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# Technical and economical evaluation of Hybrid fast-charging stations for electric public transport

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## Executive Summary

Object of this paper is the feasibility study, technical and economic, of an electric public transport service where fast charge stations are equipped with electrical energy storage composed by batteries and/or super-capacitor, with relative power electronics, management and control, in order to improve the technical-economical dimensioning, for different possible operating conditions.

To this purpose, referring to a real case, a simulator of the charging station was made, including storage subsystems and converters. The final goal is optimizing the storage system necessary to guarantee the charging with a smoother, more levelled supply from the network.

## Introduction

Main advantages of fast charge stations for electric vehicles are an extended range autonomy and a smaller "on board" storage system, respect to the slow charge version of the vehicles. But the introduction in the electricity distribution network of such unforeseen electrical loads may create unwanted effects or even to be impossible to satisfy, because of great power demands for times of the order of tens of seconds.

An additional storage can reduce the power requested to the grid network: for a service with 4 vehicles per hour the power passes from about 150 kW to about 40KW. But the investment cost is obviously higher.

Performances and cost optimization of stationary electric storage systems passes through the use of second life batteries and technological solutions that integrate devices with different functions. This is the case of hybridization ([1],[5],[6]) of innovative electrochemical batteries, such lithium-ion batteries, or supercapacitors (SC), storage devices with high performance in power (several kW per kg of weight) and a useful life next to one million complete cycles.

In the paper, a real line from a city of L'Aquila, has been taken in consideration together with and an economical evaluation of electrification made as in [2] .the new line, with a proper bus has been simulated in order to optimize the charging process. Several combinations of grid power and storage capacity have been simulated for different services (from 1 to 10 vehicles per hour) and compared with the solution without storage, made by a standard charger for each vehicle.

To optimize investment cost, the "Second life" lithium batteries are taken in consideration, for the lower costs and to the fact that the steady state charge and discharge (and made in this case) can be performed by such batteries without problems. The present work follows the RSE (Ricerca di Sistema Elettrico) report [5] and [6] where an economical evaluation of flash charge stations at bus stops has been published.

## The hybrid charging station modelled

To represent a real case of public transport line, the data input have been taken from an Italian RSE (Ricerca di Sistema Elettrico) report [2], where a public transport line has been analysed and an economical evaluation has been made to be electrified.

A real bus line operated with a Tecnobus Gulliver has been taken in consideration, from l'Aquila, the 12A line, about 10 km with 30 bus stops[2]; the bus has been modified with a storage of 40 kW, charged every time it reaches the terminal with a power of 40 kW.

| Orario | Durata sosta da esercizio (min) | Durata giro (min) | Velocità (km/h) | Tratta | Metri | Massa | Consumo kwh | Consumo unitario (kwh/km) | Energia Ricarica (kWh) | kwh batt | SOC% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 40,96 | 100,00 |
| 06:45 | | 00:25 | 29,20 | "A1" | 12.168 | 3.400 | 7,37 | 0,61 | | 33,59 | 82,01 |
| 07:10 | | 00:50 | 23,63 | "B1" | 19.691 | 5.500 | 10,53 | 0,53 | | 23,06 | 56,30 |
| 08:00 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 14,27 | 34,84 |
| 08:25 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 8,42 | 20,56 |
| sosta programmata da allungare | 00:25 | | | | | | | | 16,67 | 25,09 | 61,25 |
| 09:25 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 16,30 | 39,79 |
| 09:50 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 10,45 | 25,50 |
| sosta programmata da diminuire | 01:00 | | | | | | | | 30,51 | 40,96 | 100,00 |
| 11:25 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 32,17 | 78,54 |
| 11:50 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 26,32 | 64,26 |
| 12:25 | | 00:20 | 28,08 | "D2" | 9.360 | 3.400 | 3,47 | 0,37 | | 22,85 | 55,79 |
| sosta programmata | 01:20 | | | | | | | | 18,11 | 40,96 | 100,00 |
| 14:05 | | 00:15 | 39,84 | "D1" | 9.961 | 3.400 | 4,92 | 0,49 | | 36,04 | 87,99 |
| 14:20 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 27,25 | 66,53 |
| 14:45 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 21,40 | 52,25 |
| sosta programmata | 00:40 | | | | | | | | 19,56 | 40,96 | 100,00 |
| 16:00 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 32,17 | 78,54 |
| 16:25 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 26,32 | 64,26 |
| sosta programmata | 00:40 | | | | | | | | 14,64 | 40,96 | 100,00 |
| 17:40 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 32,17 | 78,54 |
| 18:05 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 26,32 | 64,26 |
| sosta programmata | 00:20 | | | | | | | | 12,50 | 38,82 | 94,78 |
| 19:00 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 30,03 | 73,32 |
| 19:25 | | 00:35 | 20,87 | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 24,18 | 59,03 |
| sosta programmata | 00:10 | | | | | | | | 4,17 | 28,35 | 69,21 |
| 20:10 | | 00:25 | 26,39 | "C1" | 10.998 | 5.500 | 8,79 | 0,80 | | 19,56 | 47,75 |
| 20:35 | | | | "C2" | 12.177 | 5.500 | 5,85 | 0,48 | | 13,71 | 33,46 |
| | | | | "D2" | 9.360 | 3.400 | 3,47 | 0,37 | | 10,24 | 24,99 |

*Table 1 daily mission of the bus of the present study.*

The bus works for about 13....Hours?? plus the transfer from and to the deposit. The average speeds, the consumption and the energy supplied at the terminal are reported in Table 1 and used for the calculation: the charge station will be located at the terminal, the charge power will be 40 kW and the charging time is the time which the bus is stopped at the terminal.

To perform the proposed mission, the Tecnobus Gulliver has been modified as follows (Table 2):

- An electric motor with higher maximum power, about di 80 kW instead of 24 kW, in order to run the extra urban parts of the driving cycle with slopes and speed higher than available with the original motor;
- Battery voltage of 400V instead of 72 V of the original vehicle,
- Lithium iron-phosphate batteries, with higher specific power and energy than the original lead acid, able to charge with currents up to 3 times the nominal current.

*Table 2 Tecnobus Gulliver specification*

| **Maximum weight** | **6300 kg** |
|---|---|
| **length** | 5.1 m |
| **width** | 4.3 m |
| **passengers** | 28 |
| **Battery capacity** | 585 Ah/Lead Acid |
| **Max discharge current** | 1 C |
| **Max charge current** | 0.2 C |
| **Battery voltage** | 72 V |
| **Electric Motor** | CC 24kW max |

Further information can be found [2]. In [5], where the present work derives, an economical evaluation of , two types of quick charging have been analysed (fast charge at terminal and flash charge at bus stop) have been evaluated.

The performances of the different combinations of Grid power and storage capacity have been compared with the standard configuration without any hybrid storage, made by standard chargers (one for each vehicle in charge). In [6] is reported an economical evaluation of flash charge stations at bus stops for public transport.

## The simulation model

To evaluate the performances of the above configurations of hybrid charging stations, a simulation model has been used. Such model takes into account for grid with its AC/DC converter, battery pack and DC/DC converter for each vehicle to charge to communicate with the vehicle. In [5] and [6] has been taken in consideration also a DC/DC converter for the batteries and also Supercapacitors banks (when adopted) with or without their DC/DC converter

The electricity grid is the energy source for the station, it charges, together with the Supercapacitors and the batteries the storage of the bus and, at the end of the charge, charges them to be ready for the next charge. For the economical evaluation, the cost is a function of the maximum requested power and the consumed energy; for decreasing values of charging power, the cost decreases.

The technology adopted for the battery packs is lithium-iron-phosphate, a good compromise between performance and costs. The batteries are simulated as composed by a electromotive force generator in series with a one or more RC circuits [1],[3] and all the coefficients have been set correlating with the data measured in [9]. In addition, a thermal model has been used to calculate the instantaneous temperature of the cells and check if they are reaching the limit values.

The converters are taken into account through 3D Efficiency maps in function of power and voltage ratio in order to calculate the real value of power and energy during charge and discharge [4],[5].

In the present work, the connection between station and the bus has not analysed, but on the market, there are several products that can transfer high power such those of the present project. Pantographs like [7] and [8] can be used for this kind of application.

## Results

To evaluate the performances of hybrid storage and compare them with the configuration without storage, first of all the output parameters have to be chosen: the maximum grid power, global efficiency, the battery storage, the maximum battery power / maximum available battery power have been chosen.

Moreover, the transport can be made with 1,2,4 and also 6 vehicles /hour.

The advantages of the hybrid storage can be understood in figure below (with a service of 1,2,4,6 bus/hour) where the power requested to the grid decreases rapidly with the battery storage capacity.

*Table 3. Results with only grid energy used to charge the vehicles.*

| V/h | Time h | P grid max kW | Grid Energy kWh | Vehicle kWh | Global Efficiency % | Maximum vehicles in charge |
|---:|---:|---:|---:|---:|---:|---:|
| **1** | 16 | 43.5 | 124.821 | 116.078 | 0.93 | 1 |
| **2** | 16 | 87 | 249.642 | 232.156 | 0.93 | 2 |
| **4** | 16 | 172 | 499.3 | 464.3 | 0.93 | 4 |
| **6** | 16 | 215 | 748.919 | 696.4667 | 0.93 | 5 |
| **10** | 16 | 344 | 1248 | 1161 | 0.93 | 8 |

In Table 3 it is shown that the grid network will supply all the power needed to charge the vehicle plus the losses (the efficiency is 0.93) and with an increase of the number of vehicles/h there is a linear increase of maximum power requested to the grid network.

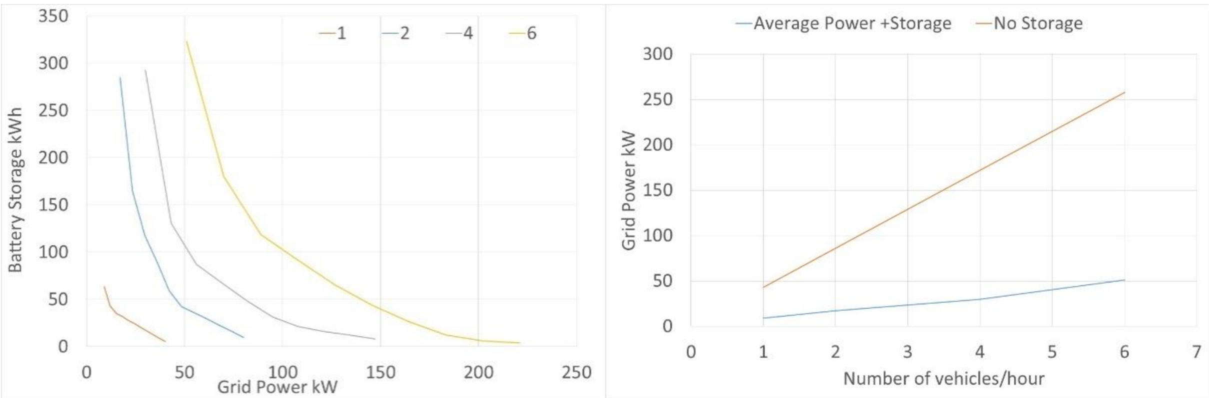


*Figure 1 capacity vs maximum grid power (at left) and grid power in function of the number of vehicles per hour.*

In Figure 1 at left it can be seen how an additional storage can reduce the power requested to the grid network: for a service with 1 vehicle per hour the power passes from 43.5 kW to about 9 kW and for 4 vehicles/hour from about 150 to about 40. There is a big decrease of the power and in the extreme case (maximum battery capacity and average power requested to the grid network, Figure 1 at right) there is a reduction factor up to 5. It results in a more leveled power requested to the grid, much positive for the energy manager.

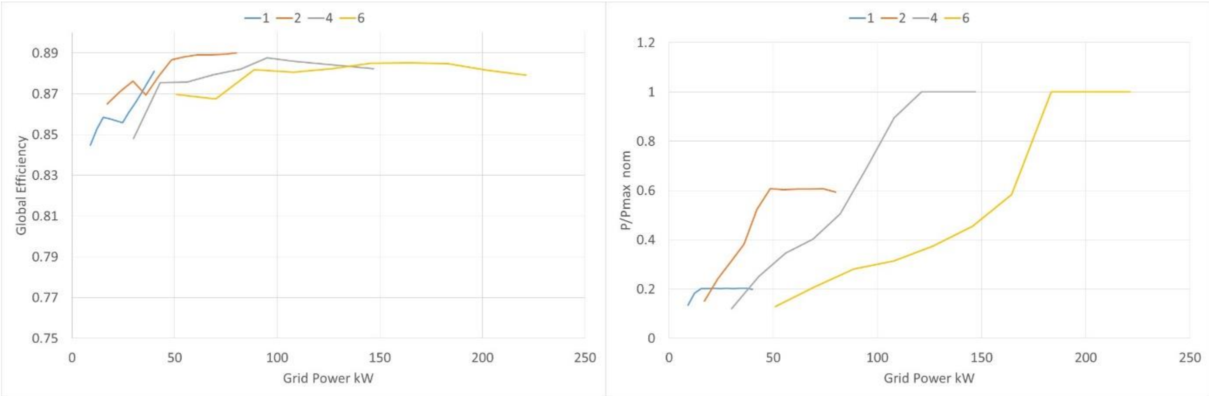


*Figure 2 and efficiency versus grid power (at left) and battery power/maximum battery power versus grid power (at right).*

In Figure 2 the efficiency is reported in function of the grid power and also the power ratio of the batterie in order to evaluate the stress of the batteries.

## Economic analysis

The economic analysis evaluates the possibility of installing an hybrid charging system composed by second life battery pack supporting the power from the grid compared to commercial 40 KW DC charging station. The maximum number of buses charging simultaneously is five, so for the hybrid charging system there will be a single plant and five electrical connection outlets while for the grid scenario five charging stations will be installed. Charging takes place at the unique terminal on the bus line 12A, feeding four buses in an hour maximum.

The investments refers to grid connection in Low (LV) or Medium Voltage (MV) **Errore. L'origine riferimento non è stata trovata.**, considering that the MV fares are applied when the needed power is higher than 100 kW, for the reference case, each 40 kW charging station withdraws electricity directly from the grid only while the hybrid hypothesis needs a stationary storage composed by second life battery pack which could come from own electric vehicles when the battery capacity has been reduced, but in this case it is assumed to buy a remanufactured pack which costs 200 €/kWh **Errore. L'origine riferimento non è stata trovata.** and the charging system (AC/DC and DCDC) and electronic power connection components. The installation cost refers to this total as it is already internalized in the cost of the connection to the grid.

The assumption of the study is reported in **Errore. L'autoriferimento non è valido per un segnalibro.**, highest specific values are for the MV equipment. The study does not consider the stationary storage replacement and the common investment items.

*Table 4:Assumptions of the study*

| | | |
|---|---|---|
| **N. of charging points** | *n.* | 1 |
| **Max simultaneously buses in charge** | *n.* | 5 |
| **n. of buses charging in an hour** | *n.* | 4 |
| **Time period** | *n. of years* | 12 |
| **Discount rate** | *%* | 5 |
| **Days of annual service** | *n. of years* | 320 |
| **Annual cost of maintenance** | *% of equipment* | 5-10 |
| **Cost of installation** | *% of equipment* | 20 |
| **Cost ACDC** | *€/kW* | 500 |
| **Cost DCDC** | *€/kW* | 500 |
| **Outlet connectors** | *€/unit* | 300 |
| **Cost of remanufactured Second life** | *€/kWh* | 200 |

| | | |
|---|---|---|
| **battery pack** | | |
| **Cost of control electronics and connection** | *€/unit* | 4.000-6.000 |
| **50 kW DC charging Station + installation** | *€/unit* | 30.000 |
| **Max distance from nearest LV cabin** | *Km* | 1 |
| **Max distance from nearest MV cabin** | *Km* | 3 |

The most convenient solution is proved in two steps. In a first phase, the best economic hybrid solution is investigated among all possible cases by inversely varying the power from the grid and the power of the stationary storage as shown in Table 2. Firstly, this process has been iterated for different situations, considering as variable the number of buses. The analysis gives positive results for a moderate usage of the station, precisely for four buses charging each hour. The financial indicator of profitability is the Present Value (PV) calculated for each LV or MV alternatives. The best hybrid solution need a level grid power of 43 kW and the stationary storage should provide the other 130 kW, feeding an energy consumption of 535 kWh/day.

*Table 5: Comparison for hybrid solutions*

| | Grid (kW) | Stationary Storage (kWh) | Energy from the grid (kWh/station) | Investments (€) | *Annual energy bill* | *Annual Maintenence cost* | *Investment + Net Present Value* |
|---|---|---|---|---|---|---|---|
| Hybrid_LV1 | 30 | 143 | 540 | 217.650 | *23.718* | *8.954* | **507.225** |
| Hybrid_LV2 | 43 | 130 | 535 | 187.524 | *23.902* | *7.661* | **467.269** |
| Hybrid_LV3 | 56 | 118 | 535 | 185.661 | *24.289* | *7.545* | **467.821** |
| Hybrid_LV4 | 69 | 105 | 532 | 189.696 | *24.549* | *7.676* | **475.311** |
| Hybrid_LV5 | 82 | 92 | 530 | 193.731 | *24.843* | *7.806* | **483.113** |
| Hybrid_LV6 | 95 | 80 | 525 | 198.380 | *25.055* | *7.962* | **491.020** |
| Hybrid_MV7 | 108 | 68 | 526 | 206.898 | *27.501* | *16.625* | **597.994** |
| Hybrid_MV8 | 121 | 56 | 525 | 214.143 | *28.327* | *17.169* | **617.385** |
| Hybrid_MV9 | 134 | 48 | 526 | 221.788 | *29.162* | *17.746* | **637.544** |

In a second phase, the results for hybrid solutions are compared to the grid solution's result (Table 6). The operating costs are relative in both cases to energy bill **Errore. L'origine riferimento non è stata trovata.** and to maintenance cost. Although the initial investment decreases as grid power decreases, the impact of energy and maintenance costs over the period results in the convenience of intermediate solutions ranging up to 95 kW from electric grid and stationary storage respectively sizes 80 kW. In fact, in these cases the PV is better than the only grid solution's PV for a 5-13%. Instead, none MV hybrid solution seems to be convenient as the lowest cost is to about € 598.000, at least 12% more.

*Table 6: Grid solution versus hybrid solution*

| | LV-MV connection | Charging system | PV | Investment+PV |
|---|---|---|---|---|
| Hybrid_LV2 | 3.667 | 187.524 | 279.745 | 467.269 |
| GRID_MV | 10.279 | 150.000 | 375.225 | 535.504 |

## Conclusion

Main advantages of fast charge stations for public transport electric vehicles are an extended range autonomy and a smaller “on board” storage system, respect to the slow charge version of the vehicles. But the introduction in the electricity distribution network of such unforeseen electrical loads may create unwanted effects or even to be impossible to satisfy, because of great power demands for times of the order of tens of seconds.

In this paper an economical evalutation of fast charging station have been made and on a public transport line, made by a simulation model

Different combinations of Grid Power and storage capacity have been simulated and increasing the battery capacity, the grid requested to the grid decreases up to 20% than the solution without storage. With this lower power request in Italy a reduction of energy tax can be obtained because it is function of energy consumption and the maximum power request)

From an economic point of view, second life batteries have been take in consideration due to the lower cost of them compared with the brand-new version. Such economic evaluation shows that during the station life, for the service with 4 vehicles per hour, there is a reduction of about 13% (Figure 3) with the solution Hybrid_LV2 that has 130 kWh of battery capacity (serving 4 buses with 40 kWh batteries).

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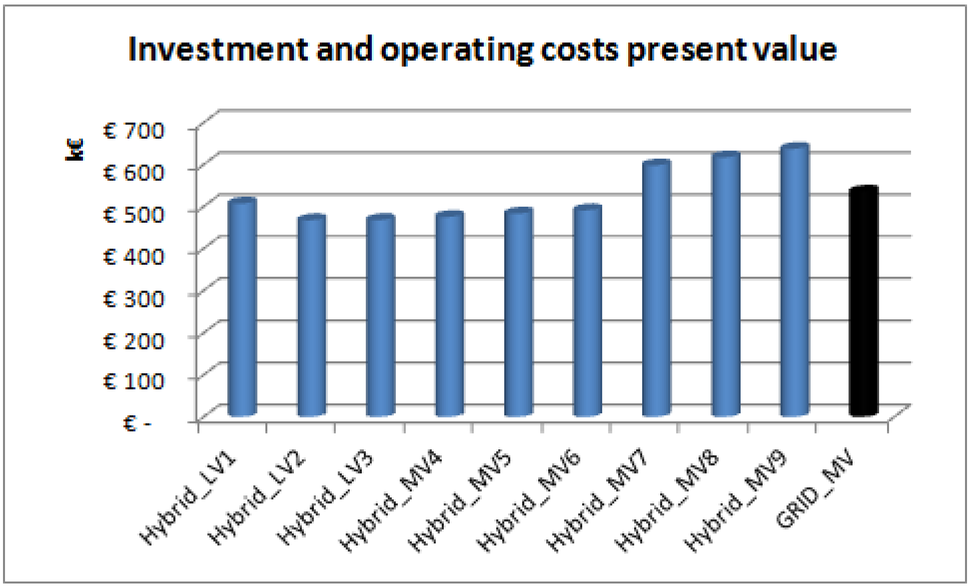


*Figure 3Comparison between different hybrid charging station with the “only grid” station*

The hybrid charging stations can be a solution to realize fast charging station without making modifications to the grid infrastructure and also with benefits for public transport companies that can reduce the global costs of transport.

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