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Economic and environmental benefits of supercapacitor-based energy storage solutions for the Brussels metro network

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Abstract

This article aims to assess the benefits of investing in supercapacitor-based energy storage solutions for the Brussels (Belgium) public transport operator in order to reduce the energy consumption of the metro network. Different energy storage systems (ESS) configurations were designed for the metro trains to be placed at the substation level. The investigation consists in defining the required specifications of the supercapacitor modules in terms of energy capacity and power. In view of the identified systems, potential energy savings will be estimated and, based on a well-to-wheel approach, the reduction in emissions will be measured and monetarily valuated. To conclude, a cost-benefit analysis will be carried out to determine whether the benefits exceed the estimated costs on a life cycle basis. This approach is innovative in the sense that few studies analyse in-depth the economic and environmental benefits of energy storage applications for mass transport networks.

Keywords: Public transport, supercapacitor, energy storage, energy savings, LCA

1 Introduction

Although mass transit vehicles enable large reductions in terms of emissions, their energy efficiency could be significantly improved with the inclusion of an energy storage system (ESS) for energy recovery purposes [1,2,3]. In conventional urban rail systems, the rate of energy that can be fed back to other vehicles depends on the traffic density. The more vehicles circulate nearby, the higher the chances of utilizing the energy recovered during the braking phases. For a high density metro network, the energy fed back to the network can achieve at least 20% of the supplied energy in rush hours while the remaining braking energy is lost in the resistors [4]. Introducing a stationary ESS at substation level can increase the global efficiency of the system by capturing the, otherwise lost, braking energy. Supercapacitors are very convenient for this purpose. Although their energy density is limited compared to that of batteries, they have optimal power characteristics and can cope with the braking power peaks [5,6]. Benefits such as voltage stabilization [7,8], peak power shaving and reduced losses on the line can also be achieved.

This article aims to evaluate the costs and benefits of using supercapacitor-based energy storage systems (ESS) on the metro network of the Brussels public transportation company. A stationary application at the substation level will be assessed from technical, economic and environmental criteria. The technical assessment consists in defining the required specifications of the supercapacitor modules in terms of energy capacity and power. In view of the identified systems, potential energy savings will be economically estimated. Then, based on a well-to-wheel approach, the reduction in emissions will be measured and monetarily valuated. To conclude, a cost-benefit analysis will be carried out to determine whether benefits exceed the costs on a life cycle basis and to show whether it is worth investing in supercapacitive solutions for the Brussels public transport company.

2 Case-Study

The exercise has been applied to line 2 of the Brussels Metro network (before the reorganisation of the network that took place in April 2009). This line has a total length of around 8 kilometres with 14 stops and is fed by 9 unidirectional substations. Metro trains can be made up of 3 to 5 cars depending on the time schedules. Each car has a tare weight of 30.400 kg and a capacity of 223 passengers (counting on 4 persons/m^2), for a total weight of 45.100 kg when fully loaded. Auxiliaries' consumption is set at 20kW per metro car.

2.1 Technical approach

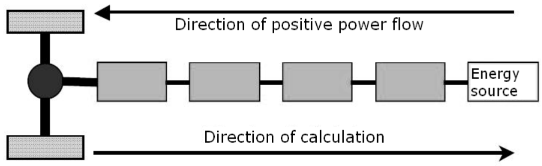
The calculations of energy savings expected from the use of a stationary ESS for a metro line are somewhat different than for a mobile application. Given the high frequencies of metro lines, significant energy exchanges occur between vehicles thanks to regenerative braking strategies but a portion of this kinetic energy cannot be recuperated and has to be dissipated in heat in the braking resistors. As a result, the use of energy storage solutions can still strongly contribute to energy savings and efficiency.

2.1.1 Simulation tool

A dedicated simulation tool has been developed in a Matlab/Simulink environment to simulate the power flow of the vehicle in order to determine its energy consumption when following a representative driving cycle. The conventional and enhanced networks can be simulated with the model and by comparing the energy flow and energy consumption, energy savings can be estimated. The simulation tool is also used to design and size the ESS in terms of energy and power.

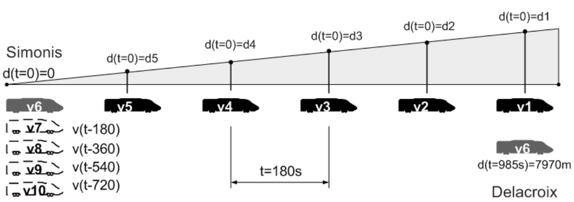
Reverse or 'effect-cause' simulation method is often used for energy consumption assessment in vehicles. It determines the requested power at wheel level according to the driving cycle followed and vehicle properties. The simulation method goes upstream the vehicle components until it reaches the energy source as it is depicted by Figure 1. Comprehensive explanations about the technical methodology can be found in [9].

Figure 1: "effect-cause" method iteration direction [10,11]



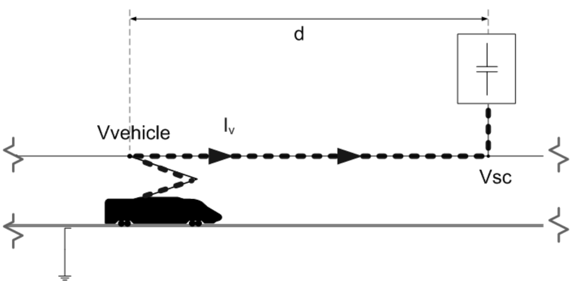
The network is modelled in the way that the total distance of the route is covered by a vehicle (vehicle 6, in green as shown on Figure 2) that starts from the first stop (d=0) at t=0. At that moment, there are already 5 vehicles running ahead with a time span of 180s. The distance between them depends on the driving cycle part. Every 180s after t=0, one vehicle starts the cycle from the first station. Thus, the network is populated with vehicles while vehicle 6 is covering the route. The off-peak and night/week-end scenarios are based on the same simulation principle but with fewer vehicles on the line at the same time with a time span of respectively 240s and 600s.

Figure 2: Detail of peak period traffic density model



Stationary applications have some advantages and drawbacks when compared to on-board applications. On the positive side, they are installed at ground level, where weight and space is not a big handicap. The system, as showed on Figure 3, consists in one or more static devices located in the substations and potentially serving all the trains running on the line, which results in a more active system. On the negative side, the losses on the line will not be reduced as much as with on-board systems and the storage capabilities are reduced with the increase of the distance of the vehicles to the ESS.

Figure 3: Example of vehicle sending energy to the ESS



2.1.2 ESS configurations and expected savings

Based on [12], four alternative module configurations, whose characteristics are given in Table 1, have been configured with an energy content ranging from 2.26 kWh to 9.06 kWh.

Table 1: Metro line 2 modules specifications

Small-size configuration	**Large-size configuration**
Cells: C=1500F, V_{max}= 2.7 V.	Cells: C=3000F, V_{max}= 2.7V.
Configuration: 10 strings x 232 cells in serie s	Configuration: 15 strings x 232 cells in serie s
Usable energy: **2,26 kWh**	Usable energy: **6,79 kWh**
Max Voltage: 580 V	Max Voltage: 580 V
Cells weight: 742 kg	Cells weight: 1914 kg
Medium-size configuration	**Extra large-size configuration**
Cells: C=3000F, V_{max}= 2.7V.	Cells: C=3000F, V_{max}= 2.7V.
Configuration: 10 strings x 232 cells in serie s	Configuration: 20 strings x 232 cells in serie s
Usable energy: **4,53 kWh**	Usable energy: **9,06 kWh**
Max Voltage: 580 V	Max Voltage: 580 V
Cells weight: 1275 kg	Cells weight: 2552 kg

One way to evaluate the benefits of a stationary ESS is to measure the energy saved per module every hour. In general, the energy saved per module increases with its size but a higher number of ESSs on the line decreases the amount of energy saved by each module. The reasons of these variations are several. First, the more ESSs on the line, the more the braking energy is, somehow, split among them. Second, the amount of energy saved by an ESS module is much higher when it is installed at the end of line due to the smaller chances of the vehicles approaching the end of line to send its energy to other vehicles. It is therefore not straightforward to choose the best option in all circumstances, but considering that saving energy is the primary goal, simulations have proved that at least 1 ESS every 2000 m is required and the distribution of 1 ESS every 1500 m also seems fair. Figure 4**Erreur ! Source du renvoi introuvable.** (on next page) shows graphically the results obtained when 4 ESSs and 6 ESSs are installed on the line, this for different module configurations and at different moments of the week (peak, off-peak and night/week-end). The energy saved per ESS depends on the traffic conditions, its size and positioning. Simulation results show total savings ranging from 30kWh/h up to 150kWh/h. It must be mentioned that simulations only consider the traffic in one direction and do not take into account the potential energy exchanges between vehicles running in the opposite direction. As a result, simulation results could be slightly overestimated, especially during peak time. Regarding the module size in the case where ESSs modules are spread every 2000m or 1500m, the small (2.27 kWh) or medium size (4,53 kWh) modules seem the best compromise

2.2 Economic and environmental approach

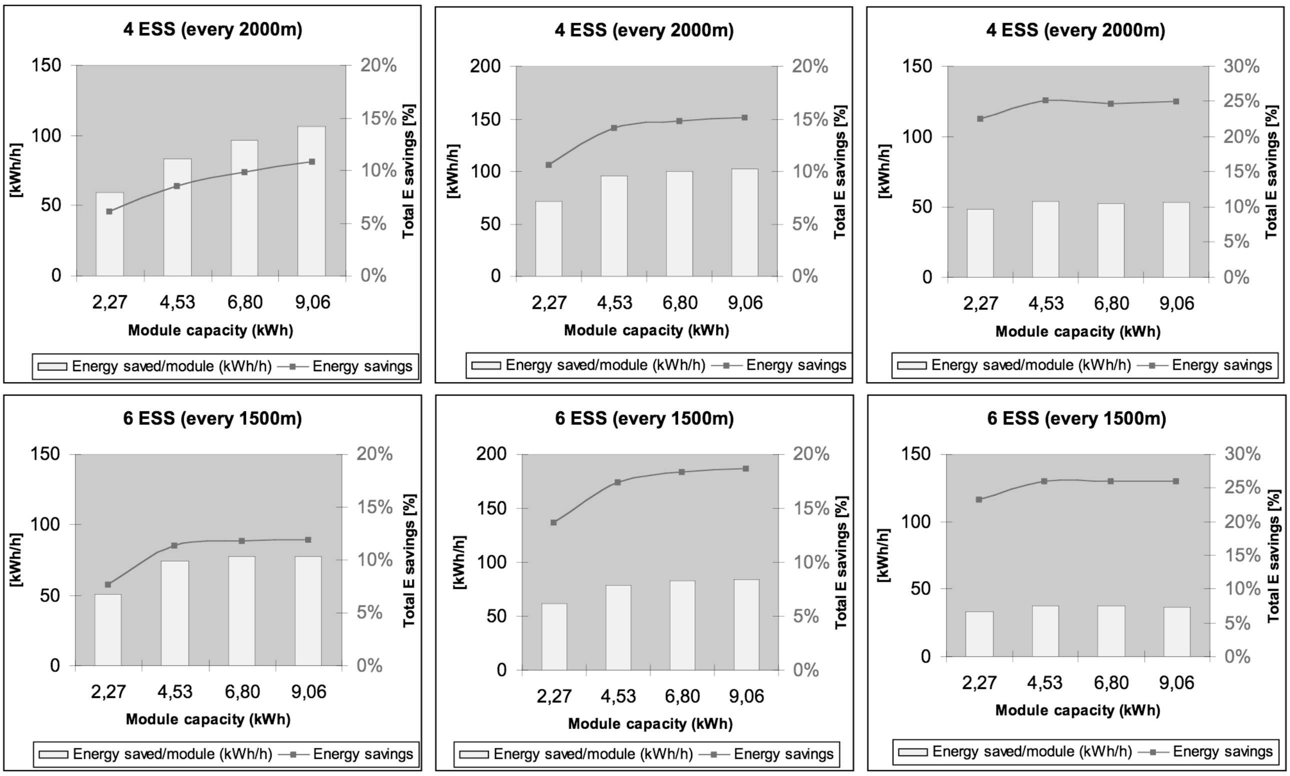
2.2.1 Energy consumption reduction

As mentioned earlier, energy savings of a stationary ESS are measured on an hourly basis. Consequently, it is necessary to determine the number of hours during which the system will be used annually considering the traffic variations (peak, off-peak, night and week-end). Table 2 presents the metro line 2 timetable in 2008 expressed in operating hours.

Table 2 Metro line 2 timetable (hours) [**13**]

	Days	**Peak**	**Off-peak**	**Night/ Week-end**
Weekdays	179	1253	1432	895
Saturdays	44		572	264
Sundays	61		793	427
Weekdays (holidays)	45		630	270
Weekdays (summertime)	28		364	196
Saturdays (summertime)	8		104	56
TOTAL	***365***	***1253***	***3895***	***2108***

Figure 4. Summary of energy savings at peak time (left column), off-peak (central) and night (right)



The annual energy savings of the four selected scenarios are given in Table 3 and take into account the operating hours calculated in Table 2 and their respective savings.

Table 3 Stationary ESS annual energy savings for metro line 2

Scenario	Usable energy per module [kWh]	Total installed energy [kWh]	Total savings in one year (kWh)
4 ESS (small-siez)	2,27	9,06	**1 817 203,76**
4 ESS (medium-size)	4,53	18,13	**2 364 408,73**
6 ESS (small-size)	2,27	13,59	**2 237 978,46**
6 ESS (medium-size)	4,53	27,19	**2 858 459,34**

2.2.2 ESS economic benefits

Considering a baseline price of 74€/MWh and various price increases, the economic benefits of a stationary ESS are shown on Figure 5 (on page 6). The expected benefits range from almost 2.000.000€ up to more than 7.000.000€ in the case of a 200% increase, linearly applied over time.

2.2.3 ESS environmental benefits

The Brussels public transport company STIB is exclusively supplied in electricity by the energy provider ELECTRABEl. This makes it convenient for estimating emissions related to the electricity consumption of the metro network. Emissions per kWh of the 2007 ELECTRABEL production mix [14] are given in the third column of Table 4. Annual emissions reductions due to the installation of a stationary ESS are computed for the four scenarios and show, among others, CO_2 emissions reductions of between 400 and 670 tons for the whole line.

Table 4: Annual emissions reductions due to the inclusion of an ESS aboard a tram

Classification	Emission type	ELECTRABEL production mix emissions in 2007 (mg/kWh)	Emissions avoided with scenario 1 (kg)	Emissions avoided with scenario 2 (kg)	Emissions avoided with scenario 3 (kg)	Emissions avoided with scenario 4 (kg)
Global Warming	CO_2	233 136,00	**423 655,62**	**551 228,79**	**521 753,35**	**666 409,78**
	CH_4	4,00	**7,27**	**9,46**	**8,95**	**11,43**
	N_2O	1,59	**2,89**	**3,76**	**3,56**	**4,54**
Human health / Ecosystems	VOC	3,91	**7,11**	**9,24**	**8,75**	**11,18**
	CO	19,78	**35,94**	**46,77**	**44,27**	**56,54**
	PM10	5,42	**9,85**	**12,82**	**12,13**	**15,49**
	NO_x	234,16	**425,52**	**553,65**	**524,05**	**669,34**
	SO_2	234,45	**426,04**	**554,34**	**524,69**	**670,17**

Better energy efficiency induces a reduction in electricity consumption and a proportional decrease of harmful emissions. The methodology used to monetize the environmental impacts of the production of electricity is based upon externality assessment. Environmental damages are considered as external costs, as they are not supported by the electricity producers but borne by the environment and the society. Table 5 gives the unitary cost (€/kg) for each pollutant and impact category. These values are taken from different reports that economically valuated the damages of air pollutants due to transport and energy generation activities in the European countries [15], [16], [17]. The price of CO_2 is set at 25€ per ton emitted (central value applicable in 2010) as stated in [17]. As far as CH_4 and N_2O emissions are concerned, the unitary cost is calculated proportionally to their Global Warming Potential (GWP). Intergovernmental Panel on Climate Change (IPCC) works [18] have estimated that, for a time horizon of 100 years, CH_4 has a GWP of 23 and N_2O a GWP of 296, values retained in this analysis. The baseline for the external cost of one MWh produced by the Electrabel facilities in 2007 amounts to 11.65€ as presented in Table 5.

Table 5: ELECTRABEL production mix external costs

Classification	Pollutant	Unitary cost (€/kg)	ELECTRABEL production mix emissions in 2007(mg/kWh)	Economic valuation (€/MWh)	Source
Global Warming	CO_2	0,025 €	233 136,00	5,8284 €	*Handbook*
	CH_4	0,58 €	4,00	0,0023 €	*IPCC*
	N_2O	7,40 €	1,59	0,0118 €	*IPCC*
Human health / Ecosystems	VOC	2,50 €	3,91	0,0098 €	*CAFE/CBA*
	PM 2,5	91,1000 €	19,78	1,8020 €	*HEATCO*
	PM10	36,50 €	5,42	0,1978 €	*HEATCO*
	NO_x	5,200 €	234,16	1,2176 €	*CAFE/CBA*
	SO_2	11,000 €	234,45	2,5790 €	*CAFE/CBA*
TOTAL (€/MWh)				**11,65 €**	

The results of climate change studies for the evaluation of CO_2 external cost present a large span ranging from 5€ to some 280€ per ton of CO_2. This large sample indicates a certain level of uncertainty. The most recent studies obtained higher values (between 50€ and 100€ per ton of CO_2) than previous studies, due to improvements in modelling techniques and increased knowledge on the global warming impacts. Table 6 shows the impact of choosing other values for the GHG emissions on the total cost of the electricity generation externalities.

The expected environmental benefits expressed in monetary terms are shown on Figure 6 (on next page) and range from 250.000€ up to almost 2.000.000€.

Table 6: ELECTRABEL production mix external costs according to CO_2 ton valuation price

CO_2 ton values (€/ton)	Production mix externalities (€/MWH)
25€	11,65 €
55€	18,66 €
100€	29,18 €
180€	47,87 €

2.2.4 ESS costs

Lifetime cost estimations for one stationary ESS are given in Table 7, both for a prototype and large-scale production. Costs are based on authors' calculations whose explanations can be found in [19]. The total cost for the line will depend on the number of energy storage systems that will be installed along the line.

Table 7: Stationary ESS on metro line 2 cost estimations

	Stationary ESS - small-size module (prototype)	Stationary ESS - small-size module (large-scale)	Stationary ESS - medium-size module (prototype)	Stationary ESS - medium-size module (large-scale)
Fixed costs	**338 011,20 €**	**186 483,44 €**	**457 444,80 €**	**246 863,76 €**
Cells	*113 680,00 €*	*79 576,00 €*	*164 720,00 €*	*115 304,00 €*
Packaging	*34 104,00 €*	*23 872,80 €*	*49 416,00 €*	*34 591,20 €*
Power converter	*40 000,00 €*	*40 000,00 €*	*40 000,00 €*	*40 000,00 €*
Development	*140 838,00 €*	*35 862,20 €*	*190 602,00 €*	*47 473,80 €*
Installation	*9 389,20 €*	*7 172,44 €*	*12 706,80 €*	*9 494,76 €*
Variable costs	***5 633,52 €***	***4 303,46 €***	***7 624,08 €***	***5 696,86 €***
Annual insurance	*1 877,84 €*	*1 434,49 €*	*2 541,36 €*	*1 898,95 €*
Annual maintenance	*3 755,68 €*	*2 868,98 €*	*5 082,72 €*	*3 797,90 €*
Lifetime costs *(15 years)*	**422 514,00 €**	**251 035,40 €**	**571 806,00 €**	**332 316,60 €**

2.3 Cost-benefit approach

The cost-benefit assessment is a decisive step, which aims to see if the project is socially profitable and if an investment should take place. The approach consists in calculating the net present value (NPV) of the selected alternatives. NPV is defined as the total present value of a series of future cash flows. When NPV is higher than 0, the investment is socially desirable. In order to discount these cash flows to their present values, a rate of discount must be used. In this study, a discount rate of 4% has been taken and is based on the results of a French report aiming at determining the appropriate discount rate for the evaluation of public-funded projects in France [20].

$$NPV = \sum_{t=0}^{T} (B_t - C_t) \frac{1}{(1+r)^t}$$

In this assessment, lifetime is assumed to be equal to 15 years, fixed costs are linearly amortized on the first 5 years and variable costs occur every year. The financial burden (loan interest rate) of the investment is not taken into account.

Figure 5 Economic benefits of stationary ESSs on metro line 2

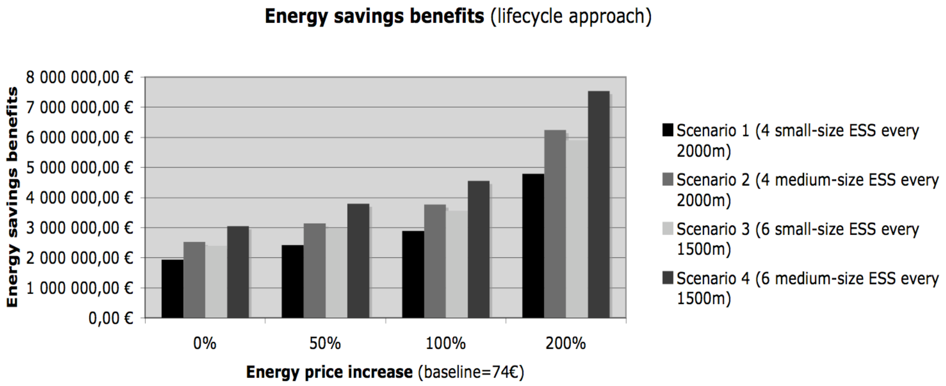


Figure 6 Environmental benefits of stationary ESSs on metro line 2

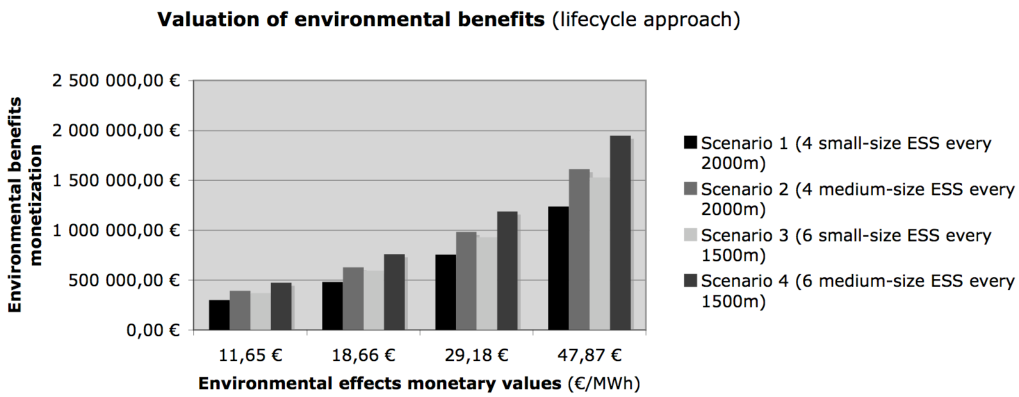


Table 8: NPV values for a stationary ESS on metro line 2

		Scenario 1 (prototype)	Scenario 1 (large-scale)	Scenario 2 (prototype)	Scenario 2 (large-scale)
Energy price increase (%)	0%	198 594,98 €	797 407,02 €	182 454,16 €	1 018 140,15 €
	50%	511 505,52 €	1 110 317,57 €	589 589,81 €	1 425 275,80 €
	100%	824 416,07 €	1 423 228,11 €	996 725,46 €	1 832 411,45 €
		Scenario 3 (prototype)	Scenario 3 (large-scale)	Scenario 4 (prototype)	Scenario 4 (large-scale)
Energy price increase (%)	0%	-145 840,96 €	752 377,10 €	-352 271,64 €	901 257,35 €
	50%	239 524,23 €	1 137 742,29 €	139 936,28 €	1 393 465,27 €
	100%	624 889,41 €	1 523 107,48 €	632 144,19 €	1 885 673,18 €

The net present values of the four scenarios (externalities of 1 MWh valuated at 11.65€) are summarized in **Erreur ! Source du renvoi introuvable.**, and this for different energy price increases. Most of the scenarios have a positive NPV. Scenario 2 appears as the best option as it scores almost the best both for the prototype and large-scale versions. Considering the prototype price, scenarios 3 and 4 do not perform well in the case where the energy price stabilizes and should thus be avoided.

3 Conclusion

The assessment of the installation of energy storage systems along metro line 2 has revealed that significant benefits can be expected, both in terms of energy bill reduction and environmental pressure. Scenario 2 seems the best option and consists in installing a medium-size module in four substations spread every 2000 meters. The main advantage of the stationary application compared to the mobile solutions is that the vehicles must not be retrofitted. It must also be pointed out that technical simulations did not take into account energy exchanges occurring between two vehicles running in the opposite direction. As a result, expected energy savings could have been overestimated and impact on the present results. This study was innovative in the in the sense that it involves a multidisciplinary research team and analyzes in-depth the economic and environmental benefits of energy storage applications for a metro network.

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