ECONOMICAL EVALUATION OF A HYBRID STORAGE SYSTEM FOR AN INDUSTRIAL AGV

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Abstract

Most Automated Guided Vehicles (AGV) still use lead-acid batteries as prevailing energy storage systems, despite of the significant technological advancements in the other components of the electric drivetrain. The use of lead-acid batteries is mainly related to their mature technology, design simplicity, large availability, well-known maintenance needs and competitive costs. However, the continuous progress in competing storage technologies, such as alternative batteries and electrochemical capacitors (or supercapacitors), is favoring the evaluation and possible introduction of new configurations, such as the hybridization with supercapacitors or the substitution with more advanced batteries and innovative charging methods, which may substantially affect AGV performances, service modalities and costs.

As part of the SIFEG (Integrated system for goods transport) Project, funded by the Italian Ministry of Economic Development, ENEA (Italian National Agency for New Technologies, Energy and the Economic Sustainable Development) has been carrying out an economical evaluation and technical comparison of different configurations and operation modes with the conventional one: by hybridizing the currently-used lead acid battery with an SC bank, by introducing more advanced Lithium-ion (Li-ion) batteries in various sizes with and without a fast charging device.

The comparison has been made using an electric vehicle simulator and a defined daily mission of the reference AGV. Simulation results, based on current market price of the major components analyzed, assumed that the benefits of each solutions had to be compared exclusively on the economic advantages at the end of the AGV life. With this hypothesis, the hybrid storage system (lead-acid battery and SC) resulted the most economically convenient modification, but, with the continuous decrease of the price of the Li-ion batteries, the Li-ion battery together with a fast charger for intermediate charging will be a potentially competitive alternative in the next years.

I. INTRODUCTION

Nowadays the lead-acid batteries are still the reference storage system, mostly used in Automatic Guided Vehicles (AGV), even though the other components of the electric drivetrain have been technologically advanced. The preferred use of lead-acid batteries is mainly due to their management simplicity, well-defined maintenance schedule and limited costs. However, the hybridization with supercapacitors (SC) or the substitution with more advanced batteries and innovative charging methods may substantially affect AGV performances, service modalities and costs.

In the framework of the National Programme - Industry 2015 - Sustainable Mobility, the Italian Ministry of Economic Development funded a large research and development project, named SIFEG (Integrated train-road system for goods transport) Project, with an overall budget in excess of 19 M€, for developing an integrated and optimized goods transport system, embedding a variety of technological innovations, able to favor intermodal connections between trucks and trains and goods automated handling.

As part of the SIFEG, ENEA (Italian National Agency for New Technologies, Energy and the Economic Sustainable Development) has been carrying out an economical evaluation and a technical comparison of the possible technological modifications of the storage system of an AGV used for moving and transferring heavy loads, such as stainless steel coils. The study has considered alternative storage systems with the respect to the currently-used lead acid battery:

- A hybrid storage system, coupling a lead acid battery with an SC bank
- Li-ion batteries
- A Li-ion battery and a fast charger that works during the AGV loading phases.

The comparison and practical analysis of these possible technological modifications have been performed with an electric vehicle simulator [1, 2] and by applying the daily mission of the reference AGV.

This paper summarizes main design assumptions of the various configurations of the storage system, based on different battery technologies and on possible hybridization with an SC bank, and an operation modality by using a fast charger to reduce battery size and weight..

II. THE REFERENCE AUTOMATED GUIDED VEHICLE (AGV) AND ITS MISSION

Fig. 1 presents the reference vehicle used for all the modifications and the subsequent simulations. The vehicle is normally used for transferring heavy stainless steel coils in the factory with a fixed origin-destination path, with 40,000 kg of weight at full load and 10,000 kg when it returns empty to the origin with a running speed of about 3 km/h. The total distance travelled at each journey is 300 m and lasts about 150 s. The loading and unloading times are about 50 s each. The daily service time is 16 hours. The analysis only considered average current delivered by the battery and not peak current during, for example, turns of the AGV.

Fig. 1. AGV Bertolotti S.p.A. – Marcegaglia Project.

The total distance travelled at each journey is 300 m and lasts about 150 s. The unloading takes about 50 s. The analysis only considers average current delivery from the battery and not peak current during, for example, turns of the AGV. Fig. 2 reports the duty cycle of the AGV.

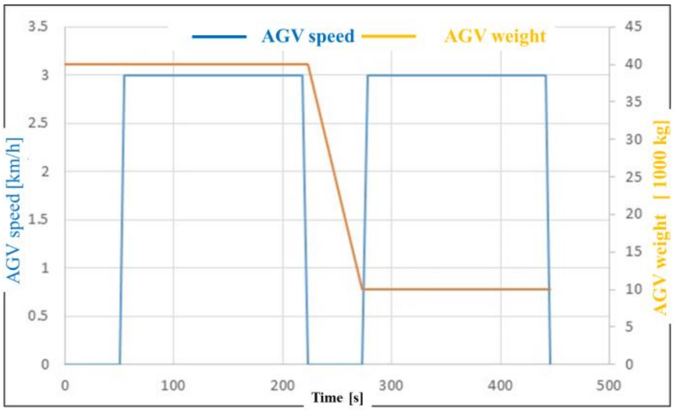

Fig. 2. AGV average duty cycle.

The basic configuration of the storage system considers a set of 120 lead-acid modules (360 Ah each) to reach the nominal voltage of 240 V. The overall weight of the battery is 2,628 kg to guarantee an overall working time between charges of 11.62 h.

III. THE SIMULATION MODEL

The electrical model of the AGV has been fully developed in MATLAB- Simulink environment, fully described in [2], and is mostly phenomenological, because it is aimed at calculating energy consumption and travelled distance.

For such model the main information and input data to be given are the vehicle characteristics, with simplified models for each major component of the electric drivetrain and the physical properties of the entire vehicles, together with the planned travel mission and service duty to be accomplished. Fig. 3 sketches the entire simulation model for electric vehicles, used at ENEA, to be adapted to the AGV case.

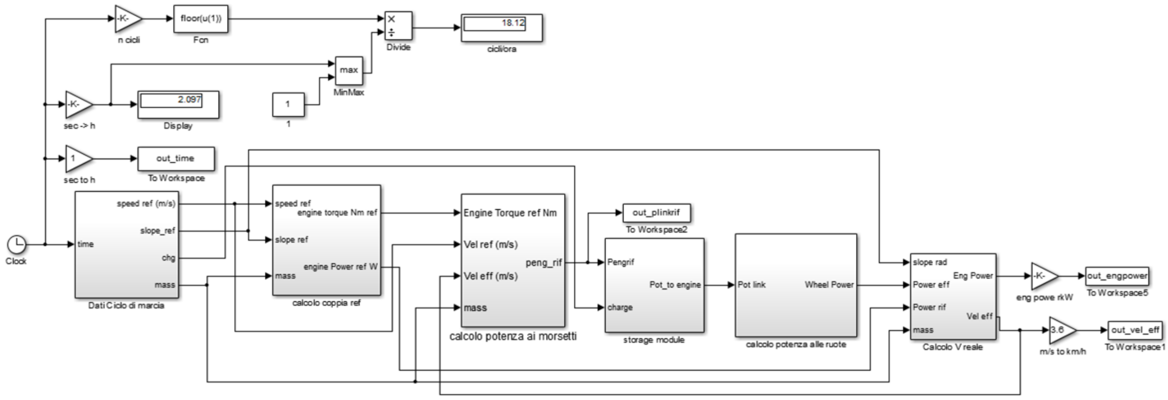

Fig. 3. The simulation model of electric vehicles, used at ENEA.

Apart from the definition and validation of the mathematical model for the various energy storage configurations, specific models of major drivetrain components, the planned duty cycles and the related behaviour of the AGV have been used and carefully analysed and adapted [2]. In the specific case of energy storage systems, a survey of the available technologies and market availability was performed with the identification of the major factors having significant impacts on the system behaviour. In particular, the determination of the capacity in function of the operating conditions, such as working temperatures, charge and discharge current and depth of discharge. Fig. 4 shows, for example, reports the equivalent electrical circuit used for the lead-acid battery.

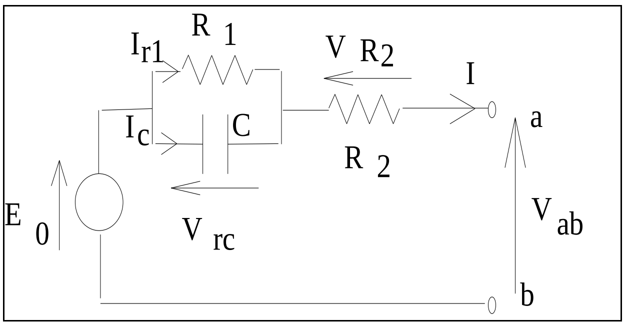

Fig. 4. The equivalent electric circuit of a lead-acid battery.

The simulations analyzed five different configurations and operation modes by combining storage technologies and charging conditions, including the current design based on the use of a lead-acid battery. The simulations, detailed below, regarded technical and economical aspects:

- Lead-acid battery alone: the reference configuration
- Lead-acid battery integrated with an SC bank
- Double Li-ion battery: two batteries (one as back up) with the same capacity of the lead-acid battery
- Li-ion battery: one battery with the same capacity but with the possibility to charge in half an hour at the end of the service, or whenever possible
- Li-ion with a fast charger: one battery with a reduced capacity (50% of the normal one) with a fast charger (with a peak power of 27 kW) at the loading point.

A. *The lead-acid battery (conventional)*

A preliminary analysis was related to the sizing of the lead-acid battery in current AGV configuration to optimize technical performances in terms of energy saving and cycle life as a function of the duty cycle recommended by the vehicle manufacturer. The first simple simulation calculated the effect of energy requirements on the size (weight) of the lead-acid battery and on the working time (in hours) between charges of the AGV. The present lead-acid battery of 360 Ah (at a discharge rate of 72 A in five hours) has an energy content of 86.4 kWh with a corresponding working time of 11.62 h.

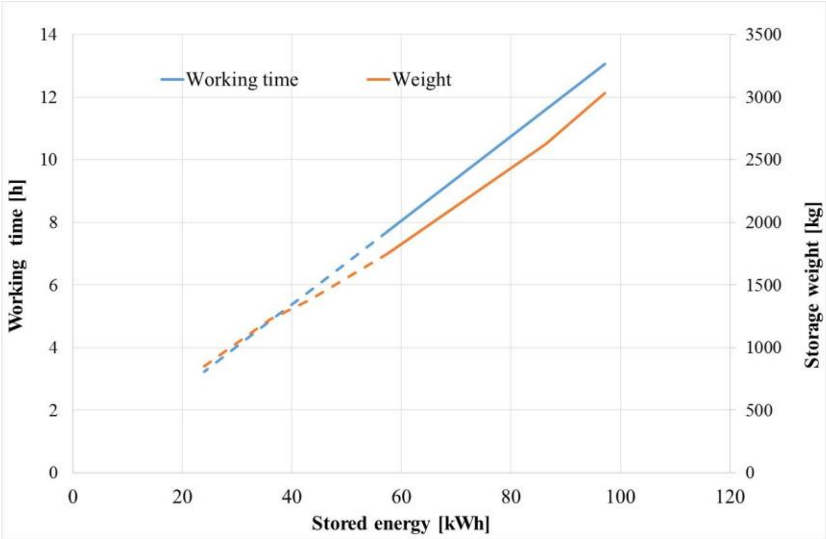

Fig. 5. The variation of working time of the AGV and weight of the lead-acid battery as a function of the available energy on board.

As expected, the working time reduces linearly as the stored energy (and capacity) decreases with the only limiting factor in the peak current delivered by the battery, which depends on the nominal capacity of the battery. Further simulations showed that at a capacity of 180 Ah (50% of the present one) with an energy current of 43.2 kWh the peak current reaches the minimum acceptable value for the planned operation. This effect is also related to the limited Power/Energy (P/E) ratio of lead-acid batteries for traction applications, which are mostly designed for energy functions with reduced power capability, differently from technologies like Li-ion batteries and SC.

B. The lead-acid battery with an SC bank

The hybridization of the lead-acid battery with an SC bank was subsequently investigated, also in other research projects, to verify the possible effects on functionality, performances and costs. In addition, the introduction of a DC/DC converter in alternative to direct parallel connection of the battery with the SC bank was also evaluated. In this study, the hybridization of the storage system with the addition of the SC was aimed at improving behavior of the lead-acid battery by reducing the maximum current delivered by the battery and substantially increasing battery cycle life.

The simulation regarded a hybrid system composed of a lead-acid battery of 360 Ah and 240 V (the presently used one) with an SC (from Maxwell) of 63 F and 125 V, connected with a dc/dc converter. With this configuration, the maximum current delivered by the lead-acid battery substantially reduced from 85 A down to 37 A, thanks to the assistance of the SC bank. In questo modo è possibile ridurre ancora l’energia a bordo e quindi il peso del sistema di accumulo e si possono installare batterie più piccole, fino a 100Ah (24 kWh).

The first result of the use of the hybrid system is a large reduction of the lead-acid battery weight and size (with a capacity of 100 Ah and an energy content of 24 kWh). The overall storage system weight was more than halved, at about 950 kg, taking into account that the additional weight added for the SC bank and the dc/dc converter is around 100 kg (61 kg for the SC and 41 for the converter of 10 kW).

Much more efficient resulted the benefit achieved with the hybridization on the cycle life, as shown in Fig. 6: the battery cycling moved from only 66 complete cycles up to 166 cycles.

With this reduced capacity of the lead-acid battery, the working time between recharges went down to about three hours, much less than the normal eight hours of daily service. To mitigate this problem, various operative solutions were proposed, such as opportunity charging during loading or unloading operations with wireless charging systems.

However, among the various alternative of battery sizes, the selection went on a lead-acid battery with unchanged capacity (360 Ah) to strongly limit the battery stress during operation without significantly modifying the overall weight. The effect on the duration of the battery life during the planned service is clearly demonstrated in Fig. 7 in function of the energy content of the battery.

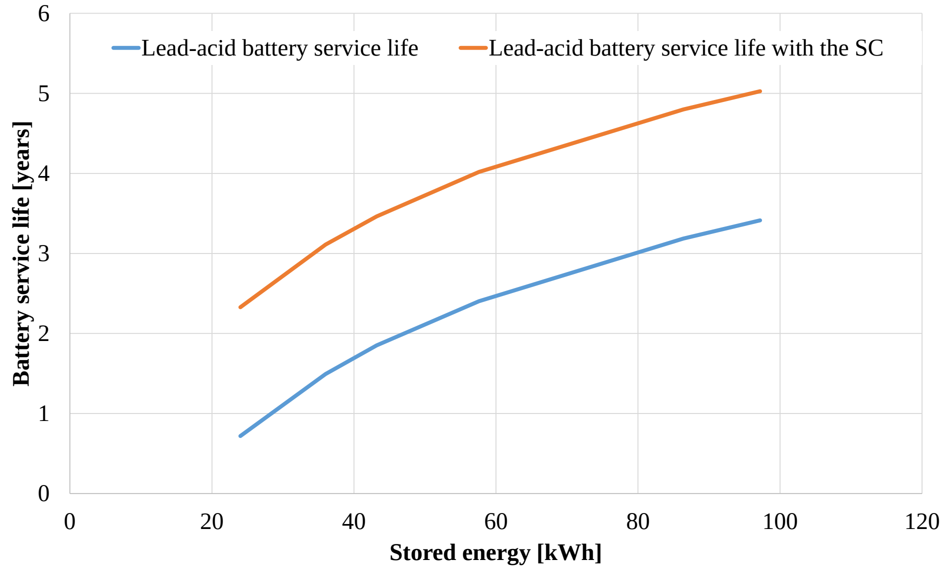

Fig. 6. Service life of the lead-acid battery with and without the SC bank.

The simulation results confirmed that with a peak current delivered by the battery reduced at less than 50%, thanks to the use of SC, the service life of the lead-acid battery is evidently improved. In the case of a battery capacity of 360 Ah (86.4 kWh), the service life goes up from three years to about five years.

C. The Li-ion battery in different configurations

The simulation of Li-ion batteries was prepared with a survey of the major market offers. Many Li-ion cells, modules and batteries are now available on the market, but they are not all suitable for mobile applications for technical and economical reasons. The survey, summarized in Table I, has also covered the evaluation of some key aspects to take into account for properly using this battery, such as: voltage balancing, battery management, thermal conditioning and safety.

TABLE I. LI-ION MARKET AVAILABILITY SURVEY

Chemistry		Cell producers/System integrators	Energy density (Wh/l)	Specific energy (Wh/kg)	Power
Cathode	Anode				
LCO	graphite	Thundersky	450-490	170-185	1C
LFP	graphite	Thundersky, HyPower, EIG, A123 (Nanophosphate)	130-300	90-125	5C cont. 10C pulse
			200-240	80-108	30C cont. 50C pulse
NMC	graphite	Kokam, Molicel, Panasonic - Sanyo	270-290	150	20C cont. 40C pulse
			330-365	155-190	3C cont. 5C pulse
LMO	graphite	Enerdel, Yuasa/Axeon, SB (Samsung/Bosch) Limotive . Molicel, LG Chem	280	90-110	3-5C cont.
NCA	graphite	JCS/Continental	130	70	14C cont. 35C pulse
NCM - LMO	LTO	JCS, Altairnano, Enerdel, Toshiba	118-200	65-100	10C cont. 20C pulse

LCO (Li Cobalt) = $LiCoO_2$; LFP (Li Iron Phosphate) = $LiFePO_4$; NMC (Li Nickel-Cobalt-Manganese oxide) = $Li(NiCoMn)O_2$; LMO = $LiMn_2O_4$; NCA = $Li(NiCoAl)O_2$;LTO (Lithium Titanate) with anode of $Li_4Ti_5O_{12}$

The Li-ion battery simulated in this study is a system integrated by an Italian assembler using NMC cells from Kokam, with the brand name of SLPB (Superior Lithium Power Battery) with specific energy and power suitable for the AGV application. Three Li-ion battery sizes were considered of different capacity: 100 Ah, 200 Ah and 400 Ah, whose basic characteristics are reported in Table II. The retail prices varied from about 76,000 € to 23,000 € (VAT excluded).

TABLE II. LI-ION BATTERIES SELECTED FOR THE AGV STUDY

Capacity kWh (Ah)	Weight kg	Discharge current, A	Charge current A
97.68 (400)	800	3C	1C
48.84 (200)	440	3C	1C
24.42 (100)	250	3C	1C

The better performances and physical characteristics of Li-ion batteries with respect to lead-acid are evident in terms of power capability in charge and discharge, making them more appropriate for fast charging mode, and significant weight reduction. The working time for the largest Li-ion battery reached about 12 h with a useful life at 50% of depth of discharge of 7000 cycles.

No one of the three sizes was able to meet the requirement of satisfying the overall daily service time of 16 hours with one charge and then alternative solutions were analysed:

- The use of two batteries of the same size with fast substitution
- The intermediate charging of a smaller system
- The fast charging

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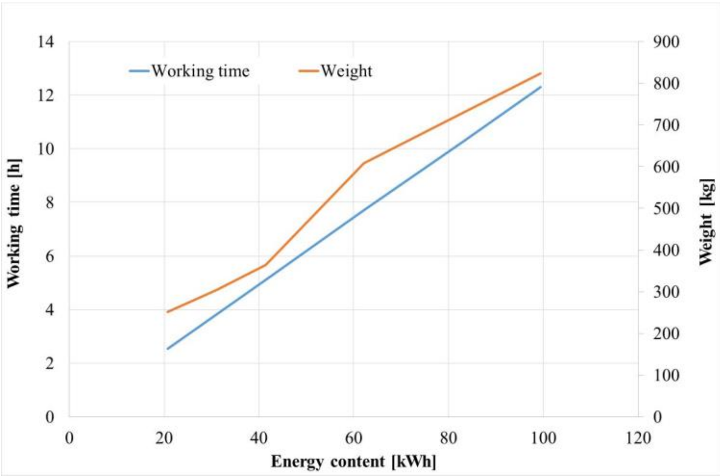

Fig. 7. Li-ion service life and weight in function of the energy content.

D. The Li-ion battery of a reduced capacity

The use of the largest Li-ion battery of 400 Ah was considered oversized with respect to the need and the foreseen AGV working life. In fact, the useful life of 7000 cycles corresponded to a service life of 28 years, considering an yearly working period of 250 days. Consequently, two smaller Li-ion batteries with 200-300 Ah or even slightly less would be more suitable and cost-effective. However, the daily service required to be modified and adapted with midday substitution to be able to fully meet the planned 16 hours per day (divided in two steps of eight hours each). However, the

E. The Li-ion battery with a fast charger

Another possibility investigated with the simulations was the intermediate charging at loading and uploading stops using a fast charger able to refill the energy necessary for completing a daily service with one battery. Opportunity charging at loading station with a dedicated charger was then simulated using a Li-ion battery of 200 Ah (48.8 kWh). With various simplifications, the simulations achieved the determination of the power of 27 kW. In this case, it was not easy to determine the effective working life of the battery, which is usually affected by the fast charging process. However, an estimation of the cycle life was derived from the technical data supplied by the Li-ion manufacturer and by repeated simulations with different depths of discharge. Fig. 8 summarizes the simulation results, presenting the overall number of complete cycles and the supplied capacity in the entire service life of a Li-ion battery of 200 Ah (48.8 kWh).

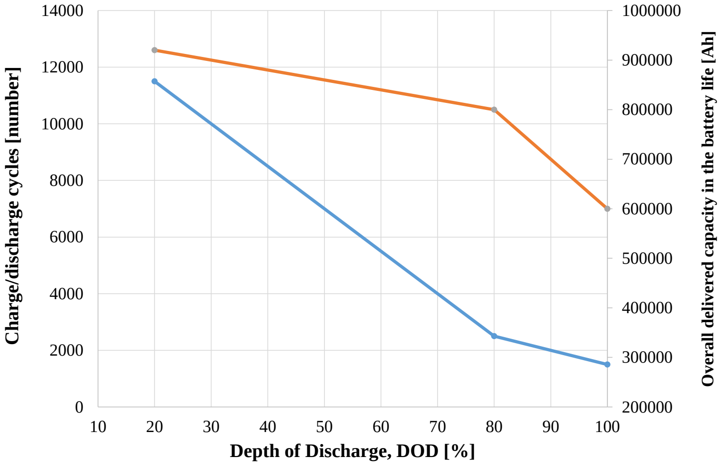

Fig. 8. Li-ion service life and weight in function of the energy content.

The estimation of the service life with fast charging for the various battery sizes was extrapolated by the simulation results and resulted in 9 years (about 2125 complete cycles) for the 200 Ah battery, while the 100 Ah battery charged with a 43 kW battery charger lasted only 2.3 years (about 578 complete cycles).

IV. COMPARATIVE ECONOMIC ANALYSIS

Finally, an economical comparison of the five solutions simulated was carried out. The economical calculations do not take into account the maintenance cost and the advantages associated with the weight reduction with the Li-ion battery.

The results of the economic analysis are reported in Table III, and shown in Fig. 9, with the estimation for a service life of the AGV up to 20 years.

The hybrid solution of lead-acid battery with an SC bank resulted the most convenient one.

TABLE III. SC CELL AND MODULE TECHNICAL SPECIFICATIONS

System	Battery size, kWh (Ah)	Working time, h	Useful life, years	Weight kg	Reference cost	Cost after 10 years	Cost after 15 years	Cost 20 years
Lead-acid	86.4 (360)	11.62	3	2628	20,000 €	67,200 €	88800	102400
Lead +SC	86.4 (360)	11.65	5	2689	+6%	-46.4%	-45.9%	-45.3%
Li-ion (2 sets)	97.68 (400)	12.74	28	800	+650%	+49%	+7%	-16.7%
Li-ion (1 set)	97.68 (400)	12.74	14	800	+274%	- 25%	+7%	-16.7%
Li-ion+fast charge	48.8 (200)	20	9	800	+134%	-11%	-36%	-27%

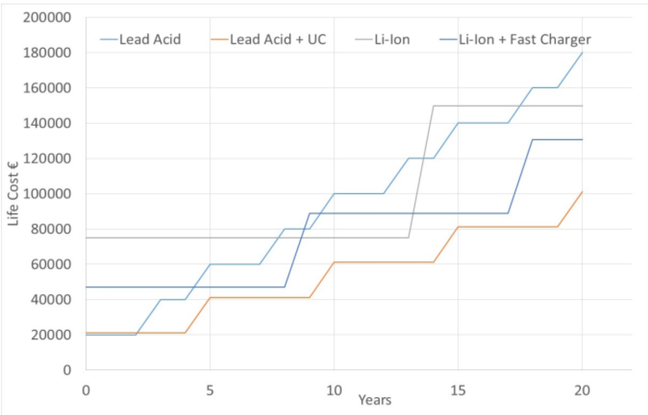

Fig. 9. Economic comparison of the various storage solutions for the AGV case.

V. CONCLUSIONS

The mathematical modelling and associated simulations of the possible modifications of an AGV for industrial services have been done by ENEA, as part of a large national project on intermodality improvements named SIFRED, considering five different technologies and operation modes.

The solutions proposed were considering alternative storage technologies, such as the more conventional lead-acid batteries together with more advanced Li-ion, the hybridization of the lead-acid battery with an SC bank, and, finally, the optimization of the operation modes by using one or two sets of Li-ion batteries of different sizes even in conjunction with various charging possibilities (slow and fast). The simulation and final comparison were driven by technical considerations, aimed at achieving the most economical solution at current market costs of the proposed technologies.

The major achievement and conclusions from the various simulation are:

- The hybrid configuration of lead-acid battery with an SC bank resulted the most economic at the end of service life, with a relevant increase of the battery cycle life, due to the appropriate assistance of the SC.
- The higher technical properties of the Li-ion batteries have a strong impact on the weight and available life. However, these technical advantages are not yet sufficient to compensate the higher cost of this battery at present time.
- The introduction of different charging modes, slow or fast with eventual opportunity charging during stops, may be beneficial in optimizing and reducing costs, but better knowledge of the effects of fast charging on Li-ion battery life is necessary.

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REFERENCES

[1] M. Conte, A. Genovese, F. Ortenzi, F. Vellucci, “Hybrid battery-supercapacitor storage for an electric forklift: a life-cycle cost assessment”, Journal of Applied Electrochemistry 44 (4), 523-532, 2014.

[2] F. Ortenzi and G. Pede, “Preliminary project of the energy storage system for the AGV” (in Italian), Technical Report SIFEG Project n. D135, June 2014Transport Research Arena (TRA) 2014, Paris, April 2014.