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Analysis of Optimal Charging Points Location and Storage Capacity for Hybrid and Electric Buses

Análisis de ubicación óptima de puntos de carga y almacenamiento de energía para autobuses híbridos y eléctricos

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Abstract— Aiming to be more attractive in a very competitive market, hybrid and electric buses need to reduce their acquisition and operation cost (TCO - Total Cost of Ownership) compared to conventional buses. In this regard, the sizing of the onboard energy storage system and the charging infrastructure becomes a key design stage. Optimal sizing of these factors is necessary to provide adequate autonomy and service, despite the impact on high investment costs for the manufacturer and fleet operator. Furthermore, the complex interrelationship between these parameters makes the best-performed system design a challenging process. To face this issue, this paper proposes an optimization methodology for the onboard storage capacity of a power system and location as well as charging stations power to reduce TCO (total cost of ownership) in hybrid and fully electric bus routes. For this purpose, several routes have been selected as a case study in Donostia city (Spain) where the proposed methodology has been assessed techno-economically regarding cost factors such as storage systems, charging infrastructure, fuel, and the electricity grid.

***Keywords*— Electric bus, hybrid bus, TCO optimization, charging infrastructure, energy storage system.**

Resumen— Con el objetivo de ser más atractivos en un mercado muy competitivo, los autobuses híbridos y eléctricos necesitan reducir sus costos de adquisición y operación (TCO - Total Cost of Ownership) con respecto a los autobuses convencionales. En este contexto, el dimensionamiento del sistema de almacenamiento de energía a bordo y la infraestructura de carga es una etapa clave del diseño. Un óptimo dimensionamiento de dichos factores es necesario para ofrecer una adecuada autonomía y servicio, a pesar de repercutir en altos costos de inversión para el fabricante y operador de la flota. Además, la compleja interrelación entre estos parámetros hace que el diseño óptimo del sistema sea un proceso desafiante. Como contribución en esta temática, este trabajo propone una metodología de optimización de la capacidad del sistema de energía y ubicación y potencia de los puntos de carga para reducir el TCO en rutas de autobuses híbridos y eléctricos. Para tal efecto, se ha seleccionado como caso de estudio varias rutas en la ciudad de Donostia (España) en las cuales se ha evaluado tecno-económicamente la metodología propuesta atendiendo a factores de costos tales como: sistema de almacenamiento, infraestructura de carga, combustible y energía desde la red eléctrica.

***Palabras Clave*— Autobús eléctrico, autobús híbrido, optimización de TCO, infraestructura de carga, sistema de almacenamiento de energía.**

I. INTRODUCTION

The transportation sector accounted for 24% of the fuel combustion related CO2 emissions in 2017 and is the only sector showing an upward trend [1]. Therefore, essential objectives in transportation involve the reduction of pollutant emissions while managing the continuous growth of the sector. Recent studies [2] emphasize the leadership role of electromobility to achieve these objectives.

One potential candidate for the massive adoption of electric powertrains is the field of urban public transport, due to its specific characteristics – predefined and recurrent routes, or several start-stop phases with low average speeds. The Full Electric Bus (FEB) has emerged as a promising solution in this field. Similarly, the Hybrid Electric Bus (HEB) is understood as an intermediate step between conventional buses and the mentioned FEBs.

Nevertheless, the high upfront costs currently slow down the large-scale adoption of these alternative bus

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topologies. To face this issue and be cost competitive in a very demanding market, HEBs and FEBs need to offer better Total Cost of Ownership (TCO) values compared to conventional buses. The Energy Storage System (ESS) sizing and charging infrastructure definition emerge as crucial design steps influencing the TCO, as several studies have already highlighted [3], [4].

Sufficient ESS capacity is required for appropriate vehicle autonomy, especially in the FEB topology. However, a huge sizing increases the initial cost, as it usually represents around a quarter of the bus total price [2]. Besides, ESS elements suffer from capacity fade over their life, which makes them show shorter lifespans than the associated power electronics [5]. A low ESS degradation must be secured if a favorable TCO is aimed.

The charging infrastructure further increases the initial costs. Different strategies can be deployed, which are divided in charging overnight and opportunity charging (i.e., charging through the route) [6]. Charging overnight requires a huge ESS, and is limited depending on the daily use of the bus. Besides, opportunity charging allows a smaller ESS, but increases the infrastructure costs. Different locations for the Opportunity Charging Points (OCPs) are possible considering the bus stations.

The ESS and the charging points need to be appropriately sized and located to reduce the TCO while providing the required energy demand. In this approach, the characteristics of the bus route need to be considered for the best-performed design, since the TCO is highly susceptible to the specific context of each project [3].

In this regard, the paper presents an optimization approach employing ESS sizing, OCPs sizing, and OCPs location, to improve the TCO of HEB and FEB lines. The proposal includes the bus route modeling with real GPS data and simulations of the vehicle performance. A use case is selected, and techno-economically evaluated regarding factors such as ESS cost, OCPs cost, fuel cost, electricity cost, and several buses driving in the line.

II. SCENARIO OVERVIEW

The optimized scenario corresponds to Line 28 of the local bus service of Donostia/San Sebastian (Spain). The general characteristics of the bus line are shown in Table I. Fig. 1 depicts the altitude profile of the bus route. As seen, for the HEB, a fully electric driving zone has been considered in the city center.

Based on the information of the proposed scenario, a speed profile has been created considering variables such as average time to cover the line, maximum speed, normal traffic, turns, and possible traffic lights. Stop time of the 20s has been considered for the intermediate stations and 5 minutes for the terminal station. The obtained speed profile is also depicted in Fig. 1. When a charging activity is considered in an intermediate station, the stop time is increased to 2.5 minutes, keeping the remainder.

The vehicle models consist of a series HEB and a FEB, both containing an ESS composed of Batteries (BTs). The general schemes of the models are depicted in Fig. 2. Besides, the general characteristics of the considered vehicles are introduced in Table II. The models and the technical characteristics are based on the HEB with hybrid ESS proposed in [5]. In the case of the HEB, the combustion engine has been downsized to enhance the electric performance.

Table I. ROUTE CHARACTERISTICS

Line 28: ”Amara-Ospitaleak”	
Round Trip	12.3 km
Time to cover the line	48’
Bus Stops	29
Buses driving simultaneously	10
Daily driving time	16 hours

Table II. VEHICLE CHARACTERISTICS

	HEB	**FEB**
Dimensions (L/W/H) [m]	12/2.55/3.4	12/2.55/3.4
Passenger Capacity (typical/max.) [-]	50/95	50/95
Electric Motor Power [kW]	196.5	196.5
Combustion Engine Power [kW]	85	-
BT Branch Capacity [kWh]	12	12

III. OPTIMIZATION METHODOLOGY

The proposed optimization approach aims to define the optimal OCPs distribution (Loc_{OCP}), OCPs power (P_{OCP}), and BT capacity (Cap_{BT}) from the TCO point of view. For that purpose, a methodology based on multi-objective optimization has been developed. The multi-objective approach aims to perform a techno-economic analysis for evaluating the influence of each factor affecting the TCO.

The TCO is an economic performance indicator, which includes manufactured price and the costs for maintenance, operation, energy distribution, infrastructure, emission, insurance, and end-of-life [7]. From this approach, the following aspects have been identified as key factors for improving the TCO: ESS cost, OCPs cost, fuel cost, and electricity cost. Therefore, the proposed optimization is focused on these terms.

The general overview of the proposed methodology is depicted in Fig. 3. The approach is an iterative sequence in which several steps (stages 2-5) are repeated. At each iteration i a set of feasible solutions is evaluated. The stages are defined as in the following subsections:

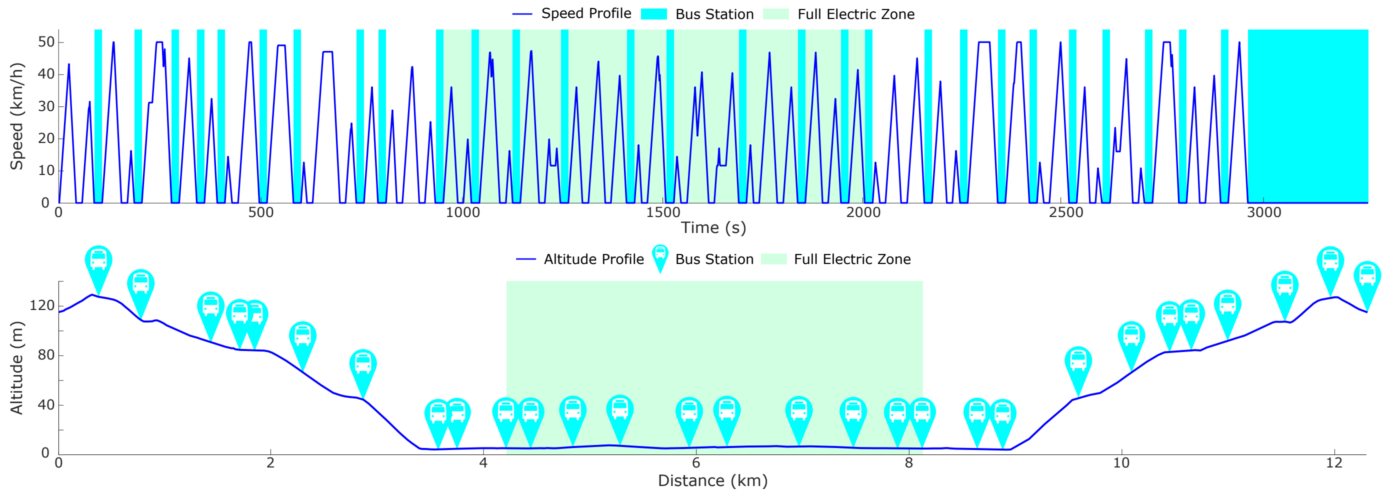

Figure 1. Speed and altitude profile of the use case.

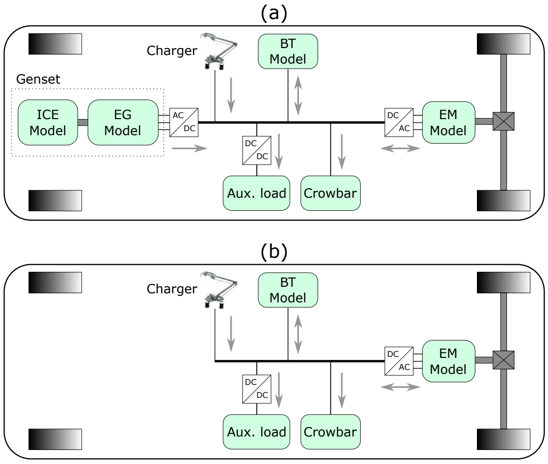

Figure 2. Vehicle Models: a) HEB. b) FEB.

Stage 1: Definition of Route Characteristics

Before initializing the optimization iterations, the data presented in Fig. 1 is defined. The geographical information of the route (i.e., the route path, location of bus stations, and location of possible disruptions or traffic lights) is obtained from .gpx files and processed in Matlab. That information allows for creating a realistic speed profile, as outlined in Section II.

Besides, some of the bus stops are defined as potential OCPs. For that purpose, the approach for Loc_{OCP} depicted in Fig. 4 is deployed. A maximum number of potential OCPs (n_{OCPmax}) is defined by means of the expression in (1), which calculates the required charging activities that fulfill the route demand (T_{Cons}) when the bus works in full electric mode with the minimum BT capacity ($min\ Cap_{BT}(i)$):

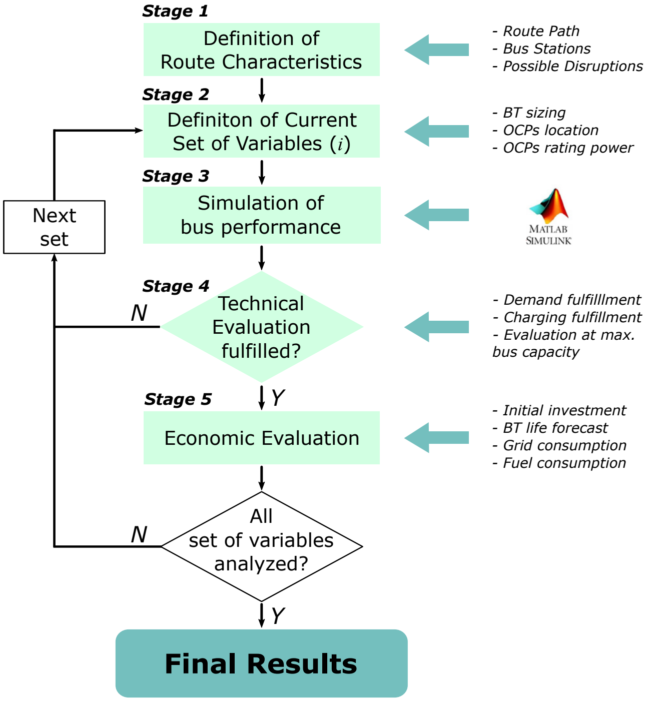

Figure 3. Optimization Approach Diagram.

$$n_{OCPmax} = \frac{T_{cons}}{min\ Cap_{BT}(i)} \tag{1}$$

The route is therefore divided in n_{OCPmax} zones, and the bus stops located closer to the end of each zone are defined as potential OCPs.

Stage 2: Definition of Current Set of Variables

At each optimization iteration i the following variables are defined and introduced in the simulation model: OCPs location ($Loc_{OCP}(i)$), OCPs power ($P_{OCP}(i)$), and BT capacity ($Cap_{BT}(i)$). Expressions (2-4) define the variable bounds, and Fig. 4 shows how they are introduced in the simulation model.

$$\begin{aligned} Loc_{OCP}(i) &\in \{[0\,0\,...\,0],[0\,0\,...\,1],...\,[1\,1\,...\,1]\} && (2)\\ P_{OCP}(i) &\in \{P_{OCP1}, P_{OCP2}, ...\, P_{OCPj}\} && (3)\\ Cap_{BT}(i) &\in Cap_{br}\cdot\{1,2,...\,k\} && (4)\end{aligned}$$

where j defines the number of the considered charging powers, Cap_{br} the capacity of a single BT branch, and k the number of maximum possible BT branches connected in parallel.

- $Loc_{OCP}(i)$ is a binary vector and defines which of the potential OCPs (defined in *Stage 1*) are equipped with a charger in the current iteration. The length of the vector is defined as the number of potential OCPs, and the number of evaluated OCPs in the current loop ($n_{OCP}(i)$) as the aggregation of the binary vector terms:

$$\begin{aligned} |Loc_{OCP}(i)| &= n_{OCPmax} && (5)\\ n_{OCP}(i) &= sum\,[Loc_{OCP}(i)] && (6)\end{aligned}$$

- $P_{OCP}(i)$ defines the power rating of the OCPs.

- $Cap_{BT}(i)$ is a multiple of the capacity of one BT branch (Cap_{br}). Each BT branch is constructed by series connected BT cells in order to reach the voltage of the electric powertrain DC bus.

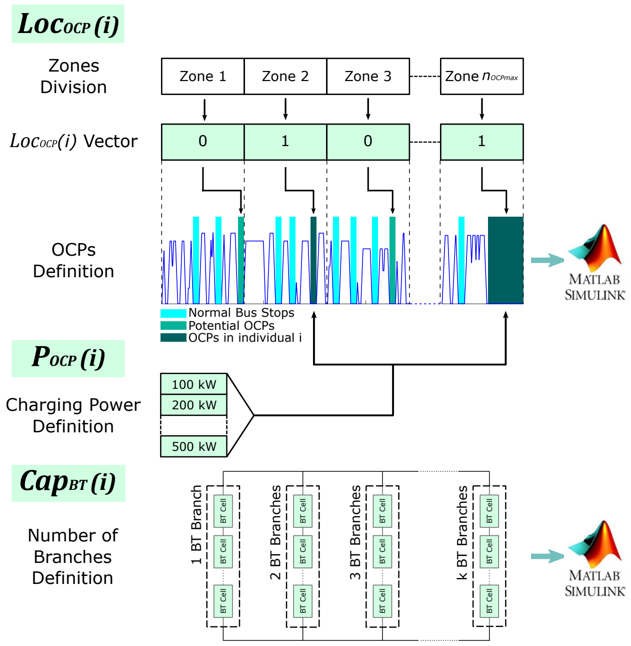

Figure 4. Definition of Variables.

Stage 3: Simulation of Bus Performance

The HEB and FEB models (Fig. 2) have been implemented in Matlab/Simulink as proposed in [5]. At each iteration i, the performance of the HEB or FEB with the current variables is simulated, and the necessary data for the technical and economic evaluations is obtained. The model simulates the performance of the vehicle during a round trip (Fig. 1), and the results are extrapolated to the whole vehicle life.

Stage 4: Technical Evaluation

The simulation results are technically evaluated, considering the following aspects:

Energy and power requirements: the demand profile of the vehicle must be fulfilled step-by-step.

Energy balance: the considered charging activities must allow the ESS to start the next cycle (one round trip) in similar conditions.

Besides, a new simulation is performed to check if the previous two constraints are fulfilled when increasing the vehicle demand (i.e., when the passengers capacity is in the maximum). If all constraints are fulfilled, the algorithm continues to Stage 5.

Stage 5: Economic Evaluation

The economic evaluation consists of the TCO calculation, which is, in turn, the fitness function of the multi-objective approach. For this evaluation, the results of the first simulation of Stage 4 are used. The fitness function is defined as follows:

$$min\;TCO(i) = [C_{BT}(i), C_{ch}(i), C_{f}(i), C_{el}(i)] \qquad (7)$$

where $C_{BT}(i)\,[€/day]$ refers to the BT adquisition and replacement cost, $C_{ch}(i)\,[€/day]$ to the charging infrastructure cost, $C_{f}(i)\,[€/day]$ to the fuel cost, and $C_{el}(i)\,[€/day]$ to the electric charging cost. These terms, previously identified as key factors affecting the TCO, correspond to the objective functions of the multi-objective approach.

- *BT Cost:*

$$C_{BT} = \frac{C_{BT\_Ca} + C_{BT\_Re}}{t_{OP}}\quad [€/day] \qquad (8)$$

being $C_{BT\_Ca}\,[€/year]$ the annualized capital cost related to the initial investment of the BT pack, $C_{BT\_Re}\,[€/year]$ the annualized replacement cost of the

BT pack, and t_{OP} $[days]$ the bus operation days per year. The expression for C_{BT_Ca} stands as follows:

$$C_{BT\_Ca} = C_{BT\_kWh} \cdot Cap_{BT}(i) \cdot CRF \quad [€/year] \tag{9}$$

where C_{BT_kWh} $[€/kWh]$ is the referential cost of the BT technology and CRF $[year^{-1}]$ the capital recovery factor, which is defined as follows:

$$CRF = \frac{I \cdot (1+I)^T}{(1+I)^T - 1} \quad [year^{-1}] \tag{10}$$

where I $[\%]$ and T $[years]$ refer to the interest rate and the lifetime of the whole system, respectively.

On the other hand, the expression for C_{BT_Re} from (8) is defined as follows:

$$C_{BT\_Re} = \sum_{i=1}^{r_{BT}} \frac{C_{BT\_kWh} \cdot Cap_{BT}(i) \cdot CRF}{(1+I)^{i \cdot Life_{BT}}} \quad [€/year] \tag{11}$$

being r_{BT} [-] the number of BT replacements, and $Life_{BT}$ $[yars]$ the BT life estimation.

The Wöhler Curve method [5] obtains the lifespan estimation. It defines the amount of charge and discharge cycles that the BT can withstand at each Depth of Discharge (DOD) before reaching the End-Of-Life (EOL). To count the cycles, the Rainflow Algorithm is used [5]. The algorithm analyzes the SOC profile obtained at the simulation, counting the cycles and grouping them in ranges of DODs. The lifespan expression stands as follows:

$$Life_{BT} = \left(\sum_{j=1}^{n_{DOD}} \frac{n_{BT\_dj} \cdot t_{OP}}{CF_{uj}} \right)^{-1} \quad [years] \tag{12}$$

where n_{DOD} [-] denotes the number of different DOD ranges (100 in the current approach), n_{BT_dj} [-] the cycles counted at each DOD range j, and CF_{uj} [-] the maximum cycles allowed at each range.

- *Charging Infrastructure Cost (OCPs Cost):*

$$C_{ch} = \frac{C_{ch\_Ma} + C_{ch\_Ca}}{t_{OP}} \cdot \frac{n_{OCP}(i)}{n_{share}} \quad [€/day] \tag{13}$$

being C_{ch_Ma} $[€/year]$ the value related to the maintenance cost of a single OCP, C_{ch_Ca} $[€/year]$ the annualized capital cost related to the initial investment of a single OCP, and n_{share} [-] the number of buses that share the OCPs. The last term allows normalizing the cost of the infrastructure to a single bus. C_{ch_Ca} is defined as follows:

$$C_{ch\_Ca} = (C_{OCP_{fix}} + C_{OCP_{kW}} \cdot P_{OCP}(i)) \cdot CRF \quad [€/year] \tag{14}$$

where $C_{OCP_{fix}}$ [€] represents the fixed costs of a single OCP (e.g. structure and connection point), and $C_{OCP_{kW}}$ $[€/kW]$ the costs related to the sizing of a single OCP (e.g. power electronic devices).

- *Fuel Cost:*

$$C_f = Cons_f(i) \cdot C_{f\_L} \quad [€/day] \tag{15}$$

being $Cons_f(i)$ $[liter/day]$ the daily fuel consumption, and C_{f_L} $[€/liter]$ the referential cost of the fuel.

- *Electric Charging Cost:*

$$C_{el} = C_{el\_fix} + C_{el\_var} \quad [€/day] \tag{16}$$

being C_{el_fix} $[€/day]$ the cost related to the connection of the OCPs to the grid, and C_{el_var} $[€/day]$ the cost related to its consumption. Each term is defined as follows:

$$C_{el\_fix} = \frac{C_{el\_kW} \cdot P_{OCP}(i)}{t_{OP}} \cdot \frac{n_{OCP}}{n_{share}} \quad [€/day] \tag{17}$$

$$C_{el\_var} = Cons_{el}(i) \cdot C_{el\_kWh} \quad [€/day] \tag{18}$$

where C_{el_kW} $[€/kW/year]$ represents the referential annual cost of the power connection to the grid, $Cons_{el}(i)$ $[kWh/day]$ the daily electricity consumption, and C_{el_kWh} $[€/kWh]$ the electricity referential cost.

IV. RESULTS AND DISCUSSION

For the validation of the optimization approach, a base case has been evaluated. From the conclusions obtained in the base case, a set of improved cases have been proposed and also evaluated.

Table III shows the economic values considered in the approaches of the current section, selected from actual market prices and similar approaches [3], [5], [8], [9]. Besides, Table IV shows the variable constraints considered for each bus topology.

Table III. ECONOMIC PARAMETERS

	Parameter	Value
General	t_{op} [days/year]	300
	I [%]	2.5
Battery Cost	C_{BT_kWh} [€/kWh]	1500
OCP Cost	$C_{OCP_{fix}}$ [€]	240,000
	$C_{OCP_{kW}}$ [€/kW]	60
	C_{ch_Ma} [€/year]	7,000
Fuel Cost	C_{f_L} [€/L]	1.1
Grid Cost	C_{el_kW} [€/kW/year]	25.9
	C_{el_kWh} [€/kW]	0.088

Table IV. OPTIMIZATION CONSTRAINTS

	HEB Study Case	FEB Study Case
$n_{OCP}(i) \in$	$\{0, 1...3\}$	$\{0, 1...3\}$
$P_{OCP}(i) \in$	$\{100, 200...500\}$	$\{100, 200...500\}$
$Cap_{BT}(i) \in$	$\{12, 24...60\}$	$\{12, 24...300\}$

A. Base Case Optimization

Considering that urban bus lines can be driven simultaneously by more than one bus, the base case has been set assuming a single HEB or FEB driving in the line ($n_{share} = 1$). Due to the multi-objective nature of the optimization approach, the results returned by the algorithm are a set of alternative optimal solutions with different techno-economical characteristics. For a better display, the solutions have been ranked in ascending order regarding the TCO. Figure 5 depicts the first six solutions of the base case optimization for each bus topology. The figure also indicates the best solutions regarding each objective.

The results of the HEB (Fig. 5a) show that there is a set of solutions close in terms of TCO, as it differs less than the 6% between Solutions 1-6. The results suggest that the bus line needs a single OCP located at the terminal station (Solutions 1-6). The best result with 2 OCPs (Solution 15, out of the Figure) involves a TCO gain of the 63% comparing with the best overall result. Regarding the OCP power, the best results are around 100-200 kW, what infers that the HEB does not need fast charging (>300 kW). Solution 5, which proposes exactly 300kW, allows the lowest fuel consumption.

However, Solutions 1, 2, and 6 obtain similar consumptions keeping the charging power at 200kW. It is also worth to highlight the diversity on the ESS configurations of the depicted solutions, which vary from 24 kWh to 60 kWh. The results show a correlation between the BT capacity and the number of replacements, as the latter are increased in the proposals with the lowest BT capacity. This increase, however, affects the initial investment.

The multi-objective nature of the optimization allows the comparison of the different factors affecting the TCO. Considering that the TCO variation between Solutions 1-6 can be neglected (<6%), other factors can be used to select the most suitable solution. For instance, as already mentioned, if fuel use reduction is aimed, Solution 5 is the most suitable option. On the contrary, if lower electric use is preferred, Solution 4 is the most appropriate. This solution is also the best option if a small investment in BT systems is aimed.

On the other hand, the results of the FEB (Fig. 5b) show that the TCO variation between the depicted solutions is higher than in the HEB case. Only Solutions 1-3 are in the window of 6%. All the depicted solutions propose a single OCP in the terminal station, as in the HEB. The deployment of a second OCP involves a TCO increase of the 54% in the best case (Solution 44, out of the Figure). Regarding the OCP power, all the solutions propose 400 kW, except for Solution 5 (500kW, with no noticeable advantage). Therefore, the main difference between Solutions 1-6 lies on the ESS. The BT configurations differ from 48 to 96 kWh. It is hence proved that the storage capacity and charging rate is increased when turning into a fully electric powertrain.

The comparison of the different factors affecting the TCO is only effective to obtain a comparison of the BT costs since the OCP and electricity costs are very similar. The main cause is the reduction of the operation possibilities in the FEB topology, as all the consumption

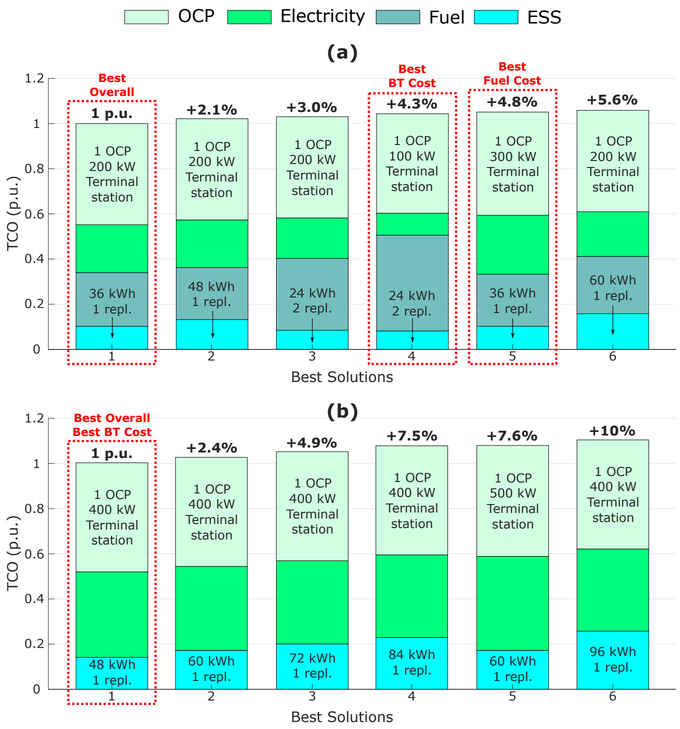

Figure 5. Results of Base Case Optimization: a) HEB b) FEB.

is electric. Consequently, the best solution regarding BT cost coincides with the best overall.

To analyze the cost-effectiveness of the base case, a comparison between the best base results (Solutions 1-2 from each topology) and a conventional diesel bus driving in the same line has been set. Fig. 6 summarizes the obtained results. To make a more comprehensive comparison, the effect of the fuel price variation has also been included (with low, base, and high fuel price scenarios). The numeric values represent the TCO variation concerning the base fuel price.

The TCO of the best HEB solution is 29% higher than the baseline of the diesel bus, while the best FEB solution is 25% higher. Neither of them shows a better TCO than the high fuel price scenario. Even if the energy cost (fuel+electricity cost) is lower for the electric options, the high charging infrastructure cost increases the TCO overmuch. Consequently, it can be deduced that the implementation of a single HEB or FEB in the current route scenario has not cost competitive.

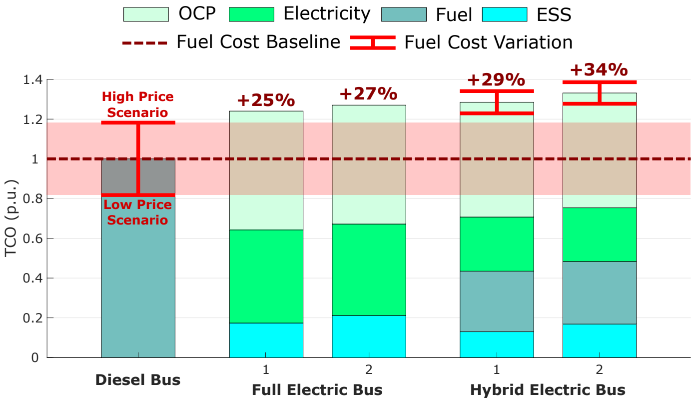

Figure 6. Base Case Results Comparison.

B. *Improved Scenarios Optimization*

More optimizations have been conducted to understand the effect of deploying several HEBs or FEBs in the current bus line ($n_{share} > 1$). A maximum of 10 buses has been considered in the analysis, in accordance with the real data of the line (Table I). The results have been normalized to a single bus cost (TCO/bus), so the different scenarios can be compared. Fig. 7 summarizes the obtained results, representing the TCO of the best overall solution of each improved scenario. In all the new scenarios, the same optimal configurations as in the base case (Fig. 5) have been obtained. The TCO of the diesel bus is also included in the graph, together with the effect of the fuel cost fluctuation. The numeric values represent the TCO variation in relation to the base fuel price.

The results show that the increase of buses involves a high TCO reduction, mainly since the OCP cost decreases. This fact makes the electrification of the line cost competitive. The increase in the number of HEBs shows that two vehicles are required to reduce the TCO below the base fuel price scenario (5% lower). One more bus makes the TCO fall beneath the low price scenario (17% lower than the base price). In the case of the FEB, the results show that two vehicles are also enough to turn the line electrification cost competitive, with the TCO reduced a 16% compared to the base price scenario. If the low price scenario is analyzed, the FEB is very close to the diesel bus. Therefore, the deployment of an additional bus is recommended (30% lower than the base price).

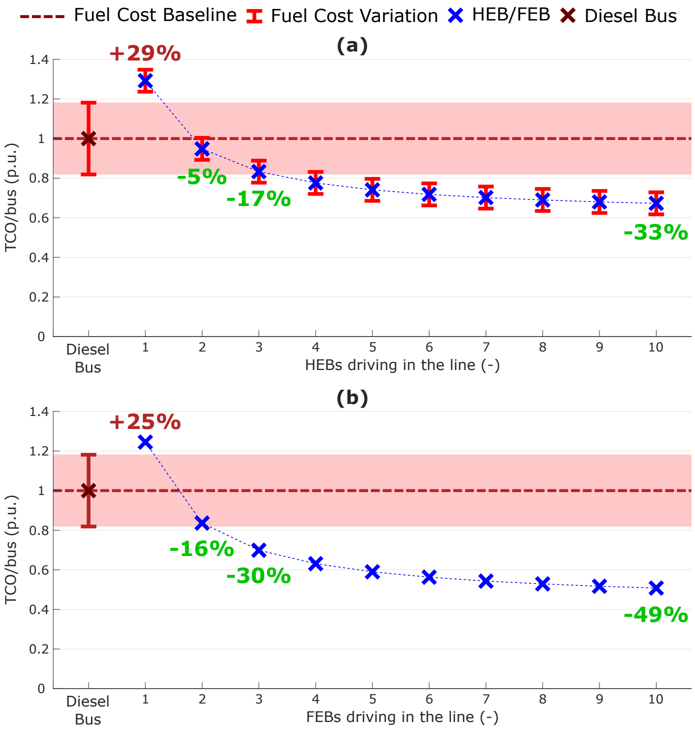

Figure 7. TCO variation of the best overall solution when increasing the number of buses driving in the line: a) HEBs b) FEBs

V. CONCLUSIONS

This paper has presented a multi-objective optimization approach to defining the OCPs location, OCPs power rate, and ESS sizing for HEBs and FEBs lines. The different steps of the methodology have been outlined. A real scenario has been selected and modeled by the real data of the bus line. Finally, the usefulness of the methodology has been validated by means of the techno-economic analysis of the results obtained at the proposed base case.

The techno-economic analysis has revealed that for both bus topologies, the optimal solution consists of an

OCP located at the terminal station. The deployment of a second OCP has been found to increase the costs of around 50-60%. The comparison of the base case with a conventional bus has proved that the deployment of a single FEB or HEB is not cost competitive (25% and 29% increase, respectively). Further analysis has shown that the bus line electrification turns into cost competitive when more buses are simultaneously driving and sharing the OCPs since the OCP costs are shared among more buses.

Future evaluations may consider the sharing of OCPs among different bus lines to improve the TCO further, or the upscale of the optimization methodology considering the energy management strategy.

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