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Cost comparison of different configurations of a hybrid energy storage system with battery-only and supercapacitor-only storage in an electric city bus

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Abstract. This paper proposes four different cost-effective configurations of a hybrid energy storage system (HESS) in an electric city bus. A comparison is presented between a battery powered bus (battery bus) and supercapacitor powered bus in two configurations in terms of initial and operational costs. The lithium iron phosphate (LFP) battery type was used in the battery bus and three of the hybrids. In the first hybrid the battery module was the same size as in the battery bus, in the second it was half the size and in the third it was one third the size. The fourth hybrid used a lithium nickel manganese cobalt oxide (NMC) battery type with the same energy as the LFP battery module in the battery bus. The model of LFP battery degradation is used in the calculation of its lifetime range and operational costs. For the NMC battery and supercapacitor, the manufacturers' data have been adopted. The results show that it is profitable to use HESS in an electric city bus from both the producer and consumer point of view. The reduction of battery size and added supercapacitor module generates up to a 36% reduction of the initial energy storage system (ESS) price and up to a 29% reduction of operational costs when compared to the battery ESS. By using an NMC battery type in HESS, it is possible to reduce operational costs by up to 50% compared to an LFP battery ESS.

Key words: hybrid energy storage system, electric bus, battery bus, supercapacitor bus, energy storage system cost, HESS cost comparison.

1. Introduction

Currently the transport sector causes about 14% of world greenhouse gases emissions [1]. Hence, the use of fossil fuels in this sector is one of the key factors that affect climate warming. The use of electric vehicles (EVs) seems to be a viable solution to that problem, especially when renewable sources have a big share in the power system. However, the transition to electrified transport is progressing very slowly.

There are a few reasons for this, but the price difference between electric and internal combustion engine (ICE) vehicles is the most important according to the report presented in [2]. With a very wide range of vehicles on the market, customer decisions are made based on a number of different criteria. One of the most important for most people is the initial price and ongoing operating costs of the vehicle [2, 3]. So, to accelerate the transition to electric transport, we should focus on this parameter.

The battery pack is the most expensive component of the electric drive system, and has a decisive impact on its price [2]. Although the specific energy of lithium batteries is sufficient to ensure an EV range of up to 400 km on one charge, the price of the lithium cells is still high. Moreover, the durability of the cells is limited. The number of cycles which batteries can perform until losing 20% of initial capacity is about 500 to 700 for lithium cobalt oxide (LCO) cells, 1000 to 2000 for lithium iron phosphate (LFP) cells and about 1000 to 4000 for lithium nickel manganese cobalt oxide (NMC) cells. These values are obtained in rated conditions. Higher load current, variable temperature and high depth of discharge accelerate the aging process of the battery [4–8]. In real-life operation on board of an EV, the batteries are subjected to higher current and temperature loads than under rated conditions. In order to prolong battery life in vehicles, the discharge depth is limited. This in turn leads to a decrease in effective specific energy.

Although an electric vehicle has a significantly less negative environmental impact during its operation, its production process results in significantly higher energy consumption and greenhouse gas emissions than in the case of an IC vehicle [9–12]. Most responsible for this is the battery pack production process. Therefore, to reduce the negative impact of the production process on the environment, EVs should be used for as long as possible. The key here is battery life.

The solution to the problem of lithium battery durability is connecting them with supercapacitors in a hybrid energy storage system (HESS). A supercapacitor has much higher specific power than a battery and can perform up to 1 million cycles. In a HESS, it is used to support a battery at high power demand, thus reducing battery current. This allows longer battery life. This solution has the greatest impact on cycle aging. Therefore, the use of HESS generates the most profit in vehicles that are used continuously such as buses, taxis, rental city cars. Increasing the durability of energy storage allows for decreasing the operational costs of an EV. The problem of greater price availability can be solved by developing a hybrid system configuration that allows for reducing the vehicle price and operational costs as much as possible.

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1.1. Related work. Scientists and manufacturers have made a great effort to improve EVs and HEVs [13–15] and hybrid energy storage systems have long been proposed as an improvement in many research papers [14, 16]. Some of these are focused on sizing and energy management optimization using initial cost and operational cost as an objective function. Victor Herrera et al. performed optimization of an HESS minimizing the operational cost of a tramway in [17] and a hybrid bus in [18]. In both cases batteries were not the main source of energy. For the tram it was a catenary and for the bus it was an ICE. Therefore, no comparisons were performed with battery powered vehicles. Optimization of a battery-supercapacitor HESS as a main source of energy for an electric bus was made by Ziyou Song et al. in [19] and [20]. In both papers, HESS life cycle cost and supercapacitor cost were minimized. However, those results were not compared to a battery-only bus. A viable comparison between a battery powered bus (battery bus) and an HESS using different energy management strategies was done by Ziyou Song et al. in [21]. The study took into account battery aging and showed the possibility of decreasing the cycle-related costs of the energy storage system. Very useful results, focusing on size and control optimization of HESS, were presented by Xiasung Hu in [22]. Initial and total costs of energy storage were minimized. The main source of energy in this case were fuel cells connected to a battery-supercapacitor HESS.

A cost analysis of different energy storage devices, based on a broad literature review, was conducted by Behnam Zakeri and Sanna Syri in [23]. In this instance, however, the study focused on energy storage in a power supply system and not taking vehicles into account.

Di Zhu et al. presented a cost driven method of designing a hybrid energy storage system in an electric car in [24]. In this analysis, a comparison was presented between a battery-only car and an HESS in terms of mass, volume and daily costs of operation. The results show the possibility of decreasing all those parameters by installing an HESS. Yet the authors did not state what type of lithium battery or value of converter efficiency were used in the simulations, and some of the vehicle's parameters seem to be too low, e.g. frontal area and converter cost, which could influence the results. No comparison was made between the initial cost of battery-only and hybrid energy storage systems.

1.2. Key contribution. The most important question that was asked in the research presented in this article is: *Is it profitable to use hybrid energy storage systems in an electric bus from both producer and consumer points of view?* To answer the question, a comparison was conducted between four different configurations of HESS, battery ESS and supercapacitor ESS in an electric city bus. The study uses the latest energy management method, current battery aging models and current energy storage device prices.

1.3. Paper organization. Section 2 discusses proposed bus power systems and ESS configurations. Models for ESS energy efficiency and degradation adopted in the calculations are described in Section 3. The energy management strategy (EMS) is presented in Section 4 and the method of calculating the operational cost of ESS in Section 5. Section 6 contains results and discussion and Section 7 – conclusions.

2. ESS configurations and driving scenarios

2.1. Battery bus. Figure 1 shows the bus power systems considered in the analysis. Vehicle and ambient parameters are given in Table 1. The reference configuration of the energy source was homogeneous battery energy storage (battery bus presented in Fig. 1), which is currently the most commonly used solution. In this instance, the batteries were sized for a range of 150 km. The analysis uses the parameters of the LFP battery (Table 2). They work in an SOC range from 10% to 90% and are charged once a day. The driving cycle used in the test is UITP (sort 2) cycle which is typical for buses driving in urban areas. The advantage of this system is the lack of DC/DC converters that significantly reduce energy conversion efficiency and complicate the power supply. The disadvantages are the high values of battery current which accelerate its degradation.

Table 1
EVs and ambient parameters

Parameter	Value	Unit
Mass – without energy storage (M)	10 336	kg
Rotating mass coefficient (k_m)	1.05	–
Frontal area (A)	7	m^2
Drivetrain and motor efficiency (η_d)	0.85	–
Inverter efficiency (η_{inv})	0.95	–
DC/DC converter efficiency (η_c)	0.95	–
Bus lifetime range (S_{bus})	500 000	km
Air density (ρ)	1.225	kg/m^3

2.2. Supercapacitor bus. Unlike for the battery bus, an analysis has been conducted of a bus with homogeneous supercapacitor energy storage (supercapacitor bus presented in Fig. 1). The reasons for choosing this type of energy storage were its high durability and wide range of working temperature. Single cell parameters are given in Table 3. Two power scenarios have been considered. In the first, ESS has sufficient energy to drive from one terminal to another (15 km) and is charged at terminals. There is no need to charge supercapacitors at stops. The disadvantage of this type of power supply is the presence of a DC/DC converter and the large mass and initial price of the ESS.

In the second scenario, the ESS provides energy to travel 5 km. It must, therefore, be recharged at the stops. The bus will be lighter and cheaper than in the first case, but the cost of the charging infrastructure will increase.

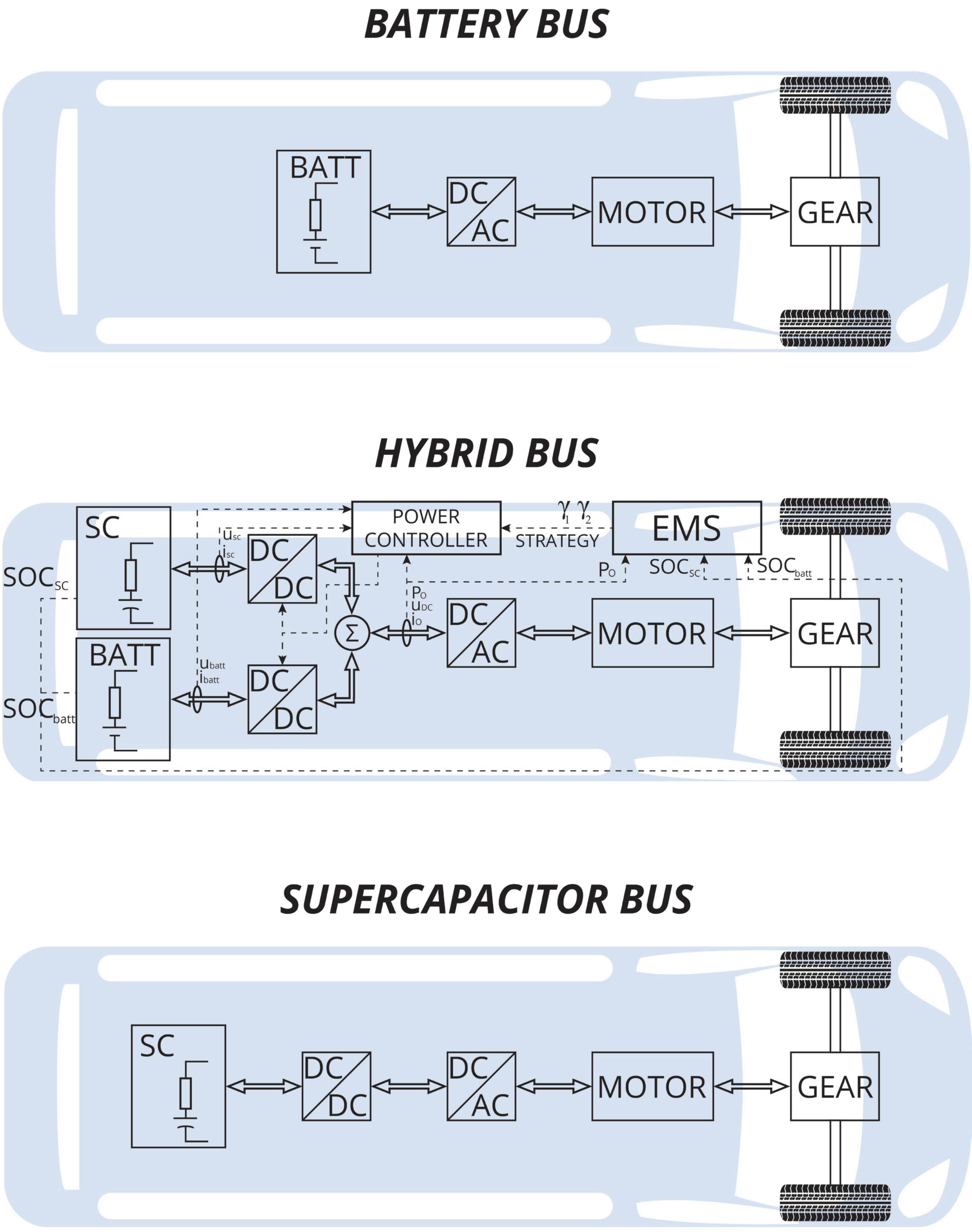

Fig. 1. Electric bus power systems configurations

Table 2
Battery cell parameters

Parameter	Value	Unit	Parameter	Value	Unit
Cell 1			**Cell 2**		
Manufacturer	HeadWay	–	Manufacturer	Boston Power	–
Type	38 120	–	Type	Swing 5300	–
Chemistry	LFP	–	Chemistry	NMC	–
Mass (m_{batt_cell1})	0.33	kg	Mass (m_{batt_cell1})	0.0935	kg
Capacity (Q_{batt_cell1})	10	Ah	Capacity (Q_{batt_cell1})	5.3	Ah
Nominal voltage $(U_{N\_batt\_cell1})$	3.2	V	Nominal voltage $(U_{N\_batt\_cell1})$	3.65	V
Maximum Discharge Current (continuable)	150	A	Maximum Discharge Current (continuable)	13	A
Maximum Charge Current (continuable)	60	A	Maximum Charge Current (continuable)	10.6	A
Internal resistance $(R_{s\_batt\_cell1})$	6	mΩ	Internal resistance $(R_{s\_batt\_cell1})$	15.5	mΩ
Cost $(Cost_{batt\_cell})$	21	\$	Cost $(Cost_{batt\_cell})$	9.6	\$

Table 3
Supercapacitor cell parameters

Parameter	Value	Unit
Manufacturer	Maxwell	–
Type	BCAP 3000	–
Mass (m_{SC_cell})	510	g
Nominal voltage $(U_{N\_SC\_cell})$	2.7	V
Nominal capacitance (C_{SC})	3000	F
Internal resistance $(R_{s\_SC\_cell})$	0.29	mΩ
Stored energy (E_{SC_cell})	3.04	Wh
Specific power	5.9	kW/kg
Cost $(Cost_{SC\_cell})$	60	\$
Nominal cycle life	1 000 000	–

2.3. Hybrid. The third studied configuration was an HESS connecting a battery with a supercapacitor (Fig. 1). Two DC/DC converters were used for all hybrids due to the strategy employed. The analysis compares four different HESS configurations. In each of them, the supercapacitor module used is identical.

In Hybrid 1, the battery module is identical to that of the battery bus. A supercapacitor module was added to reduce the battery load and extend battery life. The range of the vehicle is 150 km. Batteries work in the SOC range from 10% to 90% and are recharged once a day.

In Hybrid 2, the battery size has been halved in size. This was achieved by significantly lowering the maximum current drawn from the battery using supercapacitors. In this configuration, the bus is lighter and the initial price of the tray is lower than in the case of a battery bus. Vehicle range is 75 km. Batteries operate in the SOC range from 10% to 90% and are recharged twice a day.

In Hybrid 3, the battery size was reduced by two thirds compared to Hybrid 1. Again, this was possible thanks to the use of a supercapacitor module. The initial price and vehicle weight are considerably lower than that for the battery bus. Vehicle range is 50 km. Batteries work in the SOC range from 10% to 90% and are recharged three times a day.

In Hybrid 4, the energy parameters of the battery module are identical to those of configuration 1. Thus, the range of the vehicle is 150 km. Batteries work in the SOC range from 10% to 90% and are recharged once a day. This time, however, a Boston Power NMC battery is used, the parameters of which are given in Table 2. These batteries have a higher capacity than the LFP batteries. They are also significantly cheaper per unit of energy. Their drawback is their faster degradation at high load currents than the LFP. Still, by using supercapacitors, we can significantly extend their life.

2.3. Detailed configurations. Detailed configuration data for each power supply are presented in Table 4. For all bus solutions presented, the power, maximum mass, voltage and distance of the single drive are identical. Pack weights have been determined by increasing the weight of cells by 24% according to the data given in [25]. Therefore, the mass of the battery module $M_{batt} = 1.24 \cdot N_{p\_batt} \cdot N_{s\_batt} \cdot m_{batt\_cell}$, and the mass

Table 4
Bus ESS configuration parameters

	BATTERY BUS	HYBRID 1	HYBRID 2	HYBRID 3	HYBRID 4	SUPERCAP BUS 1	SUPERCAP BUS 2
VEHICLE							
total vehicle mass (without passengers) [kg]	13 000	13 381	12 011	11 630	11 978	15 721	12 211
motor power [kW]	200	200	200	200	200	200	200
maximum vehicle mass (with passengers) [kg]	18 000	18 000	18 000	18 000	18 000	18 000	18 000
range in UITP sort 2 (easy urban) [km]	150	150	75	50	150	15	5
DC voltage [V]	600	600	600	600	600	600	600
auxiliary load [kW]	5	5	5	5	5	5	5
distance of one ride [km]	15	15	15	15	15	15	15
BATTERY MODULE							
Chemistry	LFP	LFP	LFP	LFP	NMC	–	–
number of cells connected in series (N_{s_batt})	186	186	186	186	160	0	0
number of cells connected in parallel (N_{p_batt})	35	35	17	12	68	0	0
nominal voltage [V]	595.2	595.2	595.2	595.2	592	0	0
stored energy [kWh]	210	210	105	70	210	0	0
cells mass [kg]	2148.3	2148.3	1043.46	736.56	1017.28	0	0
module mass (M_{batt}) [kg]	2663.89	2663.89	1293.89	913.33	1261.43	0	0
cells cost [$]	136 710	136 710	66 402	46 872	104 448	0	0
module cost ($Cost_{batt}$) [$]	191 394	191 394	92 962.8	65 620.8	146 227.2	0	0
nominal power for 2000 cycles (I = 0.5C) [W]	104 160	104 160	50 592	35 712	88 563.2	0	0
SUPERCAPACITOR MODULE							
number of cells connected in series (N_{s_SC})	0	222	222	222	222	222	222
number of cells connected in parallel (N_{p_SC})	0	2	2	2	2	38	13
nominal voltage [V]	0	599.4	599.4	599.4	599.4	599.4	599.4
capacitance [F]	0	27.03	27.03	27.03	27.03	513.51	175.68
cells mass [kg]	0	226.4	226.4	226.4	226.4	4302.4	1471.9
module mass (M_{SC}) [kg]	0	280.79	280.79	280.79	280.79	5334.93	1825.11
cells cost [$]	0	26 640.0	26 640.0	26 640.0	26 640.0	506 160.0	173 160.0
module cost ($Cost_{SC}$) [$]	0	37 296	37 296	37 296	37 296	708 624	242 424
stored energy [Wh]	0	1349.8	1349.8	1349.8	1349.8	25 645.4	8773.4
usable energy [Wh]	0	1012.3	1012.3	1012.3	1012.3	19 234.1	6580.1
nominal power [kW]	0	251.7	251.7	251.7	251.7	4783.2	1636.4
maximum power [kW]	0	1335.996	1335.996	1335.996	1335.996	25 383.924	8683.974
DC/DC CONVERTERS							
number of converters	0	2	2	2	2	1	1
cost of converters ($Cost_c$) [$]	0	20 000	20 000	20 000	20 000	10 000	10 000
mass of converters [kg]	0	100	100	100	100	50	50
ENERGY MANAGEMENT STRATEGY	–	GBS	GBS	GBS	GBS	–	–
A	–	1.1	1.1	1.2	1.1	–	–
B	–	0.06	0.04	0.032	0.04	–	–
C	–	0.5	0.5	0.6	0.5	–	–
D	–	0.1	0.1	0.1	0.1	–	–
ENERGY STORAGE SUMMARY							
TOTAL ENERGY STORAGE SYSTEM MASS (M_{ESS}) [kg]	2663.89	3044.68	1674.68	1294.12	1642.21	5384.93	1875.11
INITIAL ENERGY STORAGE SYSTEM COST ($Cost_{ESS}$) [$]	191 394	248 690	150 258.8	122 916.8	203 523.2	718 624	252 424

of supercapacitor module $M_{SC} = 1.24 \cdot N_{p\_SC} \cdot N_{s\_SC} \cdot m_{SC\_cell}$. The price of modules was set based on one distributor's pricing for all cell types [26–28]. Considering data on the cost of module integration presented in [29], the prices of the modules were obtained for batteries from: $Cost_{batt} = 1.4 \cdot N_{p\_batt} \cdot N_{s\_batt} \cdot Cost_{batt\_cell}$ and supercapacitors from: $Cost_{SC} = 1.4 \cdot N_{p\_SC} \cdot N_{s\_SC} \cdot Cost_{SC\_cell}$.

Total weight and initial price were determined from (1) and (2).

$$M_{ESS} = M_{batt} + M_{SC} + M_c \tag{1}$$

$$Cost_{ESS} = Cost_{batt} + Cost_{SC} + Cost_c. \tag{2}$$

3. Simulation model

3.1. Energy storage efficiency model. The analysis conducted in this paper focuses on economic and ecological aspects of electric vehicles. The energy storage device models used here affect the energy consumption estimate. Thus, the most important parameters for the calculation are the source voltage and the internal resistance. Therefore, a series models have been used, i.e. of the voltage source and resistance for the battery (Fig. 2a) and of the RC model for the supercapacitor (Fig. 2b). The internal resistance of lithium batteries and supercapacitors varies depending on a number of factors, such as state of charge (SOC), value and direction of load current, temperature, and state of health (SOH) [5–8, 30]. These changes affect the accuracy of the estimation of the vehicle's energy consumption and consequently of its operational costs. Therefore, in such a study as this these changes cannot be omitted. Because the influence of changes in internal resistance on the value of energy consumption is not dominant, some simplifications have been adopted.

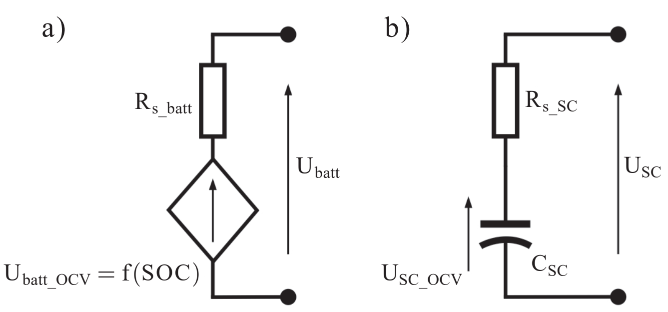

Fig. 2 Equivalent circuit of a) lithium battery and b) supercapacitor

Based on measurements results for LFP battery presented in [7, 31], for NMC battery presented in [32, 33] and for supercapacitors shown in [34–37] and manufacturer datasheets, the minimum and maximum values of internal resistance deviation from nominal values have been assumed. The internal resistance data are shown in Table 5. The calculations were made for all resistance values and the maximum deviations from the rated values were considered in the results.

Table 5
ESS internal resistance

	Minimum value	Manufacturer data	Maximum value	Unit
LFP	70	100	200	%
	4.2	6	12	mΩ
NMC	70	100	250	%
	10.85	15.5	38.75	mΩ
S.C.	70	100	200	%
	0.203	0.29	0.58	mΩ

3.2. ESS cycle life. A lithium battery is considered to reach end-of-life when its capacity drops to 80% of its initial value. According to the data provided by the manufacturer, an LFP battery can perform 2000 cycles for charging and discharging currents not exceeding 0.5C. When this value is exceeded, the number of cycles decreases significantly. These data refer to constant current values. While a battery operates on board of a bus its load is not constant and establishing the length of its life is much more complicated. The Arrhenius equation (3) was used to determine the battery life in the study. This model has been used in many studies on LFP batteries and its operation has been positively verified by measurements [20, 38]. Exponent z is constant value equal 0.6.

$$Q_{loss} = A \cdot \exp\left(-\frac{E_a - B \cdot C_{rate}}{R \cdot T}\right) \cdot Ah^z \tag{3}$$

where Q_{loss} means loss of battery capacity, $A = 26.7$ is a pre-exponential factor, $E_a = 24580$ J denotes activation energy, R gas constant, and $T = 296$ K temperature. Using C_{rate}, the current value with respect to the battery capacity is determined, and B is the C_{rate} compensation factor. Ah is the total charge through the battery terminals expressed in ampere-hours and determined by (4).

$$Ah = \frac{1}{3600} \cdot \int |i_{batt}| \cdot dt. \tag{4}$$

The values of the individual coefficients in equation (3) were determined by fitting the function to measurement results with the least square fit method. The results comparing modeled and measured degradation of the LFP battery are presented in Fig. 3. After losing 20% of its capacity the battery enters the phase of non-linear aging and the degradation process significantly accelerates. The effect of nonlinearity is greater the greater the load current of the battery [4]. Hence, the question arises as to which of the values of currents to consider in a study

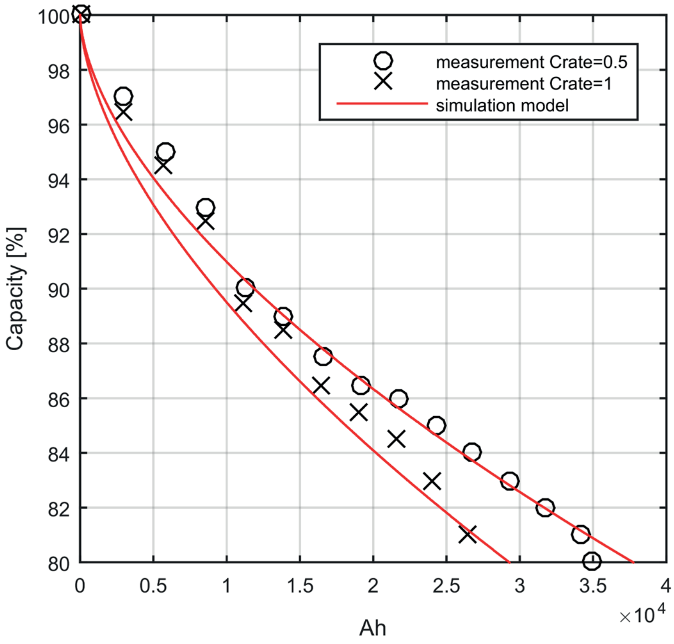

Fig. 3 Degradation model verification

of battery life: maximum or RMS. The results presented by Schuster et al. in [4] related to the nonlinearity of battery aging prompts us to use the maximum value, especially in systems where the maximum current is often reached. On the other hand, the study presented by Rizoug et al. [39] indicates that the battery can perform more cycles at traction load than at the maximum current rate. Consequently, it would be better to use the RMS current of the battery. Given both premises, this study presents the results of calculations for both the maximum and the RMS load current of LFP batteries.

In the case of the NMC battery pack, due to the lack of measurement data and because this module has only been used in an HESS where the maximum current does not exceed 0.5C, data from the manufacturer's data sheet have been used. Battery life data state that with a discharge depth of 80% and a load current of less than 1C, the battery should perform at least 3000 cycles. Exactly this value has been accepted in the calculation.

The supercapacitor aging data provided by the manufacturer speak of 1 000 000 possible charge and discharge cycles. The results of the measurements presented in [34] confirm their accuracy. The number of cycles decreases, however, at high temperatures, as shown in the results of the studies presented in [32]. Since the assumption of a constant temperature of 23°C was made for this study, the cycle life of the supercapacitor included in the calculations was 1 000 000.

4. Energy management strategy

Both the energy consumption of the bus, the life of the battery and the ultimate cost-efficiency of the HESS are dependent on the energy management strategy applied. The literature concerning HESS describes a number of methods for designing and optimizing strategies [13–15]. In this study, the GBS (gamma based strategy) strategy presented in [40] has been used. The method is based on a description of the battery power using the gamma function (5).

$$\begin{aligned} \gamma &= 2 \cdot A \Big/ \left(\frac{p_0}{B} + \frac{B}{p_0} \right) \quad \text{for } p_0 \geq 0 \\ \gamma &= 2 \cdot C \Big/ \left(\frac{p_0}{D} + \frac{D}{p_0} \right) \quad \text{for } p_0 < 0, \end{aligned} \tag{5}$$

where p_0 denotes power demand related to maximum vehicle power. Values of coefficients A, B, C and D are given in Table 4. They were chosen so that the battery current in each hybrid did not exceed 0.5C. The power of each energy storage unit in HESS was obtained from (6). The assumption was also made that the supercapacitor module is charged from the battery at standstill when the supercapacitor module SOC in lower than 90%. Charging current rate is 0.5C.

$$\begin{aligned} P_{batt} &= \gamma \cdot P_{load} \\ P_{SC} &= (1-\gamma) \cdot P_{load}. \end{aligned} \tag{6}$$

Power plots for energy storage devices for each HESS configuration are shown in Fig. 4. The simulations were performed for a UITP SORT 2 (easy urban) driving cycle. For every HESS we can observe a significant decrease in a battery's maximum power compared to a battery bus. The SOC of the supercapacitors is stable for all configurations, i.e. it does not decrease after several cycles. This is important because of the lower risk of total supercapacitor discharge and battery load with the maximum load current of the vehicle.

5. Cost calculation

From a market point of view for the bus manufacturer, the most important parameter is the cost of purchasing the energy storage device and, for the end-user, the purchase and operating costs of the vehicle. Operating costs per 100 and 500,000 km were determined respectively from (7) and (8). Both consist of three components. The first is the battery module purchase cost, spread over the life of the module and calculated per kilometer. In this instance, it is assumed that the battery is replaced after its life. After the bus has been exploited to the maximum, an ESS that is still in use can be used in the next vehicle. Therefore, the cost of its purchase is not fully attributed to the operating costs of one vehicle. The same assumption has been made for supercapacitors and converters whose purchase cost per kilometer accounts for the second component of the sum. The third component of the sum is energy cost. As the energy consumption E_{cons} is expressed per 100 km, the average consumption per kilometer was obtained by dividing E_{cons} by 100. Energy price taken for the calculations is the mean value for the European Union, i.e. 0.13 EUR/kWh.

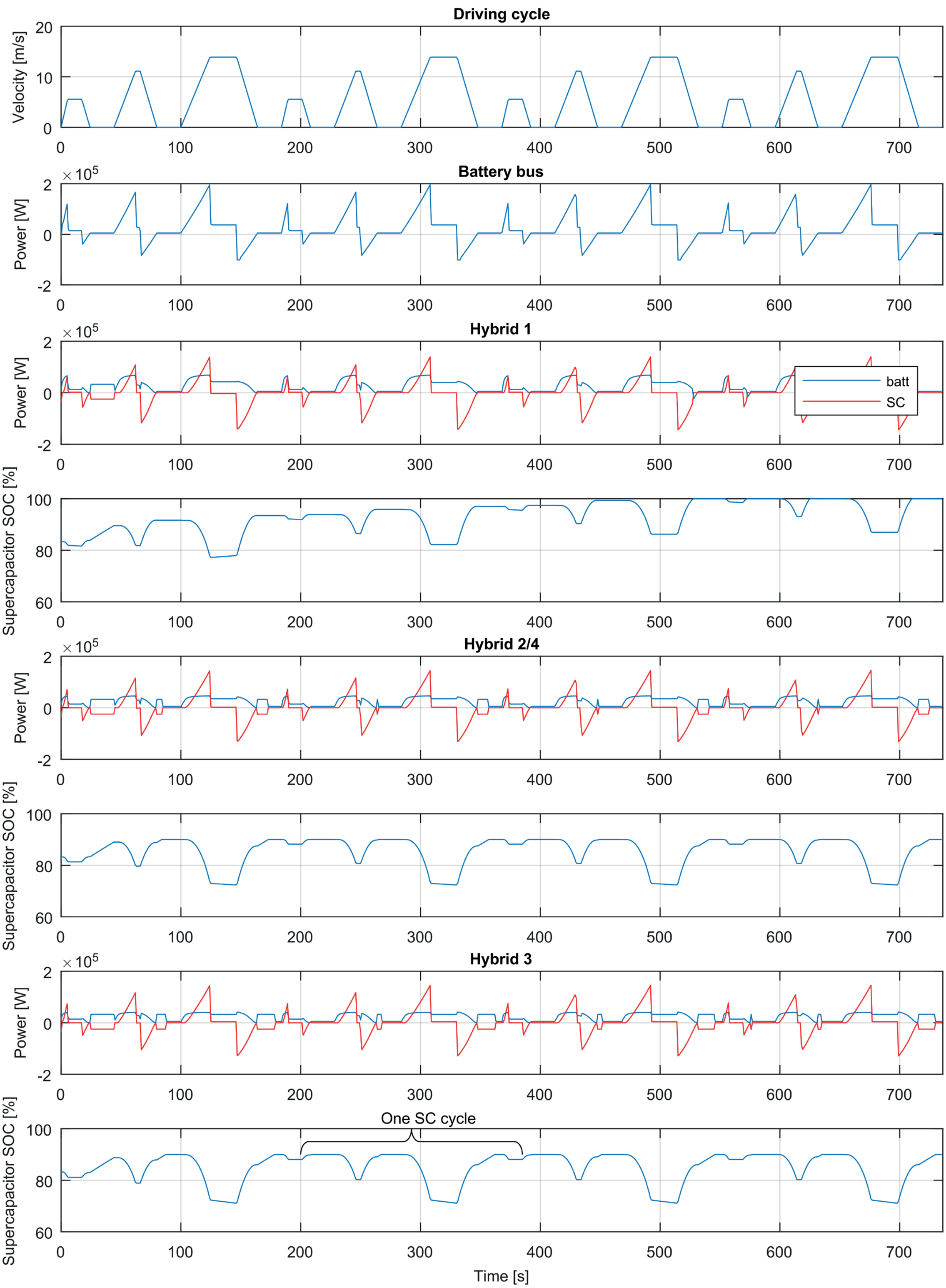

Fig. 4. EMS performance for each HESS configuration in UITP sort 2 driving cycle

$$Cost_{100} = 100 \cdot \left(\frac{Cost_{batt}}{S_{tot\_batt}} + \frac{Cost_{SC} + Cost_c}{S_{tot\_SC}} + \right. \\ \left. + \frac{E_{cons} \cdot Cost_E}{100} \right) \tag{7}$$

$$Cost_{500k} = 500\,000 \cdot \left(\frac{Cost_{batt}}{S_{tot\_batt}} + \frac{Cost_{SC} + Cost_c}{S_{tot\_SC}} + \right. \\ \left. + \frac{E_{cons} \cdot Cost_E}{100} \right). \tag{8}$$

where $Cost_{100}$ and $Cost_{500k}$ mean respectively the operational cost per 100 and 500 000 km, and S_{tot_batt} and S_{tot_SC} are the maximum ranges that can be made before the 20% degradation of the battery and the supercapacitor.

6. Results and discussion

6.1. Battery module degradation. Using the LFP battery degradation model described in Section 3.2, simulation of module aging in hybrids 1, 2 and 3 was performed. The results are shown in Fig. 5. For the battery bus, the maximum current differs significantly from the RMS value. By implementing the aging model for both values, and considering optimistic and pessimistic assessments, large differences in battery life have been obtained. On buses using HESS, the maximum and RMS load currents of batteries are similar, so in these cases the differences in the optimistic and pessimistic versions are small.

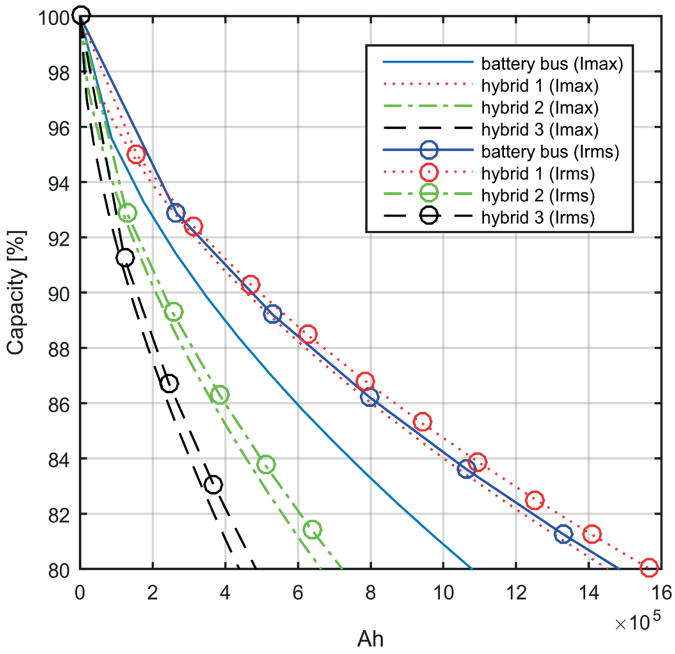

Fig. 5. Total charge through battery modules until end of life

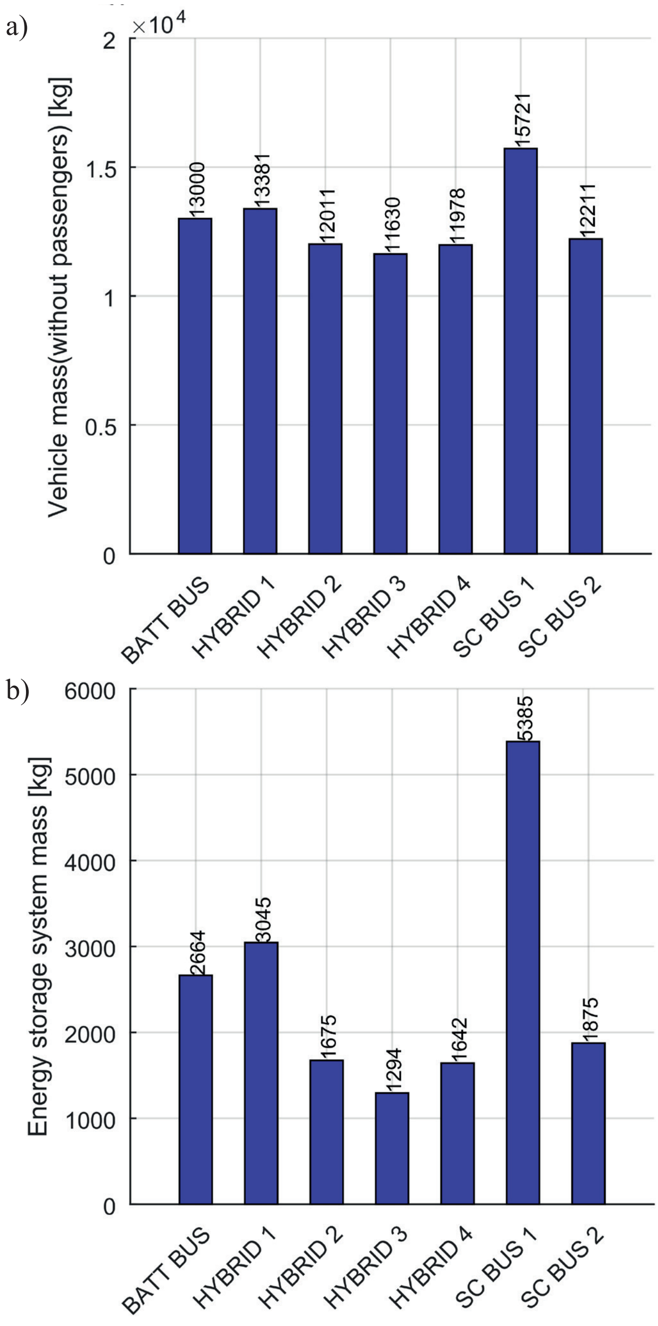

Fig. 6. Mass of a) vehicle without passengers and b) energy storage system

6.2. Energy storage and vehicle mass. The mass of a bus affects the driving dynamics, energy consumption and passenger transport ability. The results of the calculations shown in Fig. 6 show the differences in the total mass of buses and the masses of the ESS, from which the differences result. Due to the low specific energy of the supercapacitor, the heaviest is the SC BUS 1, which can travel 15 km on supercapacitors alone. The lowest weight, about 1 ton less than the battery bus, is noted for hybrids 2, 3, 4 and a supercapacitor bus recharged at stops: SC BUS 2. Of course, for Hybrids 2 and 3, this is due to the reduction of the battery tray, while in Hybrid 4, the batteries have double specific energy.

6.3. Energy consumption and ESS lifecycle range. Despite the significant reduction in the mass of buses in some configurations, it was not possible to obtain lower energy consumption than in the case of the battery bus (Fig. 7a). This is related to the presence of the DC/DC converters, and the fact that the lower internal resistance of the supercapacitors is not an advantage, because when combined into a module, the overall system resistance is similar to the internal resistance of the battery module. The increase in energy consumption compared to the battery bus is within the range of 7% for hybrid 3 to 14% for hybrid 1. SC BUS 1 consumes 23% more energy per 100 km than the battery bus, whereas SC BUS 2 consumes 4% more than the battery bus. Due to the high purchase price of energy storage units, this difference in energy consumption has a limited impact on the total operational cost of ESS. The maximum deviations caused by battery and supercapacitor internal resistance change are negligible.

In Figs. 7b and 7c, the total lifetime range of the energy storage device in the adopted cycle is presented. Comparing the battery charger with Hybrid 1, where the battery module is identical, we can notice a significant increase in total range. Considering the manufacturer's data, NMC batteries can be the most durable. In terms of this criterion, however, the supercapacitor buses have the biggest advantage over the batteries, as can be seen in Fig. 7. At several million kilometers of range, the supercapacitor module can be used on more than one bus, which has a significant impact on spreading the initial cost of ESS.

6.4. Initial and total ESS costs. The results of the calculation of operating costs per 100 km and for the life of the bus (assumed as 500 000 km) are presented in Fig. 8. Based on the presented results, the following conclusions can be drawn:

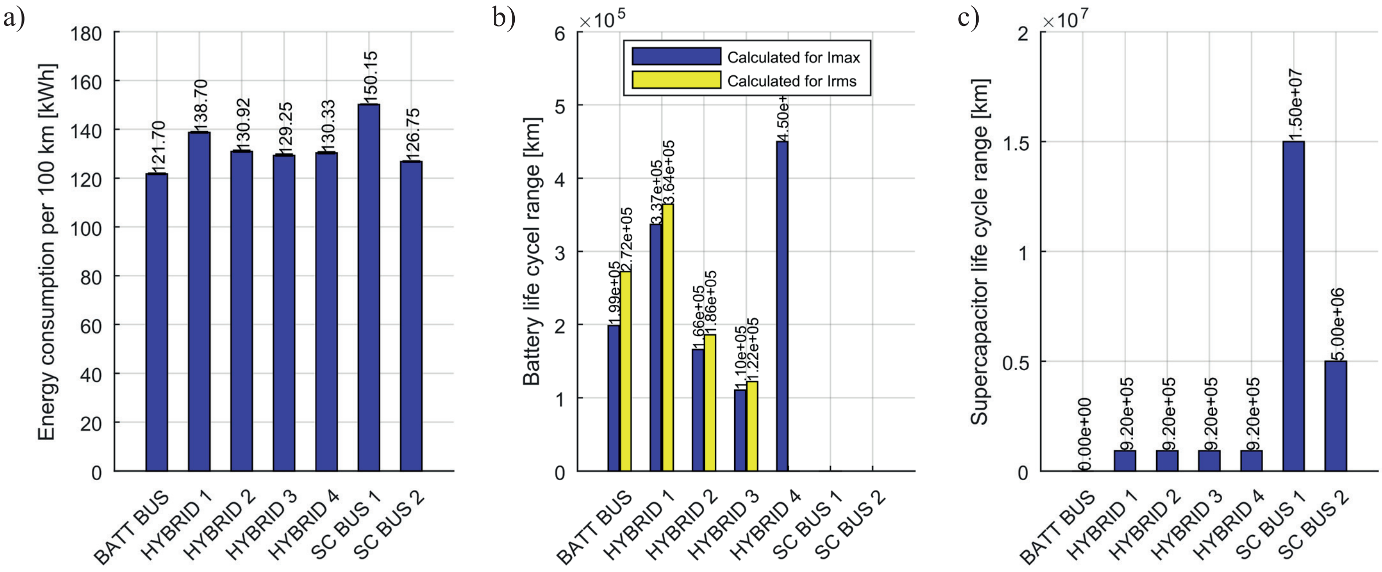

Fig. 7 Bus energy consumption (a) and ESS lifetime range (b, c)

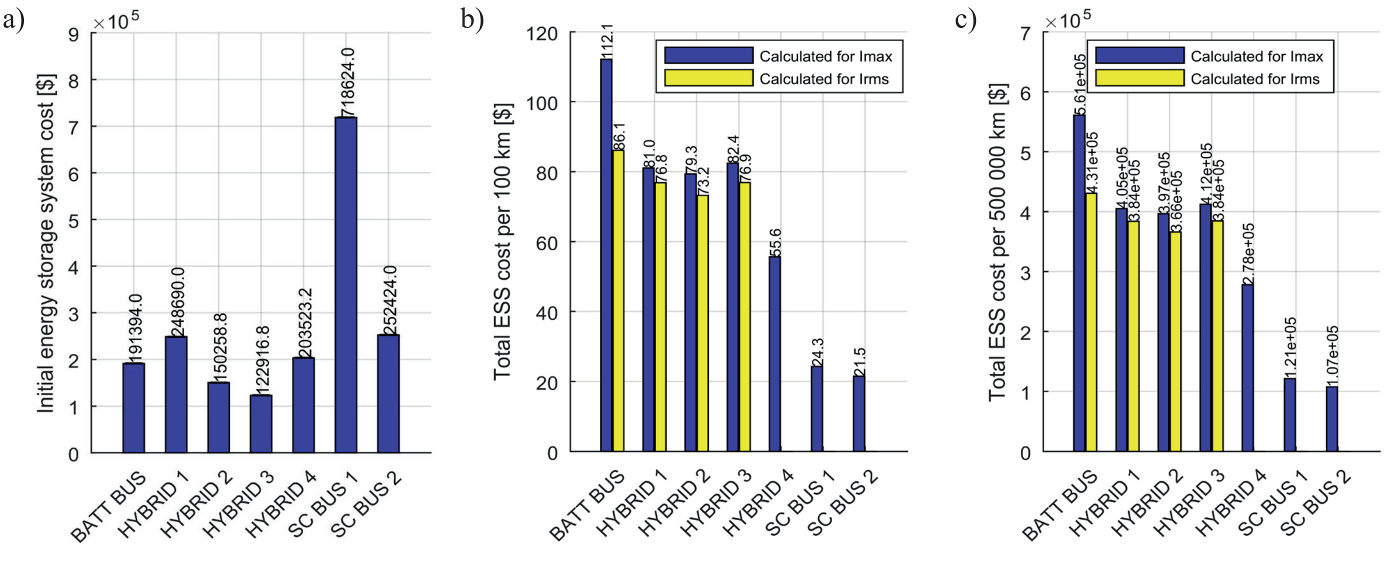

Fig. 8 Initial (a) and operational (b, c) costs of the ESS

- Adding a supercapacitor unit to the battery module without reducing its size increases the price of the ESS by approximately 25%, but by extending the battery life, it reduces its operating costs by 10 to 27% compared to the homogeneous battery energy storage.
- Reducing the battery module by half and adding a supercapacitor reduces the initial cost of the ESS by about 21% and reduces its operating costs even further than is the case with Hybrid 1, by 15 to 29% compared to the homogeneous battery energy storage system.
- Reducing the battery by 66% and adding a supercapacitor module reduces the initial cost of ESS by approximately 36% and also reduces its operating costs. These are, however, higher than those of Hybrids 1 and 2, and 10 to 26% lower than those for a homogeneous battery energy storage system.
- The use of NMC batteries in the HESS reduces the cost of operation between 35% and 50%. The initial cost of this type of ESS is only 6% greater than the homogeneous LFP battery ESS.
- The use of supercapacitors implies the highest initial cost of ESS. Compared to the LFP battery ESS, the purchase cost is 275% higher for SC BUS 1 and 32% higher for SC BUS 2.
- The operating costs of the supercapacitors are considerably lower than in the case of the battery ESS, 78% lower for SC BUS 1 and 80% for SC BUS 2. This is related to the number of cycles supercapacitors can perform.
- Expenses for supercapacitor buses do not take into account the cost of additional infrastructure, e.g. chargers at terminals and stops. Still, these costs would be spread across more buses.

For now, the most sensible configurations, in addition to the regular battery bus, are Hybrids 2 and 4. The first gives the opportunity to lower both the price and the cost of operating the vehicle. The second significantly lowers the operating costs with a slight increase in price. In the case of lower supercapacitor prices, which are now much more expensive per unit of energy than lithium batteries, supercapacitor buses could be an alternative worth considering. The cost-effectiveness of hybrid solutions will also increase.

In the research it is assumed that the SOC range to be between 10–90% because the aging model used in the research is well verified for those conditions. The model does not take into consideration the depth of discharge of the battery, which could be influenced e.g. by variable distance of one ride. The researches for the different ranges of state of charge has not been performed, because the results would be burdened with a high degree of uncertainty. Although there are some results published by other researchers, for example [7, 41–44], they are not sufficiently convergent and carried out in an area that does not allow for the development of a correct model.

7. Conclusions

The widespread use of electric vehicles is strictly dependent on the efficiency and cost of the ESS. That is why it is very important to develop ESS applications that will be economically efficient. This article proposes four hybrid ESS for urban buses and compares them with each other, a battery bus and with supercapacitor buses. The reduction of both the initial cost of the ESS to 36% and operational costs up to 29% has been shown. This ability comes with reducing the number of batteries in the ESS at the expense of more frequent recharging and adding a supercapacitor module to reduce the battery current. The use of NMC batteries with twice the energy density in the HESS has the potential to reduce operating costs by 35 to 50%. Solutions using a homogeneous supercapacitor ESS are much more expensive than others, but because of the high durability of these components, their operating costs are significantly lower. However, due to low energy density they require additional charging infrastructure.

Reducing the initial price of ESS will increase the economic availability of electric vehicles, which is essential to compete with combustion vehicles. Increasing total range and reducing operating costs further adds to the appeal of EVs from the end-user point of view.

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