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Article

Fast-Charge Life Cycle Test on a Lithium-Ion Battery Module

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Abstract: This study addresses the effects of fast charge on a lithium-ion battery module made by four lithium-iron-phosphate cells connected in series, submitted to a test profile which included a fast-charge step at a current rate of 3 C. This test profile simulated the real working profile requested by the batteries of an electric bus to perform a particular service of local public transportation, with the batteries recharging at the end of line. More than 3000 shallow cycles were performed. The battery module did not show a significant reduction in performance in terms of capacity and energy; however, a relevant increase in resistance was observed. Due to this change, the autonomy of the electric bus was reduced correspondingly. By fixing a minimum value for the autonomy, a life estimate of the battery module was made. Finally, on the base of this result, a cost estimate and comparison between slow and fast charge was made, under the same service conditions throughout the vehicle's lifespan, for a real case of a minibus equipped with a battery system sized for fast charge at the end of line, and a larger battery system sized for slow charge at the end of a working day. This comparison proved that, in the case study considered, the solution using fast charge was cheaper, and fast charge can be a valid approach to solve the problem of short autonomy of electric vehicles.

Keywords: battery; cycle life; fast charge; life cycle cost; public transport

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1. Introduction

The short autonomy of electric vehicles is one of the most important barriers affecting their large diffusion in the market, and fast charge of lithium batteries is one of the most significant enabling factors addressed. Many countries are implementing plans and strategies for the installation of electric-vehicle charging infrastructures which involve fast-charging stations. Manufacturers are bringing electric-vehicle charging stations to the market with increasing levels of power.

On the other hand, we currently know very little about the impact of fast charge on lithium batteries. Battery manufacturers give information about the life cycle of their products, but this information is applicable to conditions that differ from the applications. Literature offers a lot of data about the characterization, life cycles or aging testing, and the modeling of lithium-ion cells [1–5]; however, few results are available on tests using real working profiles, especially those with fast charging, and/or experiences with complete battery systems on board of electric vehicles [6–8].

In this scenario, fast charge appears a very important topic to investigate [9–12]. The ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) has researched life tests of battery systems for electric vehicles for a long time [13,14], and in the past few years, the experimental activities in the sector of life-cycle testing of lithium batteries for fast charging have increased.

This study generally addresses the effects of fast charge on a lithium-ion battery module. In particular, the cells inside the battery module were subject to a charging current rate much bigger than that recommended by the manufacturer. As a real challenge of the work, this choice was specially made to overdo and better enhance the effects of fast charge on lithium batteries.

After a description of the battery module, the fast-charge life cycle procedure and its effects are discussed. Finally, the correspondence of the life cycle procedure with a real application for local public transportation was considered, and a cost comparison between the battery systems of a minibus was made throughout the vehicle's lifespan. The minibus was equipped with the following:

(i) a battery system sized for fast charge at the end of line,
(ii) a larger battery system sized for slow charge at the end of a working day.

2. Battery Module

The battery module characteristics were 12.8 V and 60 Ah. It was developed and realized by ENEA in collaboration with the University of Pisa, Department of Information Engineering, under the founding of the Italian Ministry for Economic Development in the framework of the Program Agreement for the Research on National Electric Systems. It was made of four lithium-iron-phosphate cells connected in series, and it was equipped with a battery management system (BMS; Figure 1 and Table 1), which provided the following functions:

- Monitoring: the BMS measured, displayed, and registered the values of voltage and temperature for each cell.
- Thermal control: when the temperature measurement of one or more cells reached an upper limit, called "T_cell_fan_on", the BMS switched on the cooling system, which functioned until the temperature value reduced to a lower limit, called "T_cell_fan_off". The upper and lower limits were set during the BMS configuration.
- Protection: when the value of a measure (cell voltage, current, or temperature) reached the alert limit, the BMS disconnected the battery module by opening a switch.
- Active balancing by means of a DC/DC converter which drew energy from the overall module and, from time to time, supplied the cell with the lowest voltage in the module through a switch matrix. This function was only performed when the battery module was not working in charge or discharge, and the maximum value of the cell-balancing current was 2 A. The schematic of the BMS is shown in Figure 2.

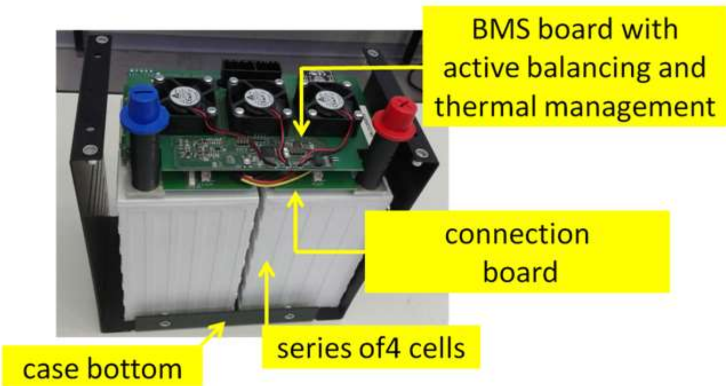

Figure 1. Battery module tested.

Table 1. Main characteristics of the battery module and the battery management system (BMS).

Cells	Type Cathode Anode Life cycle Number Connection	Lithium-ion Lithium iron phosphate (LFP) Graphite 2000 (DOD 80%; dsch CC @ C/3; ch CC/CV @ C/3) 4 Series
Capacity	-	60 Ah
Dimensions	-	297 × 166 × 236 mm^3
Weight	-	12.3 kg
Voltage	Nominal Minimum Maximum	12.80 V 10.00 V 14.60 V
Recommended current	Discharge Charge	30 A (C/2) 20 A (C/3)
Max continuative current	Discharge Charge	180 A (3C) 60 A (1C)
Working temperature	Discharge Charge	−20 ~60 °C 0 ~45 °C
Balancing (operated by BMS)	-	Active
Cooling (managed by BMS)	-	3 × 12 V_{DC} 34.5 Nm^3/h–75.5 Pa @ 7000 rpm fans

Battery technical jargon expresses current values in terms of multiples or submultiples of the nominal battery capacity. In the case of nominal capacity, 60 Ah means 60 A to 1C, 180 A corresponds to 3 C, and so on.

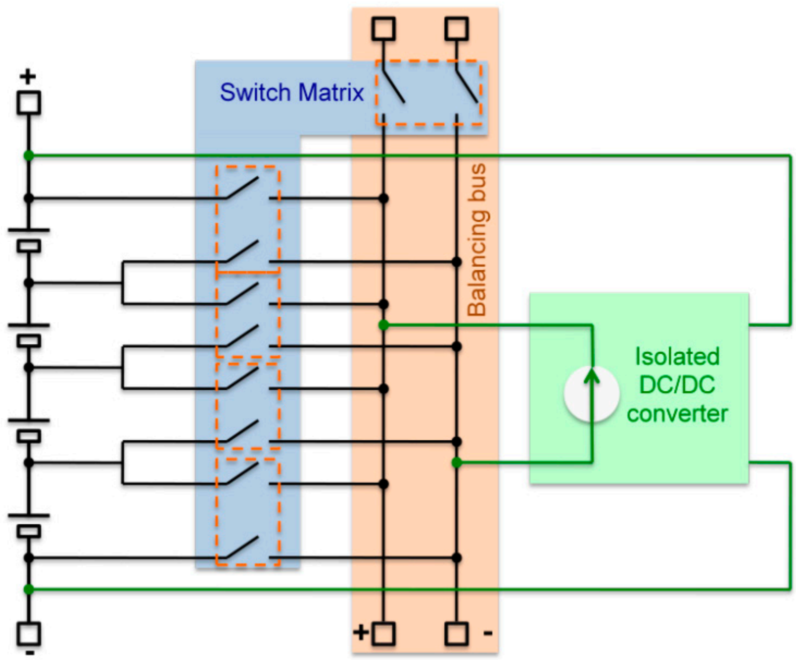

Figure 2. Schematic of the battery management system (BMS).

3. Test Procedure

The test procedure is summarized in Table 2. It was consistent with a typical local public transport (LPT) mission, where the battery system of the electric bus was recharged at the end of line, as demonstrated in Reference [15].

Table 2. Test procedure.

Step Number	Step Type	Step Characteristics	Step End Conditions	Comment	Correspondence with local public transport (LPT) Mission
1	Rest		60 s	Life cycle test profile with fast charge	Stop at end of line. Disconnection from charging station
2	Discharge	CC @ 1C	900 s or V_{min}		Travel
3	Rest		60 s		Stop at end of line. Connection to charging station
4	Charge	CC/CV I_{max} = 3C	300 s		Stop at end of line. Fast charge
5	-	Go to step 1 and repeat the loop from step 1 to step 4 48 times	-	Loop	Operation for 16 h without interruption
6	Rest		7200 s	Slow charge	Slow charge and balancing during night at the garage
7	Charge	CC/CV I_{max} = C/3	Complete charge		
8	Rest	Rest while the BMS provides the balancing function	-	Balancing	

The ENEA battery module was equipped with a battery management system which provided the thermal control. In this experiment, the temperature upper limit ("T_cell_fan_on") was set to +35 °C, and the lower limit ("T_cell_fan_off") was set to +30 °C.

The difference between the performance in charge given by the cell manufacturer (maximum charging current rate—1 C) and the one used here (charging current rate—3 C) was specially chosen to better highlight the effects of fast charge.

To avoid the cells unbalancing, a slow charge with balancing was introduced in the test procedure every night, before starting the test sequence the day after. An example of the repetitive execution of the test profile, from step 1 to step 4, is shown in Figure 3 (current in red and module voltage in blue).

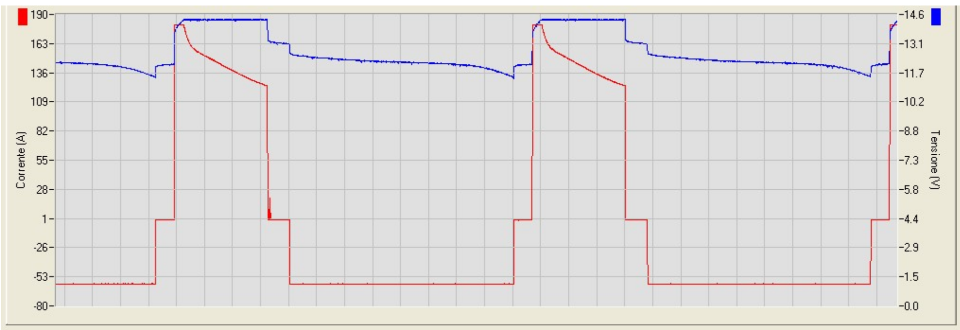

Figure 3. Test profile.

The test procedure was performed by one of the bidirectional AC/DC converters (cyclers) belonging to the ENEA Systems and Technologies for Mobility and Storage Laboratory.

The cycler is an electronic device capable of running charge and discharge of the storage system according to planned and controlled conditions. It is possible to set the method of charge/discharge, the current/power value, and the warning and alarm conditions for each step of the test procedure. It works as a power supply during charge, and as a load during discharge. The energy drawn from the storage system during discharge is given to the grid (regenerative function).

The cycler produced a test result in the form of a .csv file, and the values (measured and registered) of the physical characteristics are reported in Table 3.

Table 3. Row of data registered by the cycler.

Date Hour	Cycle Number	Step Number	Microcycle Number	Step Time	Battery System (BS) Voltage	Current	Step Capacity	Step Energy	Total Capacity on Charge	Total Energy on Charge	Total Capacity on Discharge	Total Energy on Discharge	Temperature	Temperature (Pt100)
-	-	-	-	(s)	(V)	(A)	(Ah)	(Wh)	(Ah)	(Wh)	(Ah)	(Wh)	(°C)	(°C)

During the test configuration, it was possible to set the data sampling rate up to the minimum value of 0.1 s. (This value of the data sampling rate was related to the cycler used to perform this test procedure. The best performance available from the cyclers in the laboratory was 0.01 s (100 Hz)). It was also possible to set different values of the data sampling rate in various steps of the same testing procedure.

The tests were performed at +25 °C, guaranteed by the air-conditioning system of the test room (no climatic chamber was used).

The cycler was equipped with a type K temperature sensor and a Pt100 temperature sensor. The type K temperature sensor was positioned inside the battery module (between two cells, in the middle) to register the temperature inside the module, while the Pt100 temperature sensor was positioned outside the battery module, nearby it, to register the room temperature and to ensure its value during the tests remained as +25 °C. The temperature of the cells was measured by NTC sensors applied to the cells, with one sensor on each cell. The values measured by these sensors were sent to the BMS, which registered and managed them to verify that the temperature of the cells remained as per the normal working conditions. If necessary, the cooling system was activated or the battery was disconnected (final safety action). The measure of the temperature inside the battery module, performed by the type K thermal sensor, was complementary to that performed by the NTC sensor on each cell. This thermal control made it possible to keep the cell temperature in the normal range when performing the test procedure, as shown in Figure 4, where the temperature behavior is shown during the test profile.

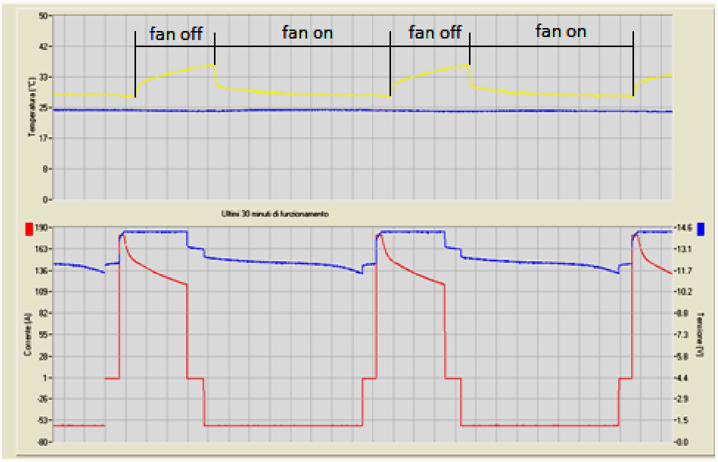

Figure 4. Test profile and temperature behavior.

4. Test Results

During the test procedure, all electric and thermal quantities remained as per the normal working conditions.

The test procedure was periodically interrupted to check the performances of the battery module. The check consisted of a capacity and energy measure, taken during a standard cycle of complete charge and discharge, according to the current rate recommended by the cell manufacturer (see recommended current rates in Table 1, rows 13 and 14). More than 3000 repetitions of the life cycle test profile were performed, without registering a significant reduction in performance in terms of capacity, energy, and efficiency, as shown in Figure 5.

As an aging indicator, the battery module resistance was also considered. Its computation was done when performing the abovementioned standard cycles, as a ratio between the value of voltage difference and current. In more detail, the voltage difference was the difference between the voltage measure (done by the cycler with an error less than 1%) 60 s after the current started, and the voltage measure without current. The computation of resistance in charge was done at the beginning of charge, while that of resistance in discharge was done at the beginning of discharge. This quantity was not a measure of real inner resistance; however, the growth of its value suggests a change inside the battery module. (The real measure of inner resistance was not set at the beginning of the tests, as a reduction in capacity was expected rather than an increase in resistance. However, after continuing cycles without registering a relevant reduction in capacity, it was thought to introduce an evaluation of resistance that was possible using the existing data (not appositely set to properly calculate the inner resistance)).

The evaluation of the battery module resistance is shown in Figure 6. A relevant increase (around twice the initial value) was registered in the parametric checks executed after 1000~2000 repetitions of the test procedure.

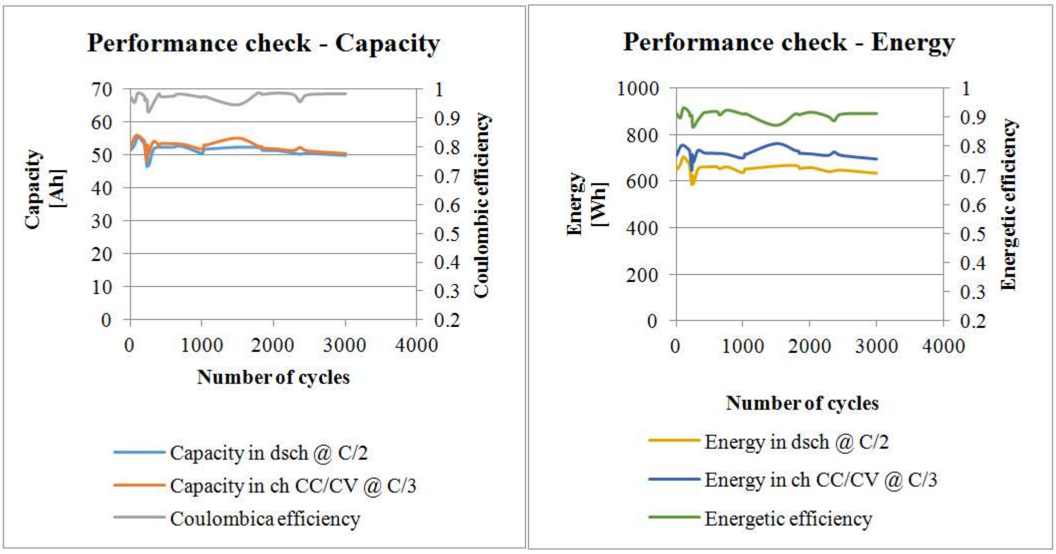

Figure 5. Capacity and energy of the battery module in the parametric check.

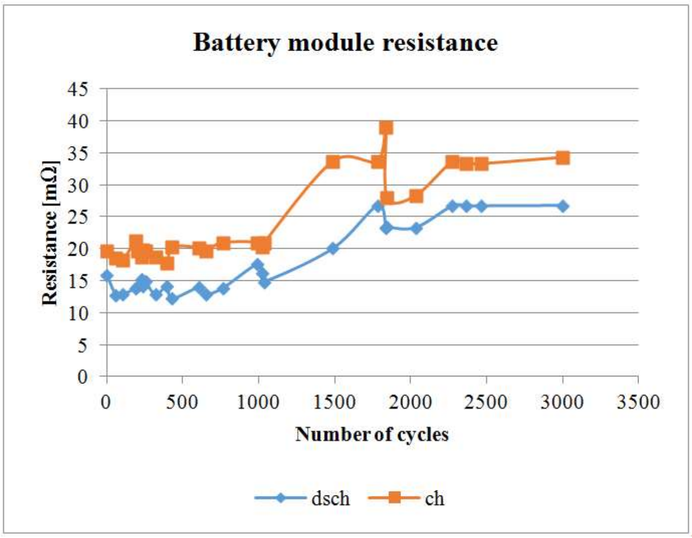

Figure 6. Inner resistance of the battery module.

5. Life Estimate of the Battery Module

Due to the increase in resistance, both in charge and discharge, the lengths of step 2 (discharge) and step 4 (charge) in the test procedure progressively reduced during aging, as the minimum/maximum voltage was achieved more quickly. Starting from the initial theoretical value of 15 Ah, the battery module progressively reduced its capacity in steps 2 (discharge) and 4 (charge) of the test procedure, and correspondingly, the electric bus, in the analogy with the LPT mission, reduced its autonomy. This situation is shown in Figure 7. For this reason, it seems more realistic that the "end of life" condition was provoked by the increase in inner resistance, rather than the reduction in capacity measured in the periodical check (as per the usual assumption for battery systems in vehicular applications).

A battery system realized by 24 modules, like the one used for the test, translates the power demand cycle used for the test of the battery module into a duty cycle for the battery system of a minibus (e.g., the "Gulliver" manufactured by Tecnobus). In fact, six modules (12.8 V each) connected in series give a voltage (76.8 V) typical of such a minibus drivetrain. Furthermore, a charging power of 55 kW (a typical value for DC charging stations) corresponds to a current of 716 A, which becomes 179 A (3 C rate, referring to the nominal cell capacity of 60 Ah) if the modules are organized in four strings connected in parallel. This translation allows the end-of-life condition to be set.

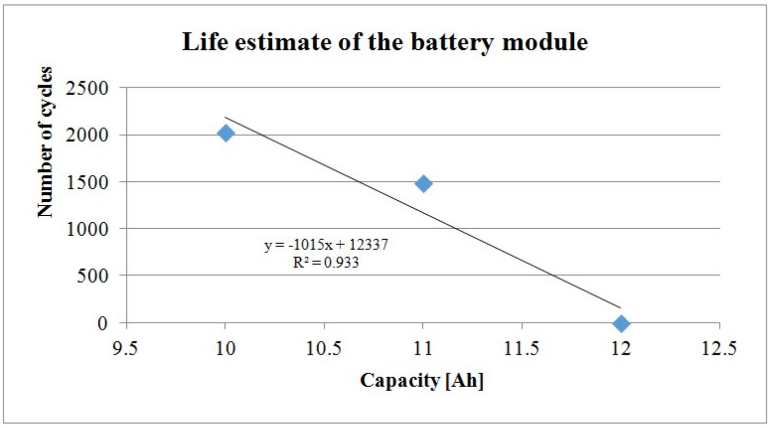

Figure 7. Life estimate of the battery module.

Considering this real case, the minimum distance sufficient for a TPL mission was fixed at 5 km, and using the correlation with the kilometric consumption, the corresponding capacity necessary to cover such a distance was calculated. In these conditions, the minimum capacity required by a single battery module is 5.5 Ah. At this point, it was possible to estimate the life of the battery module using the trend line that better fit the experimental data relating to the capacity drawn in the discharge (step 2 of the procedure), as shown in Figure 7. The expected lifespan was about 6750 cycles.

6. Cost Estimate and Comparison between Slow and Fast Charge

On the basis of the above result, a cost estimate and comparison between slow and fast charge was made, under the same service conditions throughout the vehicle life, for the real case of a minibus equipped with the following:

(i) a battery system sized for fast charge at the end of line,
(ii) a larger battery system sized for slow charge at the end of a working day.

The cost estimate is summarized in Table 4.

The comparison was based on a 16-h (two shifts, 8 h each) service, and a commercial speed of 12 km/h.

Considering a duty cycle of 75% (15 min charge and 45 min travel per hour of service), the minibus equipped with (i) (fast charge at the end of line) covered 144 km in a day. The same distance was assigned to the minibus equipped with (ii) (slow charge).

Table 4. Battery system cost estimate.

	Fast Charge (3 C)	Slow Charge
Service time	16 h	16 h
Commercial speed	12 km/h	12 km/h
Duty cycle	75%	75%
BS capacity	240 Ah	1000 Ah
Distance covered in a day	144 km	144 km
BS weight	288 kg	1200 kg
Vehicle life	12 y	12 y
BS unitary cost	500 €/kWh	500 €/kWh
BS total cost	8640 €	36,000 €
BS life	20 months	72 months

The nominal capacity of the storage system in the minibus equipped with (i) was 240 Ah (four strings, 60 Ah each, connected in parallel). This data corresponded to a battery system made by 24 modules, designed and used by ENEA, in collaboration with the "Centro Ricerche per il Trasporto e la Logistica" of Rome's University "La Sapienza", to retrofit a minibus "Gulliver" from Tecnobus, originally equipped with lead batteries. For this minibus, in the configuration with lithium batteries, a kilometric consumption of 325 Wh/km was measured on a specific route located in ENEA's "Casaccia" Research Centre. The battery system was organized with four strings connected in parallel, each consisting of six modules connected in series, allowing the working voltage required by the drivetrain to be attained. In the minibus equipped with (ii), a broad estimate of the battery system's size was possible via the multiplication of the kilometric consumption (assumed 500 Wh/km due to the bigger weight of the battery system itself) and the daily distance, the result of which was divided by the nominal voltage.

The weight of the battery system was calculated from the multiplication of the weight of one battery module (12 kg) by the number of modules used, to reach the working voltage and capacity for each case used.

According to typical values in the literature, the vehicle's lifespan is considered as 12 years.

In case (ii) (the minibus equipped with a battery system (BS) sized for slow charge at the end of a working day), the daily working cycle was similar to a standard cycle, where the vehicle covered all its daily distance using the capacity installed on its storage system, and the batteries were charged slowly and completely overnight. With good accuracy, the life of the battery system can be estimated by the number of cycles (conveniently reduced) given by the cell manufacturer relating to the standard cycle. By using the distance covered in a day, the number of cycles (that is, the life of the BS) could be immediately converted into a number of days or months.

In case (i) (the minibus equipped with a battery system developed for fast charge at the end of line), the result of the presented life cycle test could be used (even if the commercial speed relating to the life cycle test was, theoretically, about 56 km/h). Due to the discharge (step 2 of the testing procedure) theoretically drawing 15 Ah, which was $\frac{1}{4}$ of the battery module's nominal capacity, it could be assumed that four cycles of the test procedure corresponded with one complete discharge. To a first approximation, the number of equivalent cycles with deep discharge could be calculated by the number of cycles with partial discharge (from the test results) divided by four. The number of cycles with deep discharge, equivalent to the real number of cycles with partial discharge, could then be converted firstly into distance covered (by using the nominal energy of the BS, and the kilometric consumption), and then, into a number of day and months (by using the daily distance).

The purchase cost of the BS could be calculated from a multiplication of the unitary cost, assumed as 500 €/kWh (data from direct experience of recent purchases), and the nominal energy of the BS.

Considering the battery system's cost and duration, it was now possible to calculate the operational cost of the electric minibus' battery system throughout the vehicle's lifespan as a sum of the actualized purchase costs of the battery system, and the charging costs (assumed average charge cost: 0.15 €/kWh). Figure 8 summarizes the results for the following:

- For the minibus equipped with a battery system developed for slow charge at the end of a working day. The battery system's life was 72 months; thus, it must be purchased two times within the lifespan of the minibus (144 months). The corresponding line of costs in the diagram was made using two vertical lines (corresponding to the two purchases), and two straight segments, whose gradient was proportional to the average cost of recharge.
- For the minibus equipped with a battery system developed for fast charge at the end of line. The battery system's life was 20 months; thus, it must be purchased eight times within the lifespan of the minibus (144 months). The corresponding line of costs in the diagram was made using eight vertical lines (corresponding to the eight purchases), and eight straight segments, whose gradient was proportionate to the average cost of recharge.
- In the studied case, the line of costs corresponding to the "fast-charge solution" always remained under that corresponding to the "slow-charge solution" throughout the minibus' lifespan.

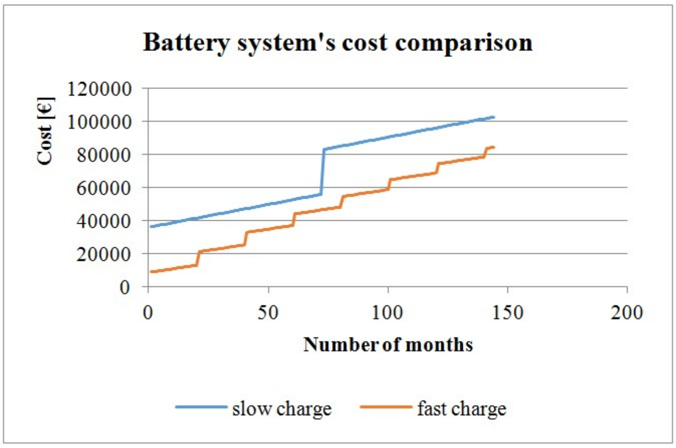

Figure 8. Cost comparison.

7. Conclusions

The life cycle test had a prudential approach. In fact, the following factors were considered:

- The cells of the battery module had 1 C as the maximum charge rate recommended by the cell manufacturer.
- The battery module used for the life cycle test was not completely new; however, it was previously used in the characterization of short, not heavy, life cycle tests.
- The life cycle test was performed in heavier conditions when compared with those strictly required for the corresponding TPL mission (5 km in 15 min, 20 km/h, about 20 A in discharge—step 02 of the test procedure, while this step was performed at 60 A throughout the test).

This choice to perform a prudential test was specifically done to highlight the effects of fast charge on a battery system, even in the case of shallow cycles as those performed in this experiment.

The test procedure was consistent with a typical mission required by the local public transportation for a minibus. The electric charge stored during the fast charge at the end of line was sufficient to cover the service distance so the minibus could work without interruption. In the absence of fast charge, the service would be stopped periodically to charge the battery, or the minibus would be equipped with a larger battery system. In fact, the fast charge allowed the implementation of a battery system into the minibus, which had the minimum size necessary for its transport mission.

Even if in a prudential approach, it was possible to demonstrate the comparison between the life cycle costs of both battery systems for a minibus. The following conclusions were drawn:

(i) The minimum size (i.e., the electric charge stored during the fast charge at the end of line) was exactly that needed to cover the service distance so the minibus could work without interruption.
(ii) With the larger size (i.e., with the same daily service/distance of the use case above), the minibus only completely and slowly charged its battery system at the end of a working day.
(iii) It was more convenient to instead equip the minibus with a smaller battery system, using fast charge at the end of line.

The case studied suggests that fast charge, in the proper combination/balance with the size of the battery system and the vehicle mission, can be a valid instrument to obtain a cost-effective solution, and to solve the problem of short autonomy of electric vehicles. This is particularly true in the LPT field.

It is important to point out that the results of this study should not be taken in an absolute sense, and a good account of the context should be considered. The test procedure related to partial charge/discharge, corresponding to a maximum state of charge (SoC) range of 25%, and particular help came from the battery management system, which provided the balancing function and thermal control, so that the cell voltage and temperature remained within the limits of normal working conditions.

Author Contributions: G.P. was the Research Manager to whom the concept of this research activity belongs. F.V. cared the experimental activity, test data processing and reporting. Both the authors drew the conclusions. F.V. cared the preparation of the article, under G.P.'s supervision.

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Nomenclature

BMS	battery management system
BS	battery system
C	nominal capacity value
CC	constant current
CC/CV	constant current/constant voltage
ch	charge
C/n	current rate stated as sub-multiple of the nominal capacity value
csv	comma separate values
DOD	depth of discharge
dsch	discharge
I_{max}	maximum allowable value of current
LFP	lithium-iron-phosphate
LPT	local public transport
nC	current rate stated as multiple of the nominal capacity value
SoC	state of charge
V_{min}	minimum allowable value of voltage
V_{max}	maximum allowable value of voltage
V_{nominal}	nominal voltage

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