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Commercial Electric Vehicle Battery Degradation modelling and charging assessing using a real driving cycle

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Abstract. This paper proposes a model to study the degradation of li-ion NMC batteries of commercial electric vehicles. The model takes into account operation variables such as operating C-Rate, Depth of Discharge (DoD), Number of Cycles and Temperature using a 4-D Piecewise Cubic Hermite Interpolating Polynomial (PCHIP). Simulations have been done considering the Worldwide Harmonised Light Vehicles Test Procedure 3 (WLTP3) standard cycle. The model has been implemented in MATLAB. In addition, recommendations on charging procedures are given in order to reduce the degradation of batteries.

Key words. Battery, Degradation, Model, Li-Ion-NMC, Electric Vehicle.

1. Introduction

Greenhouse Gas (GHG) emissions exceeded the amount of 36.79 Gigatons of CO_{2e} in 2017, with the transport sector being responsible for 35% of the energy consumption [1]. Passenger transport by road accounted for 21% of that energy, with an average consumption of 1.9 MJ / pkm (MegaJoules by passenger and kilometer) [2]. The electrification of transport is one of the proposed actions to mitigate the effects of climate change, although the origin of energy must be also taken into account [3].

Among electric vehicles disadvantages, it can be found: their low autonomy, which is directly related to the specific energy of the batteries, and the high cost and limited lifetime of batteries. Furthermore, the few available charging stations and long duration of the charging process turn the optimal management of the energy into a necessity for the correct development and integration of this technology.

In this context, transport needs vary along the countries and can be generally classified into three ranges [3]:

- About 40 km: UK is the leading country in this category.
- 50-60 km: Most countries are in this category, such as Germany France, Italy, etc.
- More than 70-80 km: Countries such as Poland and Spain.

Considering all above mentioned, an adequate model to calculate the lifetime of lithium-ion batteries is necessary to reduce the range anxiety of electric vehicles drivers, as well as to know when the End of Life (EoL) of the battery is reached. This EoL is achieved when the capacity of the battery is reduced to 80 % of the initial battery capacity [3].

Degradation in lithium-ion cells is given by two factors: capacity fade and power fade. The capacity fade refers to the reduction of the capacity of an "old" cell with respect to its original characteristics. Similarly, the power fade refers to the power reduction, related to the internal resistance increase. In electric vehicles, capacity fade is known to be the most problematic degradation mechanism, as it defines the range the vehicle can travel.

At present, only specific chemicals of lithium-ion are supposed to be appropriate for traction. These chemicals are nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminium, referred to the cathode material. Lithium-ferrous-phosphate is not considered most appropriate due to its lower specific energy, though his specific power is greater [4].

In this sense, this document addresses the development of a degradation model of a commercial electric vehicle when it is subjected to a standard cycle while charging power can be varied.

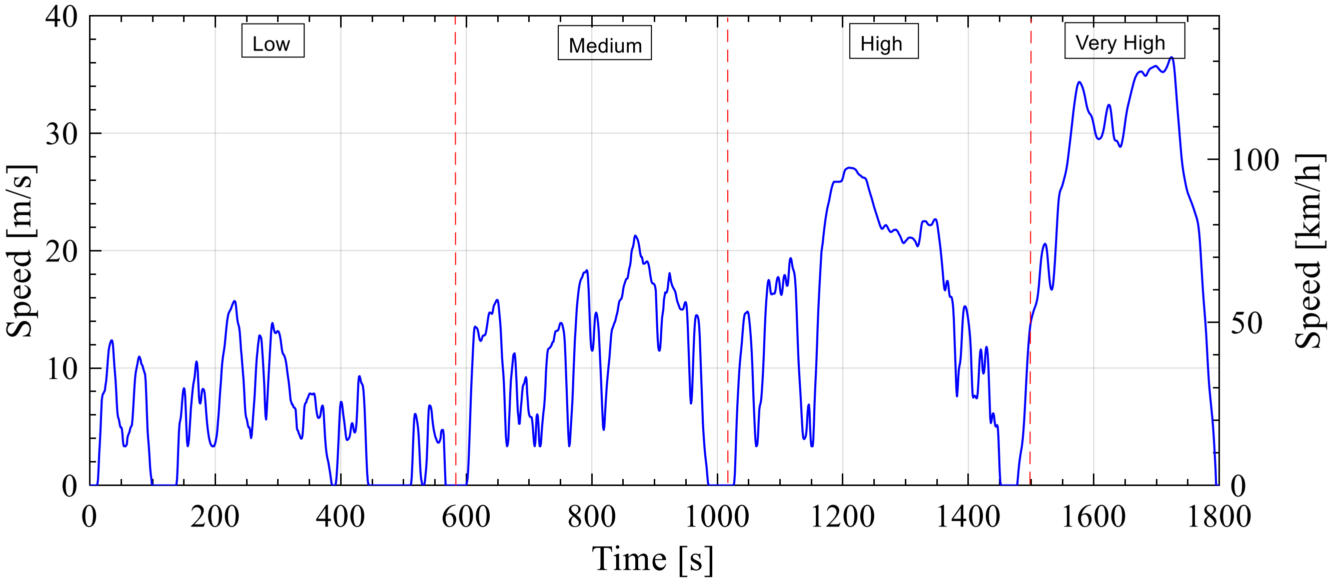

Fig. 1. World Harmonized Light-duty Vehicle Test Procedure of 3rd generation speed profile.

2. Description of test elements and procedures

A. Commercial Electric Vehicle

The selected commercial vehicle for this study is the Renault Zoe. This vehicle is among the most sold electric vehicles worldwide, with greater sales than Tesla in Europe. Its technical data are shown in Table I.

Table I. – Renault Zoe 2020 R110 Technical Data

PARAMETER	VALUE
Test Procedure	WLTP3
Avg Range in Summer	300 km
Avg Range in Winter	200 km
Motor max Power	80 kW
Battery Capacity	41 kWh
Technology	NMC (Li-Ion)
Voltage	400 V
Modules/cells number	12/192
Number of strings/cells by string	2/96
Maximum charging Power	50 kW
Max speed	135 km/h
Drag coefficient, $C_D \cdot A$	0.75 m^2
Mass (Empty/Max)	1480/1966 kg

B. Li-ion Cell

The selected vehicle for this study (Renault Zoe 2020 R110) equips a battery composed of a set of Lithium-ion Nickel Manganese Cobalt (NMC) cells, which are manufactured by LG. The specific model is LG CHEM E63, whose specification data are shown in Table II and Open Circuit Voltage (OCV) curve is shown in Figure 2.

Note that 1C means a cycling at current to be fully discharged/charged in an hour, 63.5 A in this case.

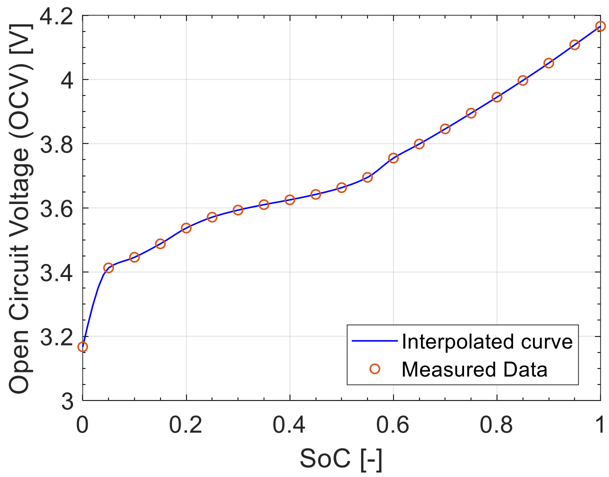

Fig.2. OCV curve of the LG E63 cell.

Table II. – LG Chem E63 Specification Data

PARAMETER	VALUE
Nominal Capacity	63.5 Ah
Nominal Voltage	3.6 V
Voltage	2.50 - 4.20 V
Continuous Operation Temperature	-10 – 45 ºC
Dimensions [LxWxH]	325x125x11.5 mm
Over Voltage Limit	4.45 V
Under Voltage Limit	2.00 V

C. Test Procedure

World Harmonized Light-duty Vehicle Test Procedure (WLTP) replaced the existing New European Driving Cycle (NEDC) in 2018. This test procedure presumes to be more realistic than NEDC, as it is based on realistic profiles and real habits and experiences of drivers. WLTP3 technical data are shown in Table III, while it is graphed in Figure 1.

Table III. – WLTP3 Data

	Low	Medium	High	Very High	Total
Duration [s]	589	433	455	323	1800
Stops Duration [s]	150	49	31	8	235
Distance [m]	3095	4756	7162	8254	23266
% of stops	26.5	11.1	6.8	2.2	13.4
Max speed [km/h]	56.5	76.6	97.4	131.3	
Avg speed w/o Stops [km/h]	25.3	44.5	60.7	94.0	53.5
Avg speed w stops [km/h]	18.9	39.4	56.5	91.7	46.5
Min acc [m/s^2]	-1.5	-1.5	-1.5	-1.44	
Max acc [m/s^2]	1.611	1.611	1.666	1.055	

This driving test procedure is supposed to be executed twice in a day, as a common roundtrip, while the charging is supposed to be performed every 2 days.

3. Development of the model

A. Vehicle Dynamic Model

The calculus of the Depth of Discharge (DoD) is approached by using a Vehicle Dynamic model, which it is explained hereunder.

The general equation that describes the movement of a vehicle is given by the Second Law of Newton [5]:

$$\frac{\boldsymbol{dv}}{\boldsymbol{dt}} = \frac{\sum \boldsymbol{F_t} - \sum \boldsymbol{F_r}}{\boldsymbol{\delta M}} \qquad (1)$$

where:

$\boldsymbol{v}$, is the speed of the vehicle [m/s], $\sum \boldsymbol{F_t}$ is the total tractive force of the vehicle [N], $\sum \boldsymbol{F_r}$ is the total resistance force [N], $\boldsymbol{M}$ is the total mass of the vehicle [Kg], and $\boldsymbol{\delta}$ is the mass factor that equivalently converts the rotational inertia of rotating components into translational mass.

Figure 3 shows all the forces involved in the movement of a vehicle.

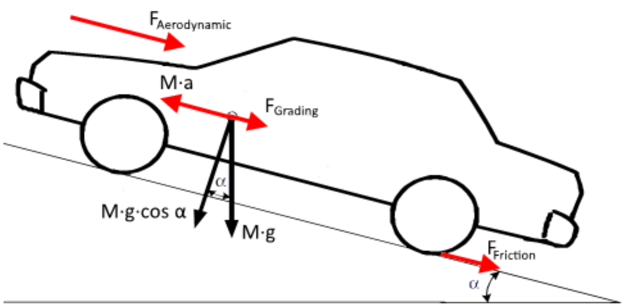

Fig.3. Forces involved in the moving of a vehicle.

As it can be deducted from Figure 3, the only force that contributes to the moving of the vehicle, $\boldsymbol{F_t}$, is $\boldsymbol{M \cdot a}$. So, the general equation can be transformed into the equation (2) in the axis of movement.

$$\frac{\boldsymbol{F}}{\boldsymbol{M}} = \boldsymbol{a} + \frac{\boldsymbol{F_{grading}} + \boldsymbol{F_{friction}} + \boldsymbol{F_{aerodynamic}}}{\boldsymbol{M}} \qquad (2)$$

where:

$$\boldsymbol{a} = \frac{\boldsymbol{dv}}{\boldsymbol{dt}} \qquad (3)$$

$$\frac{\boldsymbol{F_{grading}}}{\boldsymbol{M}} = \boldsymbol{g \cdot \sin(\alpha)} \qquad (4)$$

$$\frac{\boldsymbol{F_{friction}}}{\boldsymbol{M}} = \boldsymbol{f_r \cdot g \cdot \cos(\alpha)} \qquad (5)$$

where:

$$\boldsymbol{f_r} = \boldsymbol{0.01 \cdot \left(1 + {}^{3.6 \cdot v}/_{160}\right)} \qquad (6)$$

$$\frac{\boldsymbol{F_{aerdoynamic}}}{\boldsymbol{M}} = \frac{\boldsymbol{1}}{\boldsymbol{2}} \cdot \frac{\boldsymbol{\rho \cdot C_D \cdot A \cdot (v - v_w)^2}}{\boldsymbol{M}} \qquad (7)$$

where:

$\boldsymbol{g}$ is the gravity force [m/s^2], $\boldsymbol{\alpha}$ is the grading angle [deg], $\boldsymbol{f_r}$ is the friction coefficient, $\boldsymbol{\rho}$ is the air density in [kg/m^3], $\boldsymbol{C_D}$ is the drag coefficient [-], $\boldsymbol{A}$ is the front area of the vehicle in [m^2] and $\boldsymbol{v_w}$ is the wind speed in [m/s].

Equation (6) predicts the value of $\boldsymbol{f_r}$ with acceptable accuracy for speeds up to 128 km/h. For this case, $\boldsymbol{\alpha}$ has been supposed to be 0º, as well as $\boldsymbol{v_w}$ to be nule.

Given the instantaneous speed of the vehicle by the WLTP3 cycle (Figure 1), its derivative is calculated $\left(\frac{\boldsymbol{dv}}{\boldsymbol{dt}}\right)$, obtaining the instantaneous acceleration of the vehicle, $\boldsymbol{a}$. So, the value of the power produced by the motor is got, proportional to $\frac{\boldsymbol{F}}{\boldsymbol{M}}$ and speed. This power is supposed to be the instantaneous electric power demand from the battery.

$$\frac{\boldsymbol{F(t)}}{\boldsymbol{M}} \cdot \boldsymbol{M \cdot v(t) = P = V \cdot I(\mathbf{t})} \qquad (8)$$

Regenerative braking is modelled as a recovery of part of the energy when the vehicle has to slow down. Empirically, the recovery coefficient, $\boldsymbol{k}$, has been determined to be 0.25, by adjusting the range of the vehicle modelled to that given in datasheet.

Note that two considerations have to be made, one considering the sign of the energy flow and the other considering the energy exchanged (current throughput). First one is used to calculate the DoD after performing the driving cycle, considering regenerative braking, while the second is used to calculate the C-Rate during the driving period.

$$DoD = \frac{\int_0^t F(t) \cdot v(t) \cdot dt}{N_{cells} \cdot C \cdot V \cdot 3600} \quad (9)$$

$$C - Rate_{Driving} = \frac{\int_0^t |F(t)| \cdot v(t) \cdot dt}{N_{cells} \cdot C \cdot V \cdot t} \quad (10)$$

Considering the WLTP3 to be executed four times between each charge, equivalent to two roundtrips, DoD of the battery is calculated to be 0.156 for each roundtrip, and 0.312 every two roundtrips. Instantaneous State of Charge (SoC) of the battery is shown in Figure 4b. The battery has been supposed to be charged until 80 % of SoC because Constant Current (CC) Charge is usually performed until this limit, where it is usually swapped to Constant Voltage (CV) Charge.

B. Degradation Model

Degradation data model is taken from a technical report from the manufacturer [6]. In this reference, several experiments have been performed to obtain experimental data to emulate the degradation. The Experimental Test Matrix is shown in Table IV.

Table IV. – Experimental Test Matrix

Charging Current	Temperature	DoD
C/3	25 ºC 45 ºC	20 % 40 % 60 % 80 %
22 kW	25 ºC	20 % 40 % 60 % 80 %
43 kW	25 ºC	20 % 40 % 60 % 80 %

All the curves describing the State of Health (SoH) of the battery have been adjusted to a potential curve form, which has been determined to be the greatest adjust for the data given:

$$SoH\,[\%] = 100 - a(DoD, C, T) \cdot N^{b\,(T,C)} \quad (11)$$

where:

SoH is the State of Health in [%], *a* is the pre-potential factor that better fits the data, N is the number of cycles and *b* is the potential factor determined for each temperature and C-Rate. The value of K is maintained constant for each DoD under same T and C-Rate to preserve the tendency of the data.

Based on the experimental data and results obtained in [6], a degradation model concerning a wide range of C-Rate, Depth of Discharge (DoD), number of cycles and Temperature is obtained. For this purpose, Shape Preserving Hermite Interpolating Method or Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) has been used to obtain the data not explicitly given in the reference. Shape Preserving Hermite Interpolating Method has the advantage of preserving the tendency of the data to be interpolated. In this context, several cases can be found depending on if the value searched is directly available from experimental test result, partially available or not available at all. Possible cases are shown in Table V.

Table V. – Charging Data considered

Case	DoD	N	T	C
1	Yes	Yes	Yes	Yes
2	Yes	Yes	Yes	No
3	Yes	Yes	No	Yes
4	Yes	Yes	No	No
5	Yes	No	Yes	Yes
6	Yes	No	Yes	No
7	Yes	No	No	Yes
8	Yes	No	No	No
9	No	Yes	Yes	Yes
10	No	Yes	Yes	No
11	No	Yes	No	Yes
12	No	Yes	No	No
13	No	No	Yes	Yes
14	No	No	Yes	No
15	No	No	No	Yes
16	No	No	No	No

DoD, will be only dependent on driver transport needs, while C-Rate will be also influenced by the charging power. Charging powers considered are the standardised up to the maximum charging power of the vehicle, which is 50 kW. So, the charging powers considered are summarised in Table V.

Table VI. – Charging Data considered

	Power	Phases	Maximum current (per phase)	C-Rate @ DC 400 V
Level 2	2.3 kW	1	10 A	0.091
	7.4 kW	1	32 A	0.2913
Mode 1	3.7 kW	1	16 A	0.1457
	11 kW	3	16 A	0.4331
Mode 2	22 kW	3	32 A	0.8661
Level 3	43 kW	3	63 A	1.6929
Mode 3	50 kW	DC	100 A	1.9685

Table VI shows the charging powers considered in this study. These charging powers or C-Rates have been combined with the driving power or C-Rate, to get the weighed power or C-Rate in a driving-charging cycle.

$$C_{Rate} = \frac{C_{Rate\ Driv} * t_{Driv} + C_{Rate\ Ch} * t_{ch}}{t} \quad (12)$$

4. Simulation Results and Discussion

The speed profile used, based on WLTP3 and repeated four times which is able to travel a total distance of approximately 94 km, is shown in Figure 4a. The power developed by each cell of the battery after applying equation 8 is shown in Figure 4b. In this figure, negative values of power, corresponding to regenerative braking can be shown. On right axis, it is represented the current in each cell, proportional to power. The effect of power on the battery can be appreciated in the SoC, which is shown in Figure 4c. Furthermore, the open circuit voltage of each cell is represented in the second axis.

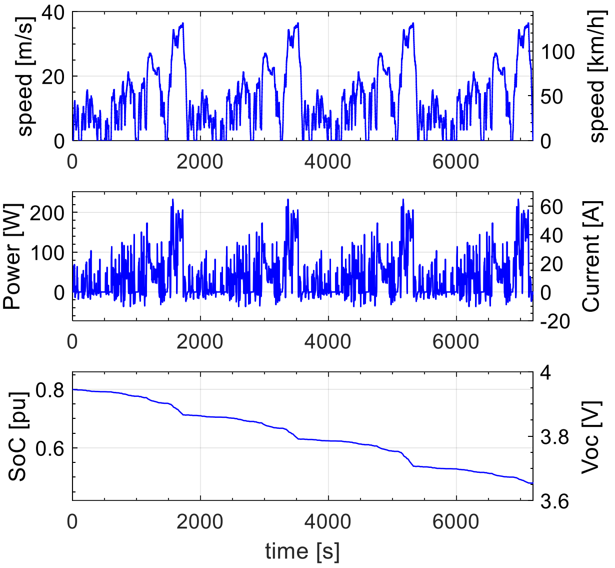

Fig.4. a) Vehicle speed b) Power and Current by cell c) SoC and VoC by cell given by 4xWLTP3

Figure 5 shows the degradation of a unique cycle for different temperatures and C-Rates with a constant DoD. It can be seen that temperature is a key factor when comes to degradation of the battery, but C-Rate has the greatest influence.

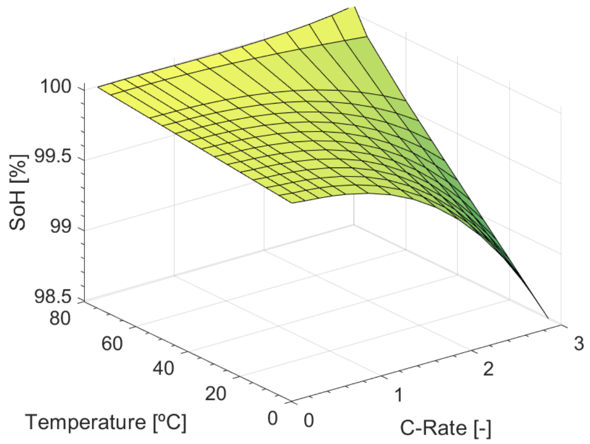

Fig.5. Degradation for 30% DoD unique cycle

As the temperature in the operation of batteries is a variable to be controlled, it has been supposed a constant temperature of 45ºC. In this sense, Figure 6 shows the degradation for 45ºC and 0.5C cycling. For bigger DoDs, degradation gets bigger.

Figure 7 shows the degradation for a DoD of 32% (four times WLTP3 cycle) and 45ªC. Numerical results are represented in Figure VII.

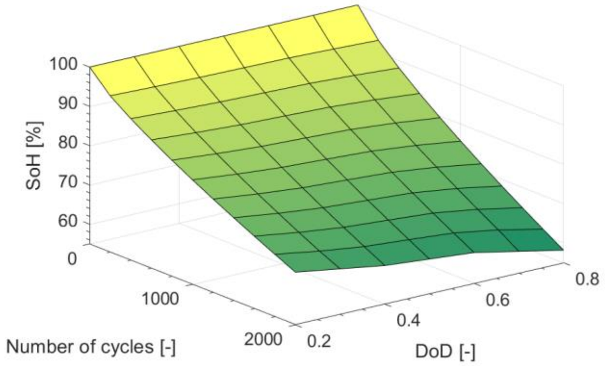

Fig.6. Degradation for 45ºC and 0.5C cycles

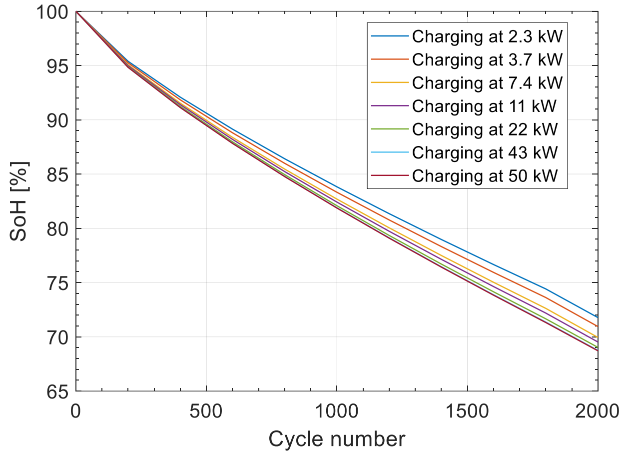

Fig.7. Degradation for 4xWLTP3 cycle (DoD=31.2 %) and 45ºC, depending on charging power.

Table VII. – Degradation Results. SoH after N cycles

	SoH	N=600	N=1000	N=1600	N=2000
Level 2	2.3 kW	89.14	83.83	76.66	71.77
	7.4 kW	88.38	82.69	75.03	69.94
Mode 1	3.7 kW	88.8	83.32	75.94	70.95
	11 kW	88.2	82.42	74.63	69.52
Mode 2	22 kW	87.97	82.08	74.15	69.03
Level 3	43 kW	87.85	81.9	73.88	68.75
Mode 3	50 kW	87.83	81.87	73.84	68.71

The number of cycles for reaching the EoL of the battery has been calculated considering data graphed in Fig. 7. In this context, Level 2 charging would allow to cycle the battery 1,314 times in monophasic and 1,204 times in triphasic. Mode 1 charging would allow 1,263 and 1,180 times in monophasic and triphasic, respectively. Mode 2 charging decreases battery lifetime to 1,152 cycles, and Level 3 to 1,137 times, while the fastest one, Mode 3, decreases to 1,135 times.

5. Conclusions

The model developed is able to evaluate the degradation of a commercial NMC lithium-ion battery when it is cycled with a determined C-Rate, DoD and temperature. This model has been evaluated considering an electric vehicle, but it can also be applied to photovoltaic, or any other application.

As result of the simulations performed, it can be said that charging power is a considerable factor when batteries lifetime maximisation is aimed. In this sense, Mode 4 fast charging of a Renault Zoe at 50 kW would reduce batteries commercial lifetime by 13.63 % comparing to a Level 2 slow charging of 2.3 kW.

In this context, it is necessary to find a later use of electric vehicles batteries, such as could be their use in grid stabilization, or stationary storage in applications where the volume capacity is not determinative, for example, a photovoltaic application.

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