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In-depth Life Cycle Cost Analysis of a Hydrogen Electric Multiple Unit

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***Abstract*—This paper analyses the life cycle costs of railway projects involving hydrogen electric multiple units. The analysis focuses on the interrelation between the selected lithium-ion battery technology, the designed energy management strategy, and the fuel cell and battery sizes. In particular, 3 lithium-ion battery technologies and 4 strategies are proposed, leading to a sensitivity analysis composed of 12 cases. For each case, an approach for the optimal sizing of the fuel cell and battery is proposed. A scenario based on a real railway line is introduced and the obtained results are compared with the performance of a traditional diesel-electric multiple unit. The results show that a reduction of the hydrogen price is required so as the hydrogen-based option becomes competitive compared to the diesel-based one. The best result of the sensitivity analysis is obtained with an off-line optimization-based strategy and LTO batteries.**

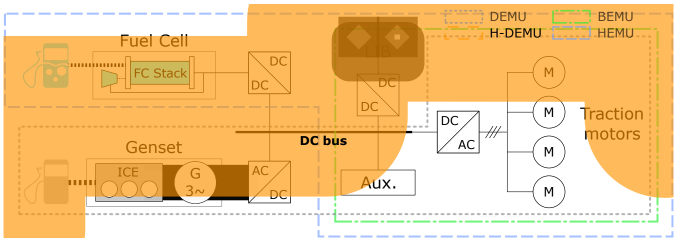
***Index Terms*—Energy management, life cycle cost analysis, hydrogen, fuel cell, lithium battery, railway engineering**

I. INTRODUCTION

Traditionally, railway vehicles have been divided into diesel and catenary powered vehicles. The Diesel-Electric Multiple Unit (DEMU) and Electric Multiple Unit (EMU) have been typical choices for mid- and long-distance passenger railway lines. DEMUs remain the preferred option in many railway systems, especially in track sections where the electrification is barely cost-efficient [1]. However, due to environmental concerns and recent developments on technologies such as Lithium-ion Batteries (LIB) and Hydrogen Fuel Cells (FC), the interest of the railway industry on new vehicle topologies is rapidly increasing [2]. Consequently, new concepts such as the Battery Electric Multiple Unit (BEMU), Battery Hybrid Diesel-Electric Multiple Unit (H-DEMU) or Hydrogen Electric Multiple Unit (HEMU) are gaining interest, but meanwhile they involve several techno-economical challenges subject to research. Fig. 1 resumes the differences between a DEMU, BEMU, H-DEMU and HEMU. Compared to the H-DEMU, the HEMU reduces the pollutant emissions of the vehicle, which can be totally avoided if the hydrogen is generated from renewable sources. Besides, the HEMU can drive larger distances compared to the BEMU, thanks to the higher energy density and faster refuelling of the hydrogen technology [3].

When dealing with hybrid vehicles (e.g. H-DEMU or HEMU), the definition of the power split ratio between the different power sources has a strong impact on the Life Cycle Costs (LCC) [4]. As this is one of its main tasks, the relevance of the Energy Management Strategy (EMS) can not be dismissed. In addition, the techno-economical influence of the selected Energy Storage System (ESS) technology has also been reported to be relevant [5]. Therefore, it is concluded that when trying to reduce the cost of a hybrid railway vehicle, the effects of the EMS and ESS technology cannot be ignored. Previous scientific works have analysed the techno-economical suitability of H-DEMUs [6]–[9], BEMUs [7], HEMUs [7], or similar vehicles such as locomotives [10], [11]. From the reviewed studies, only the authors in [6] have developed a comprehensive LCC analysis comparing several EMSs and ESS technologies, but for the case of a H-DEMU. Therefore, a lack of studies that propose an exhaustive LCC analysis for HEMUs is identified in the literature.

Consequently, the aim of this study is to analyse the influence of different EMSs and LIB technologies on the LCC of railway projects involving HEMUs. The methodology for developing this sensitivity analysis is explained in detail. It includes an optimization of the LIB and FC sizes, since they are also considered key variables to improve the LCC [2], [4]. The remainder of the paper is organized as follows. The use case scenario is presented in Section II, Section III introduces the analysed EMSs and LIB technologies, Sections IV-V present the general methodology for the LCC optimization, the obtained results are evaluated in Section VI, and the conclusions are reviewed in Section VII.



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II. SCENARIO OVERVIEW

The scenario proposed for this study is based on the ”Tardienta - Canfranc” railway line, located in Aragón (Spain). The round trip route is composed of 313 km and it is completed in 5.16 hours. Fig. 2 shows the speed and altitude profiles of the line. As it is seen, the route is characterised by a high altitude change until it arrives to the middle station, what inevitably affects in the HEMU energy consumption. The line is not electrified, and therefore the HEMU works all the time with the power generated by the FC and LIB. Fig 1 showed the configuration of the considered HEMU vehicle.

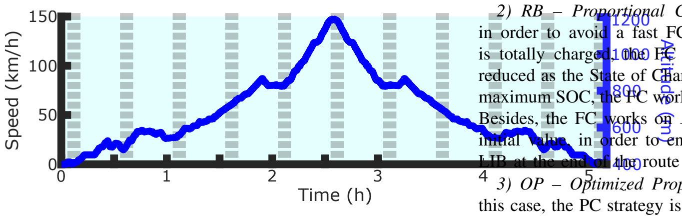

Fig. 2. Driving Profile of Tardienta-Canfranc line: speed and altitude.

III. OVERVIEW OF SENSITIVITY ANALYSIS

In the following paragraphs, the LIB technologies and EMSs analysed in the current study are introduced.

A. LIB Technologies

Depending on the deployed anode and cathode material, different LIB technologies exist [5]. In the current study the following chemistries are considered (cathode/anode): Lithium Iron Phosphate/Graphite (LFP/G), Lithium Nickel Manganese Cobalt Oxide/Graphite (NMC/G) and Lithium NMC/Titanate (NMC/LTO). For the sake of simplicity, in the remainder these technologies will be referred as LFP, NMC and LTO, respectively. They differ in terms such as nominal voltage, lifetime, specific energy, energy density, and cost (Table I).

TABLE I
PARAMETERS OF CONSIDERED LIB CHEMISTRIES (CELL LEVEL)

	LFP	**NMC**	**LTO**
Nominal voltage [V]	3.2	3.7	2.3
Continuous max. C-rate (ch/dch) [C]	4.0 / 6.5	3.0 / 5.0	4.0 / 4.5
Calendar Life [years]	10	15	20
Cycle Life (@80%DOD) [cycles]	8,200	3,300	28,800
Specific Energy (pack level) [Wh/kg]	48.0	86.9	53.3
Energy Density (pack level) [Wh/L]	81.1	122.2	52.8

B. Energy Management Strategies

The proposed strategies split the power demand between the FC and the LIB. EMSs for hybrid vehicles are divided into rule-based and optimization-based (off-line and on-line optimization) strategies [6]. In the present paper 2 rule-based (RB) and 2 off-line optimization-based (OP) strategies are proposed. The following considerations were taken when designing the EMSs: (1) the LIB charge must be sustained through the whole route since there are not charging points, and (2) a smooth FC operation must be ensured, as otherwise its lifetime is considerably reduced [12].

1) RB – Power Follower (PF): In the first approach, the FC works all the time on its nominal operation point P_{nom} regardless of the LIB state (Fig. 3). The LIB acts as a buffer, giving or absorbing the difference between the FC power and the demand. The FC reference is reduced only if the LIB can not absorb more power. This approach is also referenced as soft-run strategy in the literature.

2) RB – Proportional Controller (PC): In this strategy, in order to avoid a fast FC power reduction when the LIB is totally charged, the FC operation point is proportionally reduced as the State of Charge (SOC) becomes higher. At the maximum SOC, the FC works on its idle operation point P_{idle}. Besides, the FC works on P_{nom} when the SOC is below its initial value, in order to ensure the charge sustaining of the LIB at the end of the route (Fig. 3).

3) OP – Optimized Proportional Controller (GA-PC): In this case, the PC strategy is optimized by means of a Genetic Algorithm (GA) approach. As Fig. 3 shows, PC strategy is characterized by the values y_1, y_2 and x_1 (which were defined as P_{nom}, P_{idle} and SOC_{ini} in the original strategy). The GA approach optimizes these values in order to reduce the LCC of the HEMU. Further information regarding the GA optimization methodology is given in Section IV.

4) OP – Dynamic Programing (DP): This global optimization approach is based on an algorithm that calculates the optimal split factor (in terms of fuel consumption) between the FC and LIB for each time step based on Bellman's optimality principle. The resulting operation is characterized by frequent switches in the power split factor [6]. Therefore, in the current approach an additional term has been added to the optimization cost function J in order to ensure a smooth FC operation:

$$J = \sum_{n=0}^{N-1} \Big(\alpha \cdot \Delta m_{h2}\big(U(n)\big) + \beta \cdot \Delta P_{FC}\big(U(n)\big) \Big) \cdot T_s \quad (1)$$

where $\Delta m_{h2} \cdot T_s$ is the hydrogen consumption at each time step n (determined by the power split factor U), ΔP_{FC} the FC power change, and N the route length. α and β are weigh factors for the fuel consumption and FC power change cost terms, respectively. The DP algorithm integrated in the current study is based on the function developed by [13].

In short, PF, PC and GA-PC strategies can be easily deployed on-line in a real application, since they are all based on rules. DP optimization strategy, however, is hardly applicable

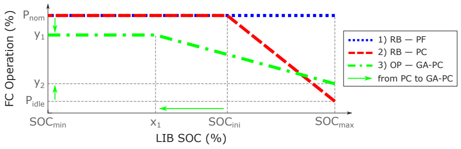

Fig. 3. Graphical Representation of EMSs (1)-(3).

in real operation, since the optimised variable is a sequence of split factors only valid for a specific drive cycle. Therefore, it will be just used as baseline for benchmarking other EMSs.

IV. OPTIMIZATION METHODOLOGY

Fig. 4 shows an overview of the process followed for the development of the sensitivity analysis. The aim is to obtain the LCC value of each case to be analysed, i.e. the LCC of each combination of EMS and LIB technology (denoted as $k \in k_{max}$). That value is obtained by means of an optimization that also returns the cost-optimal combination of installed LIB (n_{LB}) and FC modules (n_{FC}), and the most appropriate initial SOC value to start the journey (SOC_{ini}). The optimization methodology differs depending on the strategy being analysed. In the case of PF, PC and DP strategies an exhaustive search optimization is followed, while in the case of GA-PC strategy a GA optimization is proposed. The main cause for this differentiation is that in the case of GA-PC strategy the parameters of the EMS (x_1, y_1, and y_2) are also optimised, what increases the number of variables and consequently hinders the deployment of an exhaustive search approach.

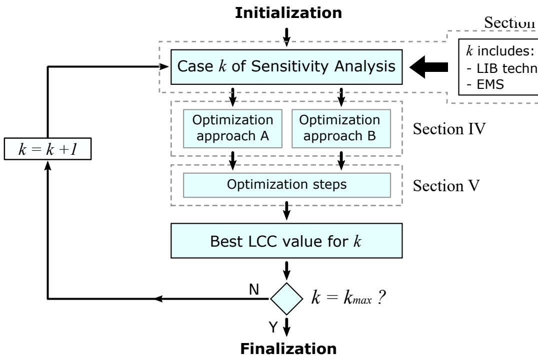

Fig. 4. Overview of sensitivity analysis.

A. Optimization Approach A: Exhaustive Search

The optimization by exhaustive search consists on an iterative sequence composed of four steps, in which all the range of feasible solutions ($j \in j_{max}$) is assessed one by one. The main steps are depicted in Fig. 5 and further detailed in Section V.

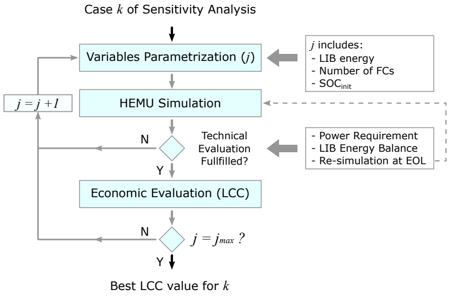

Fig. 5. Diagram for optimization by exhaustive search.

B. Optimization Approach B: Genetic Algorithms

The GA is a heuristic optimization solving method based on the concept of natural selection [4]. The algorithm repeatedly modifies a population of individuals (i). Each i includes a certain combination of optimization variables. At each step, the GA selects the best individuals from the current population to be parents and uses them to produce children, trying to keep the best features for the next generation (X). In short, it consists of an iterative process through several phases [4], as Fig. 6 shows: (1) a random initial population of N_i individuals is generated, (2) each individual is evaluated according to a fitness function, which in the current approach is the LCC value (the main steps for its calculation are detailed in Section V), (3) the best individuals are selected to join the next generation, and (4) new individuals are generated by means of crossover and mutation approaches. Steps (2)-(4) are repeated until the desired number of generations (N_X) is reached.

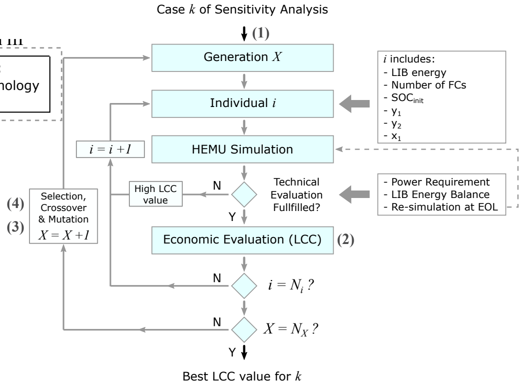

Fig. 6. Diagram for optimization by GA.

V. LCC CALCULATION APPROACH

This section further details the main steps followed for the evaluation of the fitness function (LCC value) of both optimization approaches, which were previously introduced in Section IV-A and Section IV-B.

A. Variables/Individuals Parametrization

Table II shows the bounds of the variables that compose j and i. N_{LB} and N_{FC} define the maximum number of LIB and FC modules, respectively. Each LIB module is constructed connecting cells in series and parallel to reach a nominal energy of 20 kWh, and each FC module has a nominal power of 100 kW. Due to space limitations on the HEMU, N_{LB} changes with respect to N_{FC} (i.e. if more FC modules are integrated, less space is available for the LIB). In addition, N_{LB} changes with respect to the LIB technology, as the energy densities differ (Table I). It is also worth to point out that SOC_{ini} is a continuous variable in the GA approach and an integer variable in the exhaustive search (steps of 10%).

TABLE II
OPTIMIZATION VARIABLES AND BOUNDS

Variable		Bounds		Optimization Approach
$n_{LB}(j/i)$	$\in$	$\{1, 2, \dots N_{LIB}\}$	[-]	Exhaustive Search, GA
$n_{FC}(j/i)$	$\in$	$\{1, 2, \dots N_{FC}\}$	[-]	Exhaustive Search, GA
$SOC_{ini}(j/i)$	$\in$	$\{20 - 90\}$	[%]	Exhaustive Search, GA
$y_1(i)$	$\in$	$\{P_{idle} - P_{nom}\}$	[kW]	GA
$y_2(i)$	$\in$	$\{P_{idle} - P_{nom}\}$	[kW]	GA
$x_1(i)$	$\in$	$\{20 - 90\}$	[%]	GA

B. HEMU Simulation and Technical Evaluation

The performance of the HEMU is evaluated by means of a quasi-static simulation model developed in MATLAB. For further information regarding the model development, see [4], [6]. At this step, LIB characteristics (capacity and internal resistance) are set at Beginning-of-Life (BOL) values.

Simulation results are technically evaluated considering the aspects of power requirement and LIB energy balance [6]. Then, the simulation is repeated with the LIB characteristics set at End-of-Life (EOL) values. Iteration j or individual i is considered feasible and its LCC is calculated only if the technical aspects are met in both simulations (BOL and EOL).

C. Economic Evaluation (LCC Model)

The cost model returns the LCC value of each feasible solution, which corresponds to the minimization function of both optimization approaches. The model considers the costs of the whole HEMU lifetime, divided into acquisition (C_{acq}), operation (C_{op}) and maintenance costs (C_{maint}):

$$LCC(i/j) = C_{acq}(i/j) + C_{op}(i/j) + C_{maint} \tag{2}$$

1) Acquisition Cost: C_{acq} includes the initial costs of the LIB, FC and the rest of the train.

$$C_{acq}(i/j) = C_{tr} + c_{LB} \cdot n_{LB}(i/j) + c_{FC} \cdot n_{FC}(i/j) \tag{3}$$

being C_{tr} the cost of the train without LIB and FC, c_{LB} the referential cost per module of the LIB technology, and c_{FC} the referential cost of a FC module.

2) Operation Cost: C_{op} includes the costs related to the hydrogen consumption (C_{h2}) and the required LIB and FC replacements (C_{LBre} and C_{FCre}, respectively):

$$C_{op}(i/j) = C_{h2}(i/j) + C_{LBre}(i/j) + C_{FCre}(i/j) \tag{4}$$

The cost of the hydrogen use is calculated annualising the daily consumption, being L_{h2} the daily hydrogen use, c_{h2} the referential fuel cost, t_{op} the operation days per year, I the discount rate, y the current year, and Y the service life:

$$C_{h2}(i/j) = \sum_{y=1}^{Y} L_{h2}(i/j) \cdot c_{h2} \cdot t_{op} \cdot (1 + I)^{-y} \tag{5}$$

Besides, the costs related to the replacements of both sources are calculated as follows:

$$C_{LBre}(i/j) = \sum_{r_{LB}=1}^{R_{LB}} c_{LB} \cdot n_{LB}(i/j) \cdot (1 + I)^{-r_{LB} \cdot y_{LB}} \tag{6}$$

$$C_{FCre}(i/j) = \sum_{r_{FC}=1}^{R_{FC}} c_{FC} \cdot n_{FC}(i/j) \cdot (1 + I)^{-r_{FC} \cdot y_{FC}} \tag{7}$$

being R_{LB}/R_{FC} the total replacements of any source (LIB or FC), r_{LB}/r_{FC} the number of the current replacement of any source, and y_{LB}/y_{LB} the estimated lifetime of any source.

On the one hand, the LIB life estimation is obtained by an empirical degradation model developed by the authors in [5]. The model considers the differences between LIB technologies, and parametrizes the effect of the temperature (T), depth-of-discharge (DOD), charge and discharge currents (C_{ch} and C_{dch}) and middle SOC ($mSOC$), as Eq. (8) shows. On the other hand, the FC life estimation is obtained by an empirical model first developed by Pei et al. in [12]. The model consists of a linear formula that considers the effects of start-stops (w_1), load change cycling (w_2), idle condition (w_3), and high power load condition (w_4), as shown in Eq. (9).

$$y_{LB} = f_1(T, DOD, C_{ch}, C_{dch}, mSOC) \tag{8}$$

$$y_{FC} = f_2(w_1, w_2, w_3, w_4) \tag{9}$$

3) Maintenance Cost: C_{maint} includes the costs related to the maintenance of the HEMU. An average value for the cost per year is defined (c_{maint}), which is then annualized.

$$C_{maint} = \sum_{y=1}^{Y} c_{maint} \cdot (1 + I)^{-y} \tag{10}$$

VI. RESULTS AND DISCUSSION

In this section the results of the sensitivity analysis are presented, and a discussion is developed focusing on the sizing, LIB technologies and strategies comparison. Table III shows the considered economic parameters, which are defined according to the values typically given in the literature. Then, Fig. 7 shows the LCC obtained for each proposed case, divided into the terms of Eqs. (2) and (4). The results are extended in Table IV with the LCC value, hydrogen cost, and LIB and FC optimal sizing and life estimations. All the costs in Fig. 7 and Table IV are given in per unit (p.u.) values in relation to the results of a traditional DEMU, which has been modelled and simulated following the approach proposed in [6].

TABLE III
ECONOMIC PARAMETERS

Parameter	Value	Parameter	Value
t_{op} [days/year]	320	c_{LIB} [€/kWh]	800 - 1,500
Y [years]	30	c_{FC} [€/kW]	1,000
I [%]	2.5	c_{h2} [€/kg]	11

What can be first concluded when looking to the results is that, in the proposed scenario, the HEMU is far from being economically feasible compared to a traditional DEMU. Even

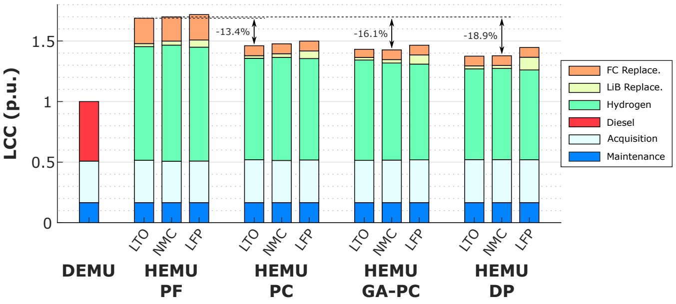

Fig. 7. LCC Results for the different EMS and LIB technologies.

TABLE IV
SUMMARY OF RESULTS

EMS	LIB	LCC [p.u.]	C_h2 [p.u.]	n_FC [kW]	n_LIB [kWh]	y_FC [years]	y_LIB [years]
DEMU	-	1	$1^{(1)}$	$1500^{(2)}$	-	-	-
PF	LTO	1.688	1.910	400	340	1.52	11.57
	NMC	1.699	1.951	400	380	1.58	6.17
	LFP	1.718	1.913	400	340	1.51	4.37
PC	LTO	1.461	1.705	600	280	5.07	10.94
	NMC	1.477	1.732	600	340	5.19	6.03
	LFP	1.499	1.704	600	360	5.20	4.37
GA-PC	LTO	1.432	1.686	500	260	5.33	10.12
	NMC	1.427	1.631	600	440	5.49	7.97
	LFP	1.465	1.609	600	380	5.42	3.92
DP	LTO	1.375	1.525	600	300	5.38	10.27
	NMC	1.378	1.532	600	560	5.44	10.16
	LFP	1.446	1.509	600	400	5.42	3.03

(1) Cost of diesel use (2) Nominal Power of Genset

with the best strategy and LIB technology (DP and LTO), the LCC of the hydrogen option is 37.5% higher. As it can be seen in Fig. 7, the main reason is the difference in the cost derived of the fuel use (hydrogen versus diesel). In the best HEMU case (DP/LTO), the cost of the hydrogen use is 50% higher compared to the cost of the diesel use in the DEMU. And in the worst case (PF/NMC), the cost of the hydrogen use is 95% higher. An important reduction of the hydrogen price (up to 4.5-5.5 €/kWh in the best scenario) is necessary so as the HEMU becomes a competitive option against the traditional DEMU. Anyway, it has to be considered that the decision on the selected topology is not only taken based on economic motivations (e.g. the HEMU avoids the emissions produced by the DEMU).

In the following lines the different HEMU cases are analysed. The discussion is divided into the analysis of the optimal sizing results, the comparison of the different EMSs, and the the comparison of the different LIB technologies.

A. Analysis of Optimal Sizing Results

The analysis of the sizing results unveils that the optimal FC size is around 500-600 kW, as it is the proposed value in the EMSs with the best results (PC, GA-PC and DP). In fact, the option of 500 kW is only proposed in GA-PC/LTO. In the proposed scenario, the options integrating FCs smaller or higher than 400-600 kW are also feasible, but never optimal.

Regarding the proposed LIB sizes, it is noticed that the values differ in relation to the technology, mainly due to the fact that the maximum number of modules that can be integrated is different. Excluding the results of PF strategy (which are not competitive), the optimal LIB sizes are around 260-300 kWh in LTO, around 340-560 kWh in NMC, and around 360-400 kWh in LFP. It can be checked that, in general, as a better result is obtained with one strategy, a higher LIB size is proposed (compare results of DP and GA-PC, or GA-PC and PC). The proposed scenario requires to sustain the charge of the LIB, and therefore, a higher LIB size does not proportionally involve a reduction on the hydrogen use. However, with a higher LIB size a lower DOD can be realized, what increases its life. An example is given when comparing PC/NMC and DP/NMC: increasing the LIB size from 340 kWh to 560 kWh enlarges its life almost a 70%.

In short, the optimal FC size is found to be around 600 kW, and the optimal LIB size stays near the maximum amount of energy permitted by each technology.

B. Analysis of EMSs

From the proposed strategies, DP obtains the best results. Even if the obtained LCC is far from that of the DEMU (37.5-44.6% higher), the results of the most simple approach (PF) are improved up to a 18.9%. The main benefit of DP strategy is the reduction of the hydrogen use. Compared to PF, the cost relative to the fuel is reduced up to 21.1%. However, the main inconvenience of this approach is its difficult integration on a real application, as the optimized variable is the split factor itself (and not a set of rules). Therefore, the results of DP are used to evaluate the performance of the other strategies.

As it was already outlined, PF is the strategy with the worst result. The LCC is 15.8-18.9% higher than in DP, and 12.7-13.4% higher than in the next strategy, PC. As it is seen in Fig. 7, the main disadvantage of PF is the high cost related to the FC replacements. The short life of the FC is caused by the frequent changes on its operation point when the SOC of the LIB is high. In fact, if the LIB cannot be further charged, it is necessary to reduce the FC operation point when the demand is low (in order to avoid a waste of FC energy). However, if the power demand increases again, the operation point must be increased. This issue is depicted in Fig. 8, where the FC power profiles for different strategies are presented. The figure shows the frequent changes in the FC operation point produced by PF strategy. In addition, it also helps understanding that the FC life is increased in GA-PC and DP thanks to the smoother FC operation provided by the EMSs.

PC and GA-PC strategies improve the LCC of PF around a 12.7-16.1%, and are just 1.3-7.2% higher than DP. Specifically, PC improves the results of PF a 13.4% (LTO), 13.1% (NMC) and 12.7% (LFP), due to a reduction on the hydrogen use (10.7%, 11.2% and 10.9%, respectively) and a high improvement on the FC life (from around 1.5 years to more than 5 years). Therefore, it is demonstrated that reducing the FC operation point as the SOC of the LIB increases is an appropriate approach, as that is the only difference between

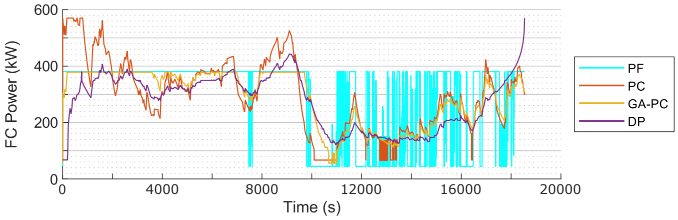

Fig. 8. Evolution of FC power for different strategies (LTO technology).

PF and PC (Fig. 3). Besides, PC strategy optimized by GA further improves these results. The LCC of the original PC is improved a 2.0% (LTO), 3.4% (NMC) and 2.3% (LFP) with this optimization approach, thanks to a better adaptation of the strategy to the proposed scenario. Therefore, it can be stated that the results of GA-PC are halfway between PC and DP, as the LCC is just 4.1% (LTO), 3.6% (NMC) and 1.3% (LFP) higher than in the global optimization of DP. Considering the difficult integration of DP, GA-PC turns to be the most appropriated strategy to be deployed in a real application.

C. Analysis of LIB Technologies

The comparison of the results obtained by the different LIB chemistries concludes that LFP is always the option with the highest LCC value, being a 1.1% (PF), 1.5% (PC), 2.3% (GA-PC) and 6.4% (DP) higher than the next option. The main drawback of LFP is its low lifetime compared to the other technologies, as it is seen in Table IV. However, it can be also checked that with LFP the potential hydrogen use reduction is high, as it is the technology with lowest fuel use in PC, GA-PC and DP strategies.

On the other side, LTO and NMC are found to be the technologies with the best results. The difference between both cases is almost negligible: LTO obtains a better result in PF (-0.6%), PC (-1.1%) and DP (-0.2%), but not in GA-PC (+0.4%). In general, LTO involves a higher acquisition cost, as this technology is more expensive. However, this disadvantage is compensated thanks to the longer life of this technology. Besides, LTO involves a lower hydrogen use, except in GA-SM strategy (in fact, the only case in which NMC is a better choice). Therefore, it can be concluded that LTO will be a slightly better option as long as hydrogen price remains high.

VII. CONCLUSIONS

This paper has presented a LCC analysis for railway projects involving HEMUs, focused on the comparison of LIB technologies (LTO, NMC and LFP) and EMSs, including ruled-based (PF and PC) and optimization-based (GA-PF and DP) approach. The LCC calculation methodology also includes an optimization that searches the best FC and LIB sizes for each case being analysed. In the case of GA-PC strategy, this approach also optimizes the internal parameters of the EMS. It is worth to point out that a case study based on a real railway line has been used to implement the proposed methodology.

The obtained results have demonstrated that with the current hydrogen fuel price, the LCC of the HEMU is far from the one of a traditional DEMU (in the best case DP/LTO, the LCC is 37.5% higher). A reduction of the hydrogen price up to 4.5-5.5 €/kWh would be necessary so as the HEMU becomes competitive. Related to the LIB technologies, the analysis has unveiled that LTO and NMC are the best choices, with almost no difference between them. Finally, the analysis of the proposed EMSs has shown that DP obtains the best results, as the LCC is 1.3-4.1% lower than in GA-PC. However, due to the inconveniences of integrating DP in a real application, it has been concluded that GA-PC is the best option.

Future developments may propose an extension of the LCC analysis to evaluate the effect of different driving scenarios or variations in the considered economic parameters.

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