High level decision methodology for the selection of a fuel cell based power distribution architecture for an aircraft application

Jesus A. Oliver(1), Pablo Zumel(2), Marina Sanz(2), Carmen Raga(2), Daniel Izquierdo(3), Oscar Garcia(1), Andres Barrado(2), Roberto Prieto(1), Ricardo Azcona(3), Bernardo Delicado(3) and Jose A. Cobos(1)

(1)Universidad Politécnica de Madrid
Centro de Electrónica Industrial (CEI)
c/ José Gutiérrez Abascal, 2
28006 Madrid. SPAIN.
Phone: + 34 91 4117517 Fax: + 34 91 5645966
e-mail: jesusangel.oliver@upm.es

(2)Grupo de Sistemas Electrónicos de Potencia (GSEP)
Universidad Carlos III de Madrid
Avda. Universidad, 30; 28911,
Leganés, Madrid, SPAIN
Phone: +34-91-6249188; FAX: +34-91-6249430

(3)Departamento de Eléctrica y UCS
Sistemas Generales EADS-CASA (MAS)
John Lennon; 28907,
Getafe, Madrid, SPAIN
Phone: +34-91-6247130; FAX: +34-91-6249430

***Abstract* - The selection of the right power distribution architecture for a given application has a tremendous impact on the overall system in terms of efficiency, cost, reliability, fault tolerance and size. Moreover, with the increasing number of power sources, storage elements, different supply voltages and strong requirements imposed at system level, the selection of the appropriate architecture becomes a nightmare for the system designer.**

The purpose of this paper is to describe a methodology for the selection of the most suitable architecture for a fuel cell based power distribution application. The methodology is based on the assessment of metric functions for all the components that can configure the architecture as a function of the electrical boundary conditions of each component.

I. INTRODUCTION

The selection and design of the most suitable power distribution architecture for a given application is a complex process that involves a careful analysis and evaluation of different decision metric parameters such as: efficiency, cost, volume, weight, robustness, complexity, fault tolerance, etc. [1-9] The application will define the weight of each parameter on the final decision. According to these weighting values different architectures will match different applications according to their boundary conditions.

Due to this complexity, the analysis and the evaluation of all the architectures via simulation are not feasible since thousands of long time simulations will be required to evaluate all the combinations for different architectures. Additionally, electrical simulation does not provide any information related to the weight, size or cost of the architecture.

In this paper, a methodology for the selection of a suitable architecture for a fuel cell based power distribution system is proposed. The methodology is based on the application of metric functions to evaluate the overall metric performance of a given architecture. The metrics considered in this work are: weight, volume, cost and efficiency of the fuel cell. Other metrics such as protections, control complexity and maintenance have also been considered in the decision but are not included in the paper due to space limitations.

For each component of the architecture (fuel cell, battery, super-capacitor and DC/DC converters) the evaluation of each performance metric is based on its boundary conditions (power, energy capacity and voltages). Simple evaluation functions have been extracted for all the components based on linear interpolations of available commercial components. In this way, this first order approximation will provide very useful information for the decision and selection of the appropriate architecture.

II. PROPOSED ARCHITECTURES UNDER EVALUATION

The proposed architectures have been divided into three groups (Fig. 1), depending on their established flow of energy: Direct architectures with direct transfer of energy to the load; Parallel architectures with a secondary energy source connected in parallel to the DC Bus and Series architectures that use a DC/DC converter connected in series to the Fuel Cell.

Direct Architectures are the simplest, they are based on a direct transfer of energy from the Fuel Cell to the load. The addition of the secondary energy source to the architectures 1B, 1C1 and 1C2 allows the Fuel Cell to handle only the average power. The secondary energy source, either the super-capacitor or the battery, will manage the difference between the peak power and the average power, so the Fuel Cell size is reduced. The slow dynamic response of the Fuel Cell is improved by means of a super-capacitor or a battery, which delivers all the required current that Fuel Cell is not able to supply during the load transients..

Parallel Architectures are characterized by a parallel transfer of energy, when needed, from the secondary energy source to the load. It is intended to improve the Fuel Cell slow dynamic response. The secondary energy source, either a super-capacitor or a battery, is connected in parallel with the DC Bus by means of a DC/DC bi-directional converter. These architectures allow a wider utilization of the secondary energy source connected through the bi-directional converter (not limited by the bus voltage limits), and so they can reduce their size.

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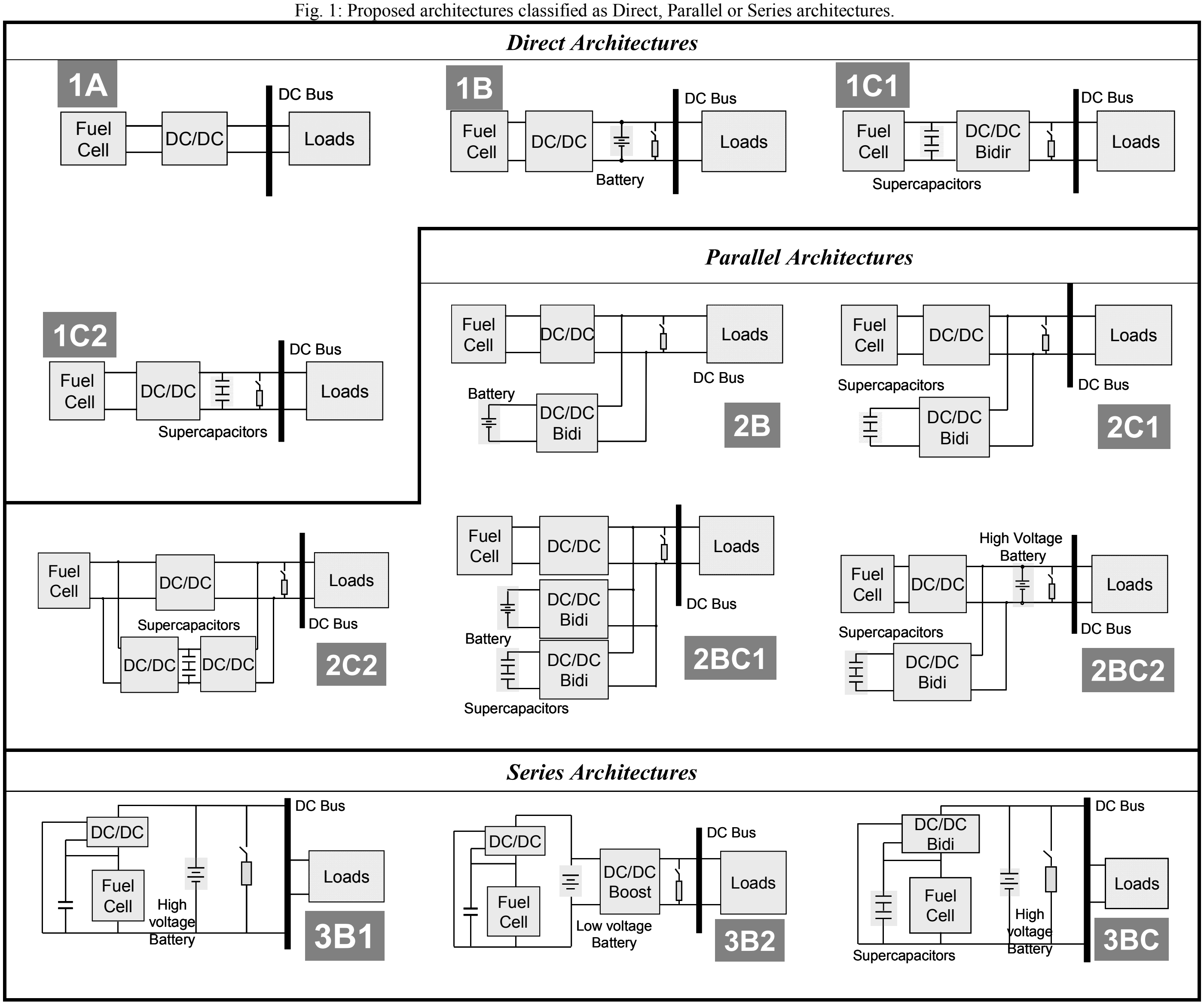
Series Architectures are characterized by the series connection of the DC/DC converter and the Fuel Cell. The DC/DC converter process less power than in the architectures described before. Only the architecture 3B2 processes part of the total energy delivered twice.

Fig. 1: Proposed architectures classified as Direct, Parallel or Series architectures.



III. PERFORMANCE METRICS EVALUATION

This section describes the performance evaluation functions used for comparing different architectures:

A. *Weight and volume*

The weight and volume of each architecture are calculated by adding the weight and volume of each element. The weight and volume of the Fuel Cell including the storage system, dc-dc converters, batteries and super-capacitors have been obtained from commercial data provided by the main manufacturers and the studies of the USA DoE [11] and other references[12]. These values have been penalized when the converter is bidirectional or the converter operates with wide input voltage range. Finally, the weight of the auxiliary sources, batteries and super-capacitors, has been calculated taking into account their power and energy densities.

Table 1 summarizes the expressions to calculate the weight of the different elements. The values used for the power densities and energy densities of each element are shown explicitly in this table. In the case of energy storage elements the weight is determined by the maximum requirement of power and energy.

TABLE 1 WEIGHT CALCULATION

Fuel Cell weight in kg	Converter weight in kg
$\frac{P_{avg}(kW)}{0.2kW/kg}+\frac{E_{avg}(kWh)}{1kWh/kg}$	$\frac{P_{avg}(kW)}{0.5kW/kg}$

Super-capacitor weight in kg	Battery weight in kg
$\max\begin{cases}\frac{E_{\max}(kWh)}{\Delta SoC}\cdot\frac{1}{0.003kWh/kg}\\ P_{\max}(kWh)\cdot\frac{1}{5kW/kg}\end{cases}$	$\max\begin{cases}\frac{E_{\max}(kWh)}{\Delta SoC}\cdot\frac{1}{0.07kWh/kg}\\ P_{\max}(kWh)\cdot\frac{1}{1kW/kg}\end{cases}$

Where:

P_{avg} is the average power demanded by the load.

P_{peak} is the peak power to be supplied by the additional energy sources (typically P_{max}-P_{avg}).

E_{max} is the maximum energy to be supplied by the additional energy sources.

ΔSOC is the maximum variation of energy allowed in the energy storage element

B. *Efficiency and Cooling*

The architecture efficiency and cooling requirements are determined by the power losses on each component. To calculate the losses, the efficiency of each element has been estimated according to [8] and [12] . The power losses expression and the different efficiency data are summarized in Table 2.

TABLE 2 POWER LOSSES CALCULATION

Converter power losses in kW	Super-capacitor power losses in kW
$\frac{(1-\eta_c)}{\eta_c}\cdot P_{avg,C}(kW)$ Where η_c =0.9	$\frac{(1-\eta_{sc})}{\eta_{sc}}\cdot E_{\max,SC}(kWh)\cdot f_{SC}(1/h)$ Where η_{sc} =0.95
Battery power losses in kW	
$\frac{(1-\eta_{BAT})}{\eta_{BAT}}\cdot E_{\max,BAT}(kWh)\cdot f_{BAT}(1/h)$ Where η_{BAT} =0.9	

Where:

$P_{avg,C}$ is the average power process by the converter

$E_{max,SC}$ is the maximum energy delivered by the super-capacitor (assumed to be repetitive)

$E_{max,BAT}$ is the maximum energy delivered by the battery (assumed to be repetitive)

η_{SC} is the efficiency of the super-capacitor

η_{BAT} is the efficiency of the battery

f_{SC} (1/h) is the frequency of the super-capacitor pulses in 1/hour

f_{BAT} (1/h) is the frequency of the battery pulses in 1/hour

C. *Cost*

The total cost of the architecture is determined by calculating the cost of the power supplied by each element. The cost assumption for each element (Table 3) has been estimated from [11] and commercial data provided by the manufacturers.

TABLE 3 COST CALCULATION

Fuel Cell cost in €	Converter cost in €
$200\frac{€}{kW}\cdot P_{avg}(kW)+5\frac{€}{kW}\cdot E_{\max}(kWh)$	$10000\frac{€}{kW}\cdot P_{avg}(kW)$
Super-capacitor cost in €	Battery cost in €
$10000\frac{€}{kWh}\cdot\frac{E_{\max}(kWh)}{\Delta SoC}$	$100\frac{€}{kWh}\cdot E_{\max}(kWh)$

Where:

P_{avg} is the average power process by the element under evaluation

E_{max} is the maximum energy to be supplied by the additional energy source.

IV. POWER PROFILE INFLUENCE ON THE ARCHITECTURE

In a fuel cell based power distribution system, the selection of the architecture depends on its power profile. Parameters such as the average power, P_{avg}, the peak power, P_{peak}, and the maximum energy E_{max} will determine the size of the main power source (fuel cell) and the size of the auxiliary power sources.

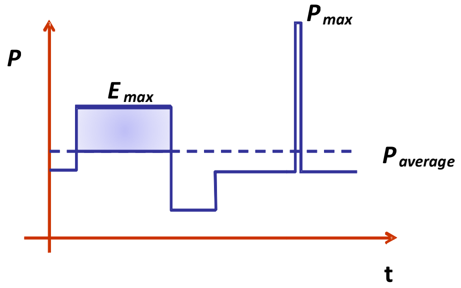


Fig. 2 Schematic representation of the power profile

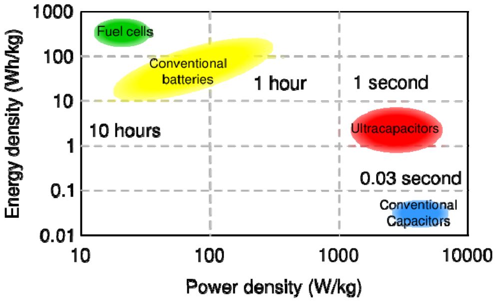


Fig. 3 Ragone's plot of some power sources

The effect of the power profile can be understood by means of the Ragone's plot, that represents the energy and power density of a power source (see Fig. 3). It can be seen that batteries will perform better than super-capacitors for large energy pulses meanwhile super-capacitors will be a better option for large and short power peaks.

In the case of an architecture with one energy storage element, the size of the auxiliary source will be given by:

$$P_{ESE} \geq \frac{1}{\eta_{ESE}}\left(P_{\max} - P_{avg}\right) \qquad (1)$$

$$E_{ESE} = \frac{E_{\max}}{SOC_{\max} - SOC_{\min}} \qquad (2)$$

Where P_{ESE} and η_{ESE} are the power and the efficiency of the energy storage element, P_{max} is the maximum power demanded by the load and P_{avg} is the power delivered by the fuel cell, P_{ESE} is the instantaneous power that will be delivered by the auxiliary source and E_{ESE} is the energy capacity of the auxiliary source [3].

In the case of architectures with two different energy storage elements, like a battery and a super-capacitor, the optimum selection in terms of total weight of the energy storage elements will be given by the solution of the minimization problem:

$$\begin{aligned} & m_{BAT} \cdot \left(\rho_{E,BAT} \cdot \Delta SOC_{BAT}\right) + m_{SC} \cdot \left(\rho_{E,SC} \cdot \Delta SOC_{SC}\right) \geq E_{\max} \\ & m_{BAT} \cdot \rho_{P,BAT} + m_{SC} \cdot \rho_{P,SC} \geq P_{peak} \\ & \min(m_{BAT} + m_{SC}) \end{aligned} \qquad (3)$$

Where:

$\rho_{E,BAT}$ is the energy density of the battery (Wh/kg)
$\rho_{P,BAT}$ is the power density of the battery (W/kg)
$\rho_{E,SC}$ is the energy density of the super-capacitor (Wh/kg)
$\rho_{P,SC}$ is the power density of the super-capacitor (W/kg)

The energy densities of the energy storage elements are multiplied by their maximum state of charge variation to account for their penalization.

Solving this minimization problem the following considerations can be extracted:

1) If $\frac{E_{\max}}{P_{peak}} \geq \frac{\rho_{E,BAT} \cdot \Delta SOC_{BAT}}{\rho_{P,BAT}}$ then, from the weight point of view, it is convenient to use only battery
2) If $\frac{E_{\max}}{P_{peak}} \leq \frac{\rho_{E,SC} \cdot \Delta SOC_{SC}}{\rho_{P,SC}}$ then it is better to use only super-capacitors
3) If $\frac{\rho_{E,SC} \cdot \Delta SOC_{SC}}{\rho_{P,SC}} \leq \frac{E_{\max}}{P_{peak}} \leq \frac{\rho_{E,BAT} \cdot \Delta SOC_{BAT}}{\rho_{P,BAT}}$ The optimum combination of super-capacitor and battery is given by the solution of (3) as equality.

In the case considered, with Li-Ion batteries and super-capacitors, and assuming the energy densities and power densities given in Table 1, ΔSOC_{BAT} of 0,4 and ΔSOC_{SC} of 0,75, the following relation can be obtained:

$$1{,}6s \leq \frac{E_{\max}}{P_{peak}} \leq 100s \qquad (4)$$

That is, for ratios bellow 1,6 seconds the optimum solution is achieved with only super-capacitors, for ratios above 100s the optimum is obtained with only batteries and for ratios between both figures a combination of batteries and super-capacitors will achieve the optimum weight of additional sources.

V. ARCHITECTURE ASSESSMENT

In this section the application of the proposed methodology for the assessment of a fuel cell based power distribution architecture for an aircraft application is shown. In this application the distribution voltage is 270VDC, the average power is 20 kW, the peak to average power ratio is 2 and three cases for the maximum energy will be considered: A) 50 Wh, B) 500Wh and C) 5000Wh. Using the above performance functions, an Excel® spread-sheet has been built in order to obtain a quantification of the performance of each architecture.

The evaluation of the energy to power ratio of $\frac{E_{\max}}{P_{peak}}$ for the scenarios considered is given in Table 4.

TABLE 4 ENERGY TO POWER RATIO

	Case A (50Wh)	Case B (500Wh)	Case C (5000Wh)
$\frac{E_{\max}}{P_{peak}}$	4,5s	45s	450s

According to these numbers, and the considerations given in the previous section, it is expected that super-capacitors will be favored in Case A) and batteries will be dominant in Case C). In case B the optimum will be combinations of batteries and super-capacitors.

Evaluation of the architectures for case A)

In this case the optimum solution in terms of weight is architecture 1BC (direct processing with battery and super-capacitor) but with a combination in weight of 65% of super-capacitor and 35% of battery due to the low maximum energy required by the load.

Architecture 3B1 is also very attractive in terms of weight (156kg). In this case the advantage is although there is some penalization for not using super-capacitors, the dc-dc converter in series process only a fraction of the energy, what benefits its size.

From the point of view of cost, solution 3B1 is cheaper than 1BC, 184 k€ vs 244 k€.

Considering only these metrics, weight and cost it seems that architecture 3B1 is clearly more interesting for this scenario.

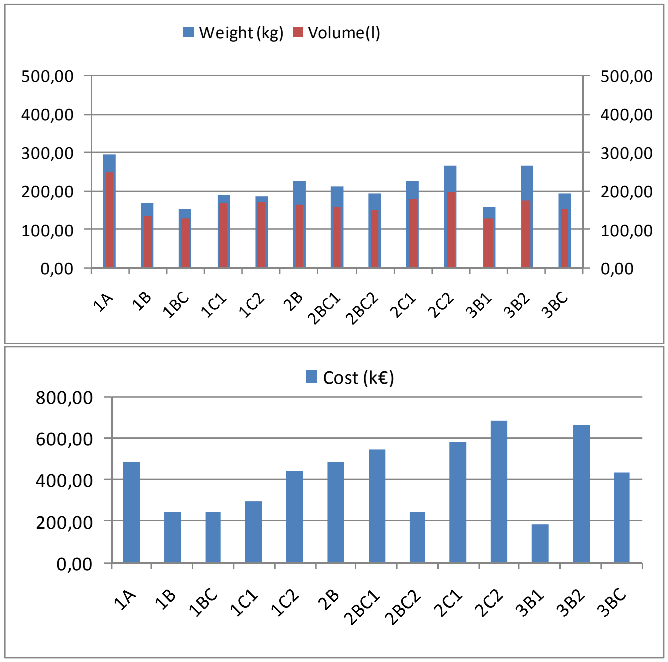


Fig. 4 Weight and Volume (top), cost (down) for case A (50Wh)

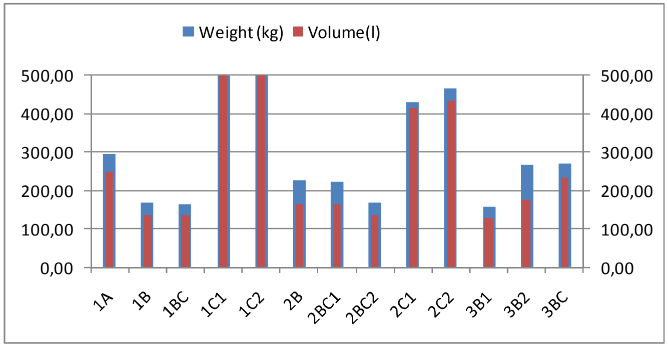
Evaluation of the architectures for case B)

In this case the optimum solution in terms of weight is architecture 3B1 (156 kg). In this case, with the same battery as in case A) this architecture is able to provide all the energy required since, in case A) it was oversized to provide the peak power.

Architecture 1BC is also interesting in terms of weight (166 kg) but is penalized with respect to case A) due to the higher requirement of energy. In this case 98% of the weight of the battery and super-capacitors correspond to the battery.

In terms of cost, solution 3B1 is cheaper than 1BC, 184 k€ vs 244 k€. The change in cost respect to case A) is not noticeable due to the small battery increment to fulfill the energy requirements.

Architecture 2BC2 (parallel processing with battery and super-capacitor) becomes interesting in terms of weight (167kg) with the same cost as architecture 1BC.



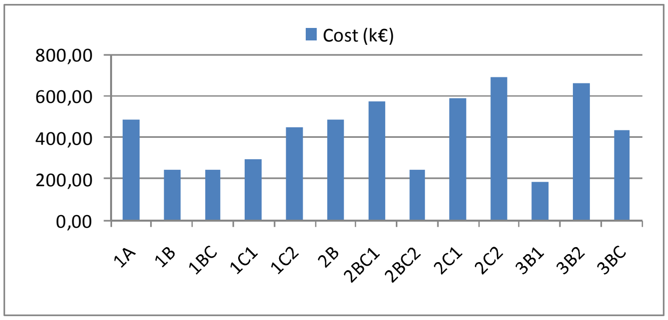


Fig. 5 Weight and Volume (top), cost (down) for case B (500Wh)

Evaluation of the architectures for case C)

In this case the optimum solution in terms of weight is also architecture 3B1 (314 kg). In this case, there is a significant increase of battery needed to supply all the energy during the transients.

Architecture 1BC does not need super-capacitor to help the battery in the transients since the battery is large enough to provide them alone. Architectures 1B and 1BC have the same components.

Architecture 2BC2 since now does not requires super-capacitor is equal to architecture 1B (direct processing of energy with battery in the bus).

In terms of cost, solution 3B1 is cheaper than 1BC, 184 k€ vs 244 k€. Again the change in cost respect to case A) is not noticeable due to the relatively small battery increment to fulfill the energy requirements. In fact, taking into account the decimals, the difference in price between 3B1 in case A) and B) is 400 €.

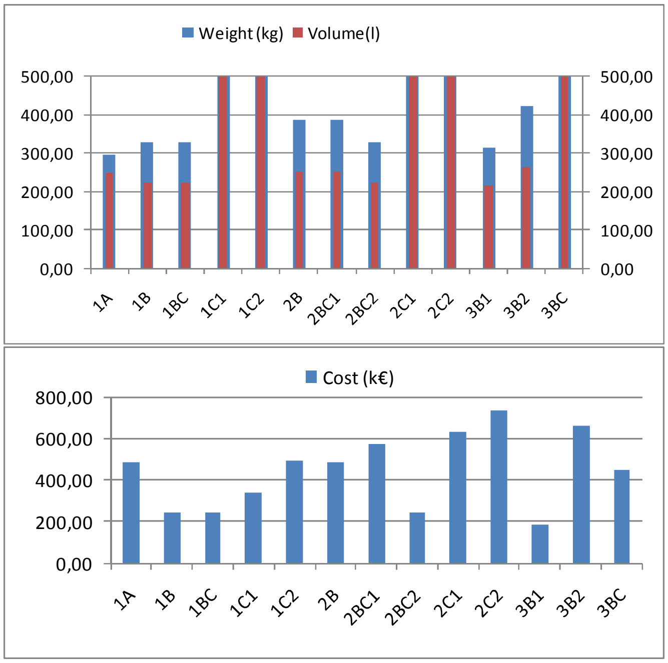


Fig. 6 Weight and Volume (top), cost (down) for case C (5000Wh)

VI. CONCLUSIONS

In this paper, a methodology for the selection of a suitable architecture for a fuel cell based power distribution system for an aircraft application is proposed. The methodology allows evaluating performance metrics of the architecture such as weight, volume, cost, efficiency and cooling requirements.

The performance metrics functions of the main components (fuel cell, batteries, super-capacitors and DC/DC converters) are also provided. These functions are based on the boundary conditions of each component (power range, energy capacity and operating voltage).

The impact of the power profile on the architecture is also analyzed, specially its impact on the selection on the auxiliary storage sources.

A classification of the candidate architectures has been proposed: direct energy transfer, parallel architectures and series architectures. And all of them have been evaluated applying the proposed methodology.

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