve (Fig. 4). The evolution of $E_{fc_{cell}}$ can be assumed to be linear for a current density j_{fc} greater than 0.1 A/cm². However, this assumption remains valid if the current density is not too high. Indeed, for high current density, the polarization curve is more strongly influenced by diffusion phenomena (the curve is not linear). Moreover, at very low and high current densities, aging phenomena in the fuel cell are accelerated [2], thereby limiting the lifetime of the fuel cell. For these reasons, in this study, the maximum current density is limited to 0.7 A/cm². For this current density operating area, the simplified model of the fuel cell can be expressed as:

$$U_{fc} = E_{fc} - i_{fc} * R_{fc} \quad (4)$$

The measured and simulated polarization curves are presented in Fig. 4. Fuel cell parameters are given in Table I.

TABLE I. MODELING PARAMETERS OF THE FUEL CELL

Component	Fuel cell
$E_{fc_{cell}}$ [V]	0.75
$R_{fc_{cell}}$ [$\Omega \cdot \text{cm}^2$]	0.306

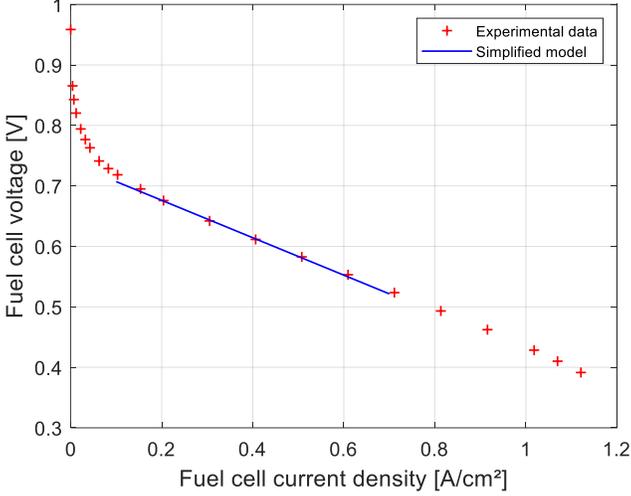


Fig. 4. Quasi-static PEM-HT fuel cell measured and simulated polarization curve.

2) Battery model

The simplified model of the battery is composed with a voltage source modeling the open circuit voltage (OCV_{batt}). The amplitude of OCV_{batt} depends on the state of charge (SoC) of the cells. The SoC reflects the residual capacity in the cell and it is calculated by using the common Coulomb counting. The internal resistance of the cell R_{cell} is connected in series with the OCV_{cell} source. The battery is composed with several cells (connected in series $Nb_{cell_{series}}$ and parallel $Nb_{cell_{parallel}}$) in order to obtain the desired voltage and capacity. Equations (5) and (6) give the relation between the cell and battery parameters:

$$OCV_{batt} = Nb_{cell_{series}} * OCV_{cell} \quad (5)$$

$$R_{batt} = \frac{Nb_{cell_{series}}}{Nb_{cell_{parallel}}} * R_{cell} \quad (6)$$

The relationship between the OCV and the SoC can be given by a linear equation when the SoC remains within a 20-80 % variation range. For this SoC variation, the internal resistance can be considered constant [12]. Outside this range, the OCV_{cell} and R_{cell} evolution is strongly non-linear. The simplified model of the battery can be expressed as:

$$U_{batt} = OCV_{batt} - i_{batt} * R_{cell} \quad (7)$$

In this study, several battery technologies have been modeled to compare their performances in a passive hybridization with a HT-PEMFC. Nickel Cadmium (NiCd) is the reference battery in aeronautics and has the advantage of being a safe and proven technology but has a fairly low specific energy of around 28 Wh/kg [13] (battery management system and packaging included) compared to lithium-ion type batteries like: Graphite/Lithium Iron Phosphate (C/LIP) and Graphite/Nickel Cobalt Aluminium (C/NCA). For this latest technology, several cells are used (energy, power or high power) in order to compare the performance of the passive hybridization. They differ on maximum charge and discharge currents, cell resistance and specific energy. To facilitate comparison between battery technologies and the optimization sizing process, the capacity of each cell is fixed at 5 Ah. Battery parameters used in this paper are given in Table II.

TABLE II. MODELING PARAMETERS OF THE ACCUMULATORS

Battery technology	Cell. NiCd [13]	Cell. C/LIP [14]	Cell. C/NCA [15, 16, 17]		
			Energy	Power	High power
OCV_{cell} [V]	1.3 + 0.08 * SoC	3.19 + 0.16 * SoC	3.33 + 0.77 * SoC		
R_{cell} [m Ω]	7.56	22.3	37.8	4.6	1.8
C-rate Charge / Discharge	4C / 10C	1C / 3C	1C / 2.2C	7C / 15C	15C / 100C
E_{batt} [Wh/kg]	28	67	81	40	34
$U_{cell_{nominal}}$ [V]	1.2	3.2	3.6		

In order to take into account the influence of the packaging on the estimated specific energy of the battery E_{batt} , E_{batt} is calculated from the specific energy of the cell, and it is then divided by a coefficient. For a li-ion NCA battery, this coefficient is estimated around 1.9 [16].

E. Simplified model validity

The differences between the two models have multiple causes. There are differences in steady state due to the simplifying assumptions in the construction of the simplified model. Also, there are differences in dynamic phases because of the absence of account of dynamic phenomena in the simplified model. The difference in the battery current is particularly impactful because it causes a difference between the two SoCs over time. Consequently, the other system variables (currents and voltages) are impacted by this SoC difference between the two models. The accuracy of the simplified model is thus improved by increasing the battery capacity. It is considered that the precision of the simplified model is quite good from a capacity of 30 Ah. The results for a system comprising a fuel cell with 76 cells connected in series and an active surface of 45 cm², a battery with 13 cells connected in series, a capacity of 30 Ah and an initial state-of-charge of 70 % are given in Fig. 5.

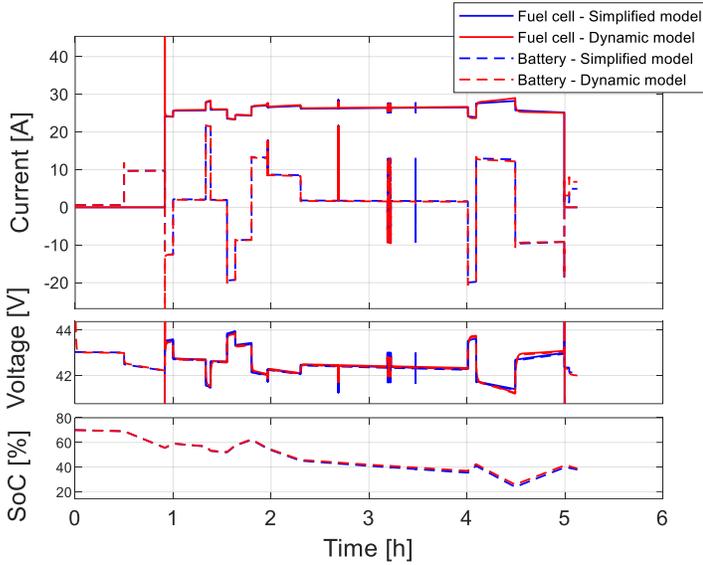


Fig. 5. Simulation of a HT-PEM Fuel cell – LIP Battery direct hybridization on an aeronautical mission with simplified and dynamic models.

III. SYSTEM SIZING

A. Sizing algorithm

The fuel cell sizing (number of cells placed in series $Nb_{fc_{series}}$) and the battery sizing (number of accumulators in series $Nb_{cell_{series}}$, number of branches in parallel $Nb_{cell_{parallel}}$ and initial state of charge SoC_{init}) are carried out by a combinatorial algorithm. This makes it possible, by combining all the possible values for these 4 sizing parameters, to test all the possible sizing. Bounds are used for the sizing parameters to limit the search space while allowing to find all relevant solutions. A great advantage of using a combinatorial algorithm is the possibility of testing every possible sizing inside the search space. The global minimum in this search space can thus be found. However, the use of a combinatorial algorithm is limited by the resolution time at each iteration. It is only interesting for fast resolution time and for a limited number of sizing parameters.

For each combination of the sizing variables, the obtained system is tested. It is only retained among the possible solutions if, during the mission, the SoC of the battery remains between 20 and 80 % in order to respect the validity range of the battery models. In addition, the fuel cell current density must remain between 0.1 and 0.7 A/cm² in order to validate the assumption of a linear polarization curve. Finally, the operating limits of the battery must be respected, in particular the maximum charge and discharge currents.

The mass of the system is then calculated by adding the mass of the fuel cell and its auxiliaries, of the battery and of the corresponding tank. Note that the stored hydrogen density is fixed to 5.5 %: a 94.5 kg tank is needed to store 5.5 kg of H₂ [18].

B. Results

Many sizings are possible for this hybridization including with a low battery capacity (minimum 15 Ah in our case). Among

all battery technologies, it is the energy-type NCA that achieves the lowest total system mass, at less than 35 kg. It is visible in Fig. 6 which shows the pareto chart of system mass and hydrogen consumption for all the possible sizings and for the 5 different types of batteries. LIP technology also gives results very close to NCA energy-type technology. Other battery technologies also allow fairly low total masses, around 40 kg. Regardless of the battery technology, the sizing results with the lowest total masses correspond to a minimum mass of the battery. It is the decrease of the battery capacity that minimizes its mass, although it is accompanied by an increase of the number of cells in series in the battery. Indeed, systems with a small battery capacity need high number of cells in series to increase the power of the battery. It also results in an increase of the number of cells in series on the fuel cell to keep voltage levels compatible. Operating with a high power fuel cell relieves the battery and subsequently it becomes possible to reduce its capacity.

The systems with the lowest total masses tend to consume more hydrogen, as can be seen in Fig. 6. This is due to the fact that low system masses are obtained for high number of cells in series on the fuel cell, and low battery capacity. The fuel cell operating point varies more with the load variation in order to relieve the battery, and so the global efficiency is reduced.

Most sizings allow multiple initial SoCs, which is important for system robustness. However, those with the lowest total system masses only fit with high initial SoCs. The low battery capacity of the lighter systems is indeed limiting during the fuel cell preheating phase. It is advantageous to have the highest possible initial SoC: this allows a higher operating voltage, and therefore better efficiency on the fuel cell. The consumption of H₂ is therefore reduced.

To give elements of comparison with the hybridized cases, we simulate a fuel cell providing current alone during the mission (pre-heating and inerting being done with an exterior source of energy), using the fuel cell dynamic model. With 108 cells in series, the system would have a total mass of 23 kg (H₂ reservoir included) and consume 0.37 kg of H₂ during the mission with a mean current density of 0.34 A/cm².

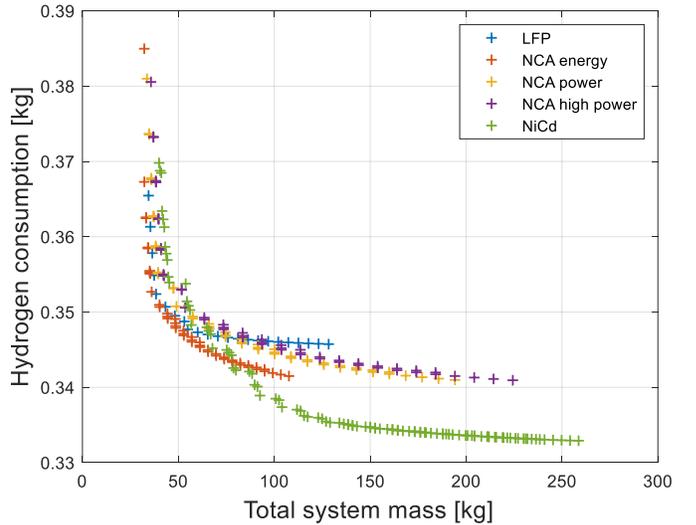


Fig. 6. Pareto chart of H₂ consumption with total system mass.

CONCLUSION

An optimization of the sizing of a HT-PEM Fuel cell - Battery passive hybridization has been implemented in order to minimize the total mass of the system. The analytical relationships used for the optimization of the different sizing were obtained from a simplified model of hybridization. Due to the fast numerical resolution of this model, the optimization is performed with a combinatorial algorithm in order to obtain the set of solutions. The results show the extent of possible sizing, the performance offered by these sizings, as well as the importance of the choice of battery technology in minimizing system mass and hydrogen consumption.

However, the optimization method can still be improved. Indeed, the comparison of the simplified model used with a dynamic model shows differences in the evolution of the SoC below a certain battery capacity. The parameterization of the simplified model must be improved. Several other areas for improvement are possible: implementation of aging laws in the models in order to analyze the impact of sizing on the aging of the fuel cell and the battery, use of a genetic algorithm to size the system with the dynamic model. In addition, the preheating of the fuel cell, carried out by the battery, strongly constrains the size of the latter: using hydrogen to preheat the fuel cell could be one way to reduce the mass of the battery.

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