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Hybrid Energy Storage Systems Dimensioning for Heavy-Duty FCHEVs regarding Efficiency and Aging

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Executive Summary

Dimensioning the energy storage systems for a heavy-duty fuel cell hybrid electric vehicle is not straightforward. This study proposes a methodology to tackle this challenge, aiming to maximize efficiency while mitigating the aging effects on the energy storage systems. Various configurations of storage system ratios have been analyzed using the concept of hybridization percentage, which indicates that as the contribution of supercapacitors increases, the proportion of batteries and fuel cells decreases, maintaining a constant total weight. Simulations were conducted using models developed in AVL Cruise MTM. Preliminary findings suggest that an optimal hybridization percentage exists, which achieves the dual goal of maximizing efficiency and minimizing the aging of both the battery and the fuel cell.

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1 Introduction and Motivation

Over the past decades, electric vehicles (EVs) have advanced significantly due to the limited efficiency of internal combustion engine vehicles (ICEVs) and the growing environmental awareness. However, energy storage systems (ESSs) remain a key obstacle to scaling EV deployment to a level comparable with ICEVs, primarily due to limited energy density (which impacts driving range) and aging (which necessitates ESS replacement).

Battery electric vehicles (BEVs) dominate the market because lithium-ion batteries (LiBs) are more advanced than competing technologies, such as fuel cells (FCs), in terms of Technology Readiness Level, Regulatory Readiness Level, and Customer Readiness Level. Despite this, considerable research has also focused on fuel cell electric vehicles (FCEVs), though FCEV powertrain efficiency remains limited, and ESS aging is a substantial concern.

In this context, integrating an additional ESS, such as supercapacitors (SCs), in a fuel cell hybrid electric vehicle (FCHEV) can significantly improve both powertrain efficiency and reduce aging impacts on FCs and LiBs. This improvement may be particularly notable in heavy-duty FCHEVs, which require high power to mobilize large masses, creating substantial power peaks in the hybrid energy storage system (HESS).

While many studies analyze FCHEVs from various perspectives, few consider dimensioning, efficiency, and both LiB and FC aging. A thorough assessment of these factors, including all equipment components, could show that heavy-duty FCHEV total efficiency improves as ESSs aging declines.

2 Dimensioning Methodology

The dimensioning methodology presented in this paper establishes various HESS configurations using the concept of "hybridization grade" (Hyb). The Hyb represents the ratio between the weight of SCs, and the combined weight of SCs, LiBs and FCs. This metric indicates how the FCHEV differs from a standard FCEV, which lacks SCs, while keeping the HESS weight constant within the EV. In this context, increasing the Hyb implies substituting LiB and FC in favor of SCs. The hybridization grade is expressed as a percentage:

$$Hyb = \frac{W_{SC}}{W_{FC} + W_{LiB} + W_{SC}} \tag{1}$$

The objective of the proposed methodology is to find the Hyb value that maximizes efficiency while minimizing the aging of both FC and LiB. This approach uses a "brute-force" optimization method, as there are three variables to optimize (HESS efficiency, FC aging, and LiB aging) and only one design variable (Hyb). Thus, a more complex optimization method is unnecessary and may not yield a better optimum. The methodology includes the following steps:

- Step 1. Select the HESS configuration and energy management strategy (EMS). Complex EMS should only be chosen if it aligns with the HESS configuration.
- Step 2. Select the vehicle, driving cycle, and ESSs.
- Step 3. Parameterize the EMS and the vehicle simulation models (as described in later sections).
- Step 4. Run simulations for each Hyb value, assessing HESS efficiency and aging of FC and LiB. If multiple EMS are suitable, repeat Step 4 for each.
- Step 5. Consolidate results and compute the cost function to determine the Hyb that optimizes efficiency and minimizes FC and LiB aging.
- Step 6. (Out of the scope of this work) Translate the results to economic terms.

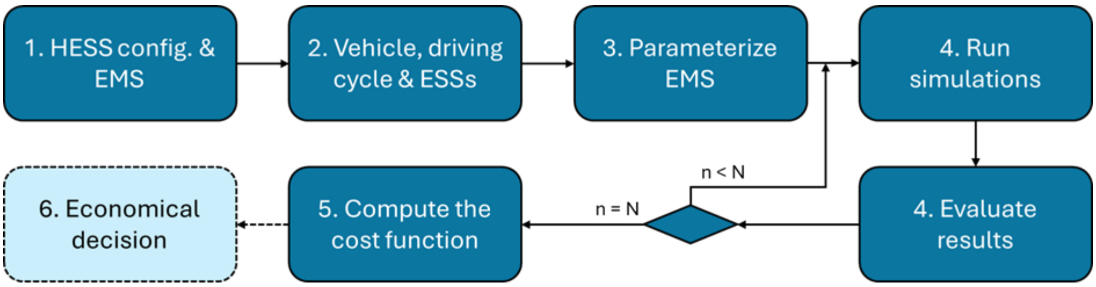

Figure 1: Flow diagram of the proposed dimensioning methodology.

For simulation purposes, a low-abstraction model of the heavy-duty FCHEV has been developed in MATLAB Simulink. This model incorporates detailed commutation-level modeling of the powertrain's power converters as well as the dynamic behavior of each ESS. Thermal dynamics are represented for both SCs and LiBs, with aging behavior included for the LiBs and the FC. It has also been utilized to validate an additional model developed in AVL Cruise MTM, which significantly reduces computation time compared to the MATLAB Simulink model. This AVL model has been used for performing the simulations.

3 Simulation Model in AVL Cruise MTM

The complete powertrain structure of the selected fuel cell hybrid vehicle is illustrated in Figure 2. The hybrid architecture resembles a range-extender design, where the HV LiB serves as the primary energy and power source, while the hybrid units provide support during transients and extend the vehicle's range. The hybrid propulsion system, located at the center, relies on an electric motor for traction, powered by the HV LiB, SCs, and FC unit. The vehicle features three axles, with the central drive axle visually connected to the propulsion system, unlike the other two. This comprehensive drive system is modeled in AVL Cruise MTM using multiple blocks, some representing actual components of the vehicle, while others are unrelated to its structure but essential for the simulation.

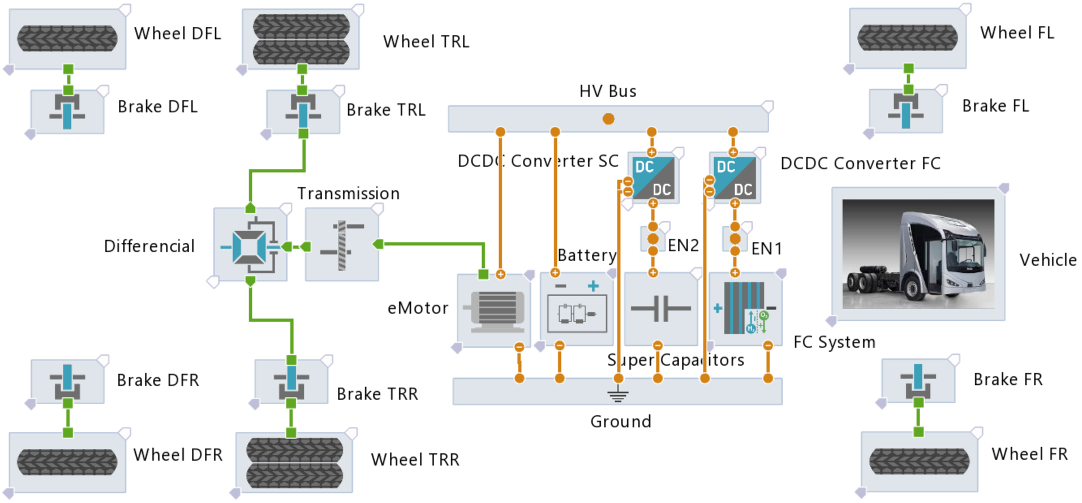

Figure 2: Longitudinal dynamics model realised with AVL Cruise MTM.

3.1 HV LiB model

The HV LiB model relies on an equivalent electrical circuit framework, enabling it to forecast voltage behavior under specified conditions of current, state of charge (SoC), and temperature. The parameterization of this model is based on data from the ANR26650M1 lithium-ion battery cell produced by A123 Systems [1].

3.2 SCs model

Similarly, the SCs model operates using an equivalent electrical circuit design. Its parameterization is derived from the specifications of the BCAP0310 P270 SC cell manufactured by Maxwell Technologies [2].

3.3 FC model

The FC model leverages electrochemical principles, formulated from the polarization curve of a PEM cathode. The approximate solution accounts for losses due to oxygen and proton transport within the catalytic layer and oxygen diffusion in the gas layer. These parameters vary with temperature, humidity, and gas pressure. The data supporting this model stem from the commercial Ballard FCmove™ HD fuel cell stack [3].

3.4 Electric motor

AVL Cruise MTM includes predefined blocks for modeling electric motors using a map-based methodology. Parameterization data for this model are sourced from the 350 kW peak power PMSM DANA TM4 Sumo™ MD motor [4].

3.5 Driving cycle

The driving cycle implemented in this study is the World Harmonized Transient Cycle (WHTC). Designed for heavy-duty engines, it replicates global road conditions and adheres to harmonized technical standards for exhaust emissions certification [5].

4 Results and Discussion

4.1 Step 1

According to the methodology described, the first step consists of selecting an EMS for the HESS. In this work, the fuel cell is operated following a range extender configuration, aiming to maximize its efficiency while extending the vehicle's range. The FC is used primarily within its optimal efficiency region, supplying power either directly to the drivetrain or to recharge the battery when the instantaneous power demand from the vehicle is lower than the FC's output level. Three discrete FC power levels are defined, taking advantage of the wide high-efficiency operating range of the selected FC. The appropriate power level is determined based on the moving average of the vehicle's demanded power over the last five minutes, smoothing short-term fluctuations and ensuring stable operation.

Additionally, the EMS incorporates a battery state-of-charge (SOC) management strategy: the FC remains inactive as long as the SOC is above 50%. When the SOC falls below 50%, the FC is activated according to the moving average demand; if the SOC drops below 30%, the FC operates continuously at its highest power level until recovery. When SCs are introduced into the HESS, the LiB power is further split, with power peaks exceeding a predefined C-rate threshold diverted to the SCs, thereby protecting the battery and reducing its aging.

A limit of 0.6C has been selected as the threshold for SC operation across all levels of hybridization (Hyb), both during charge and discharge. It is worth noting that, as Hyb increases, maintaining the same control threshold leads to a reduced contribution from the LiB, meaning that the SCs must handle a greater share of both power and energy.

4.2 Step 2

The elements selected to configure the HESS, along with the driving cycle and vehicle, are briefly described in the previous section. The initial configuration of the HESS, corresponding to a Hyb of 0, consists of the FC and a LiB composed of 200 cells in series and 72 rows in parallel. For the calculation of the different Hyb percentages, each LiB cell is assumed to weigh 70 g, each SC cell 475 g, and the FC 256 kg. Since the total weight must remain constant across the different Hyb levels, discrete steps are required. Due to the DC bus voltage requirements, each SC row introduced into the HESS must consist of 172 cells, which in weight approximately corresponds to six LiB rows. Thus, each Hyb step involves adding one row of 172 SCs and removing six rows of 200 LiB cells. Each step results in an increment of approximately 6.48% hybridization by weight.

To illustrate the proposed methodology, three Hyb levels are selected for presentation in this work: Case 0 (Hyb = 0%, 72 LiB rows), Case 1 (Hyb = 6.48%, 1 SC row and 66 LiB rows), and Case 2 (Hyb = 12.96%, 2 SC rows and 60 LiB rows).

4.3 Step 3

The AVL Cruise MTM model has been parameterized so that the submodels represent the different vehicle and HESS components. Further information can be found in the references of the previous section.

4.4 Step 4

Once the EMS has been selected, the different Hyb cases defined, the vehicle and HESS components chosen, and the models parameterized to represent them, simulations can be performed using the AVL Cruise MTM software. The power time series for the three selected cases are shown in Figures 3, 4, and 5.

As can be observed, in Case 0 there is no contribution from the SCs, and the LiB is forced to handle all the power peaks demanded by the vehicle. In Cases 1 and 2, the contribution of the SCs allows the LiB to operate under less stress during both charge and discharge, reducing the C-rate, maintaining stricter temperature control, and mitigating aging associated with cycling. In Case 1, the SCs' energy is so limited that they are unable to protect the LiB throughout the entire cycle.

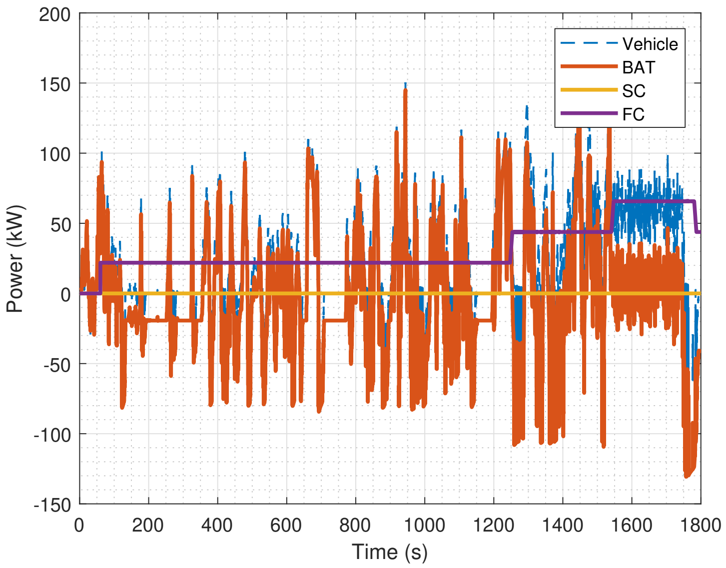

Figure 3: Case 0: vehicle, LiB, SCs and FC power.

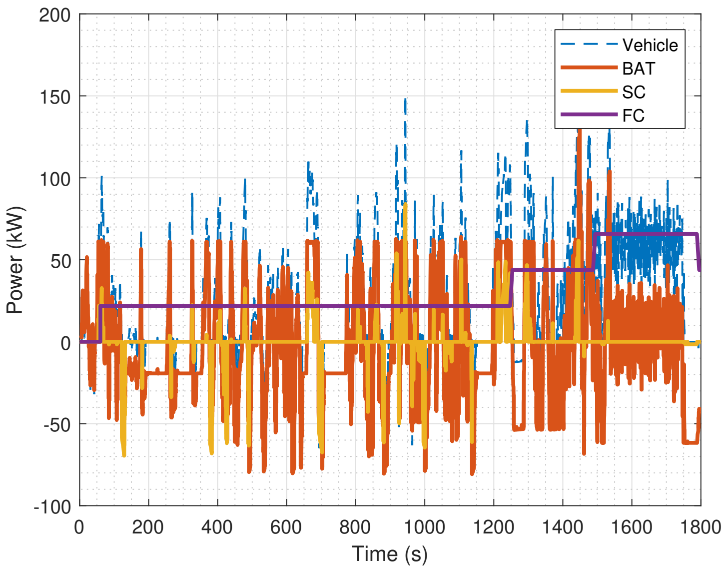

Figure 4: Case 1: vehicle, LiB, SCs and FC power.

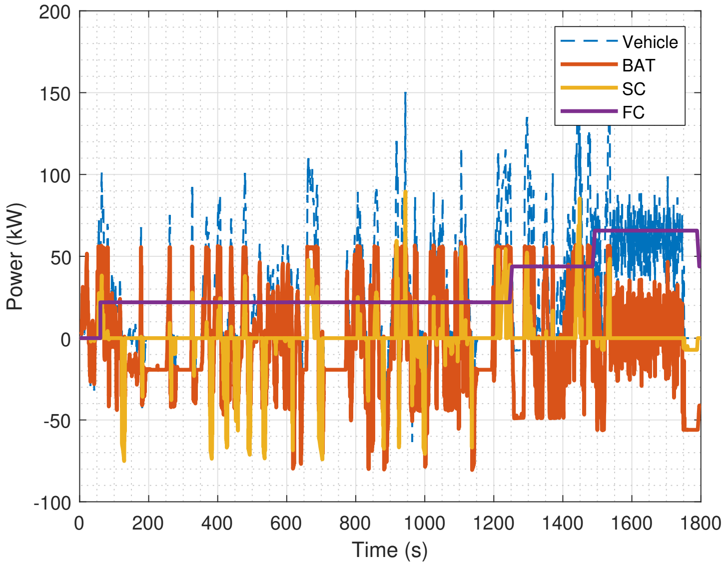

Figure 5: Case 2: vehicle, LiB, SCs and FC power.

It should be noted that, even though the SC control threshold remains constant between charge and discharge, the charging power of the battery is higher than the discharging power. This is a consequence of controlling the battery based on current C-rate: charging the battery implies applying a higher voltage at the LiB terminals, and thus a higher power. In all three cases, the FC behaves similarly, with no noticeable changes in the power it delivers.

4.5 Step 5

Once the simulations have been completed, the results for vehicle efficiency, as well as LiB and FC aging (all three variables being outputs of the simulation), can be gathered. Since the FC behavior remains unchanged across different Hyb levels, its aging remains constant for all three cases. The results for efficiency and LiB aging as a function of Hyb are shown in Figure 6. Battery aging is calculated over 2000 cycles, assuming that the performance variables are repeated without variation throughout them.

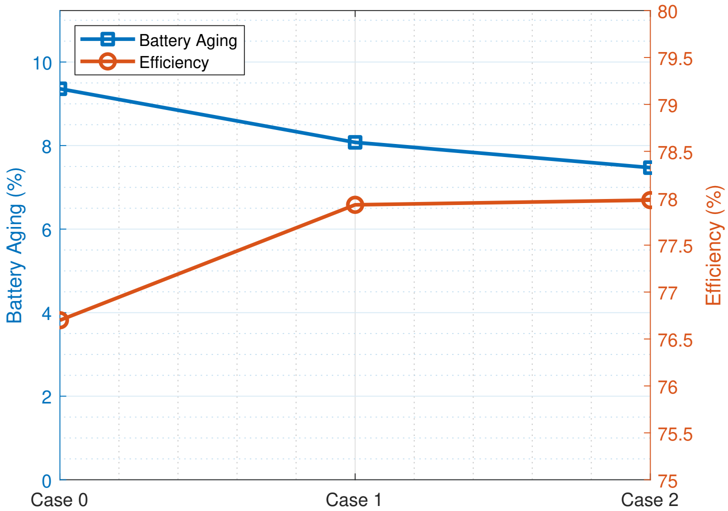

Figure 6: Battery aging and efficiency evolution with Hyb.

As can be observed, introducing SCs into the HESS leads to a reduction in LiB aging. As previously mentioned, this is a consequence of the reduced C-rate and lower thermal stress. Extrapolating the LiB aging curve, the trend line indicates that the highest improvement occurs when moving from 0% Hyb to 6.48% Hyb (one row of SCs). A similar behavior is observed for the efficiency, where the reduction in LiB losses results in an increase in overall efficiency. It should be noted that the power electronics are not modeled in this study, and thus the additional losses induced by the SC power converter when hybridizing from Case 0 to Case 1 are not considered. It is likely that, with a more detailed model including power converters, efficiency would be lower for Cases 1 and 2 compared to Case 0. In this work, where those components are not included, the losses associated with the SC are lower than those associated with the removed LiB cells, resulting in an overall increase in efficiency. Trend lines equations for both LiB aging and efficiency are provided below:

$$LiB_{aging} = 0.339 \cdot x^2 - 2.3 \cdot x + 11.321 \tag{2}$$

$$Eff = 0.0071 \cdot x^5 - 0.1496 \cdot x^4 + 1.2271 \cdot x^3 - 4.8504 \cdot x^2 + 9.2158 \cdot x + 71.25 \tag{3}$$

In order to find the optimum Hyb, the trend lines must be combined into a cost function. To determine the Hyb that minimizes the cost, the derivative of the cost function must be set equal to zero. Assuming that both variables have the same relative importance (i.e., equal weights in the cost function), the optimum Hyb corresponds to Case 2, where LiB aging is minimized and efficiency is maximized. However, when translating the cost function into economic terms, introducing a second row of SCs implies a significant additional cost. The improvement achieved in both efficiency and LiB aging from Case 1 to Case 2 is relatively small compared to the improvement observed between Cases 0 and 1, suggesting that a more balanced solution could be at 6.48% Hyb, corresponding to Case 1. Moreover, when the results are interpreted in economic terms, it is likely that the inclusion of SCs may not be justified at all, as their high cost could outweigh the benefits associated with extending LiB life and improving overall efficiency.

At last, it is important to note that increasing the Hyb results in reduced FCHEV autonomy, as SCs have a lower energy density compared to LiB and FC. Figure 7 shows the HESS (LiB and SCs) energy reduction as the Hyb increases.

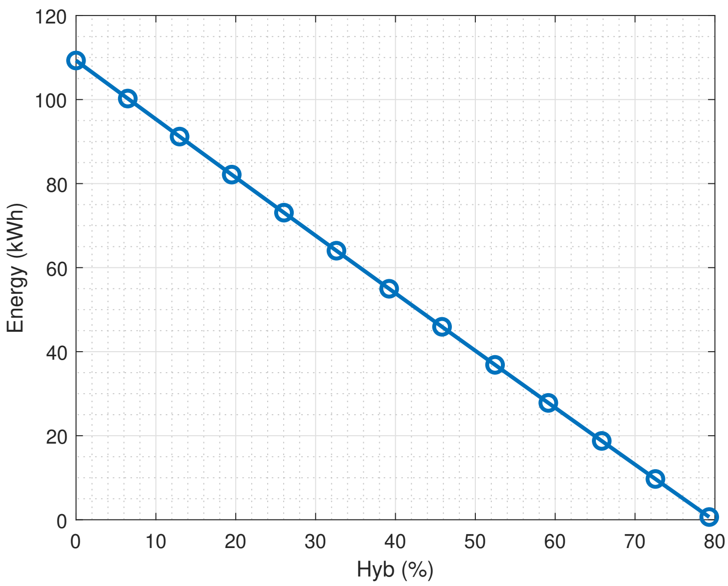

Figure 7: HESS energy variation with Hyb.

5 Conclusions

This work proposes a dimensioning methodology to size a HESS for FCHEVs, aiming to simultaneously maximize vehicle efficiency and minimize aging effects in the LiB and FC subsystems. The methodology, based on defining a hybridization percentage while maintaining a constant system weight, enables the evaluation of different configurations by assessing their efficiency and degradation under a standardized driving cycle using AVL Cruise MTM simulations. It follows a structured sequence of steps, facilitating its implementation and extrapolation to various HESS combinations and configurations.

The results show that introducing SCs into the HESS simultaneously reduces LiB aging and improves vehicle efficiency. Although power electronics were not modeled in this study, the findings suggest that moderate hybridization levels provide a better compromise between performance and durability, without compromising the vehicle's ability to complete the driving cycle.

Future research will extend this methodology by evaluating additional EMS strategies, exploring a broader range of hybridization percentages, and incorporating a detailed model of the power converters to assess their impact on system efficiency. Moreover, the cost function will be reformulated to integrate economic considerations, enabling a more comprehensive optimization that addresses both technical performance and financial viability.

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Presenter Biography

Jorge Nájera received the Ph.D. degree in Electrical and Electronic Engineering in 2021 by the Universidad Politécnica de Madrid and the Universidad de Oviedo. Since 2018 he develops his research activity within the Unidad de Accionamientos Eléctricos at CIEMAT. His expertise encompass the design and development of semi-empirical models for energy storage systems, and the design, sizing, prototyping, integration and control of energy storage systems for electric mobility, grid stability, and renewable generation applications.