A Comparison of Supercapacitor and High-Power Lithium Batteries

Vincenzo Musolino, Enrico Tironi
Politecnico di Milano – department of Electrical Engineering
vincenzo.musolino@mail.polimi.it, enrico.tironi@polimi.it

***Abstract*- This paper reports and analyses experimental results showing the performances of two state-of-the art, commercially available storage systems, i.e. a supercapacitor (SC) and a super-high power lithium battery. These devices are often subject of comparison; the aim of the article is to explore their performances and to provide guidance in choosing the right device according to the application.**

The results are expressed mainly in terms of specific power and charge/discharge efficiency as a function of the wanted discharge time; they show that, very high power lithium batteries are a very useful solution for applications where high energy density is requested and peak powers can be delivered without additional storage systems; their limits consists of the limited cycle life and a sharp system temperature rise in these operative conditions. Supercapacitors, unlike, show high power density with a cycle life two orders of magnitude higher than high power lithium batteries. Their limit lies in the energy density that is up to two orders of magnitude smaller than high power lithium batteries.

Further investigations are conducted to verify the performances and efficiency of very high power lithium batteries in cycles of high power charge and discharge very close to those typical for supercapacitors.

I. INTRODUCTION

Electric energy storage requires to evaluate, according to the application, performances in terms of energy density, power density during discharge and recharge operations, efficiency, life span and total system cost.

When supercapacitors and high power lithium batteries are considered, it is commonly accepted that the first devices are able to deliver more specific powers, while the latter have their main advantage in the higher specific energy they can deliver.

Others two important characteristics that must be considered when comparing these two devices are the useful life and the operative temperature limits. It is well known indeed that supercapacitors show a cycle-life that is two orders of magnitude larger than that of lithium batteries, when they are fully discharged. The comparison is more open when the devices are only partially discharged. Particular attention has to be paid in analyzing the high power lithium batteries overtemperature according to their operative conditions. This aspect defines real capability limits.

One important field of application of energy storage is onboard hybrid vehicles [1]-[2]: here the balance power/energy, which depends on vehicle mission specification, may be such that supercaps or lithium batteries alone, or a combination of the two devices, may be the right choice.

Another growing field is that related to the uninterruptible power supply (UPS) [3]-[4]. The choice of the correct storage system for these devices is related to the UPS mission: a power mission (medium-high peak power for short time) or an energy mission (constant power for medium long time).

The respective fields of application of supercapacitors and lithium batteries, however vary with time, as long as technological evolution brings new products into the market.

In particular recent improvements in the power capability of lithium batteries and improvements in supercapacitor devices in terms of reduced internal resistance and increase life cycle until 1 million, calls for an update in the cross evaluation of the characteristics of these two devices and their relative vocation in relation to the application in which they are to be installed.

As a consequence of this, a previous paper [5] was presented having the aim of this work is therefore to present an up-to-date comparison between supercapacitors and high power lithium batteries to evaluate the respective performances according to common comparison criteria, especially specific power and energy and cycle efficiency, based on some experimental results obtained on two systems.

This paper resumes the main results of [5], and presents some additional results in terms of experimental and simulated data that make the comparison more complete. It shows how the supercapacitor experimental behaviour can be well explained by means of an equivalent mathematical model. A lithium battery model is under development, and will be presented in future papers.

II. DEVICES UNDER TEST

A. Supercapacitor Module

The supercapacitor considered in the tests is a 20 F 15 V module, manufactured by Maxwell Technologies (BPAK0020 P015 B01), whose declared data are reported in Table I.

TABLE I
SUPERCAPACITOR MODULE DATA

R_{dc} (mΩ)	I_{sc} (A)	E_{max} (Wh/kg)	P_{max} (W/kg)	m (g)
32	730	2.72	13587	230
Cycle test: capacitors cycled between specified voltage and half rated voltage under constant current at 25 °C (500,000 Cycles)				

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In Table I:

- R_{dc} is the "Equivalent Series resistance" computed as the ratio between the voltage variation $\Delta V=(V_f - V_{min})$ and the current step ΔI that has caused it. By a constant discharge current, V_{min} represents the minimum voltage reached at the end of discharge, while V_f is the voltage 5 seconds after removal of load.
- I_{sc} is the maximum peak current during a short-circuit starting from fully charged capacitor.
- E_{max} is the maximum specific energy stored in the device, measured as $\frac{1}{2}CV_n^2$, with C the nominal capacitance and V_n the nominal voltage of the device.
- P_{max} is the conventional peak specific power, measured as $V_{max}^2/(4mR)$ where R is the conventional inner resistance, measured at a frequency of 1 kHz. Rather obvious it is the maximum instantaneous power the capacitor would be able to deliver, when fully charged, if it behaved exactly as an ideal capacitor in series with the 1-kHz resistance.
- mass m includes inner equalisation system.

The real supercapacitor's performances can be better understood using the model represented in Fig. 1 and introduced in [13], [14]. In particular the first branch can represent the dynamics of the device over a frequency range of 0.01 Hz – 1 kHz; the second and third branches allow us to represent the slow dynamics of the device, such as the redistribution and leakage phenomena.

However, it must be immediately said that the parameter P_{max} is not a power the final user can exploit in practice, if not for an instant of time: first because when this power is delivered, the supercap voltage immediately drops because of the discharge, and therefore the maximum power reduces accordingly, second because when this power is delivered the discharge efficiency of the capacitor is 50%, by large unacceptable for the majority of applications.

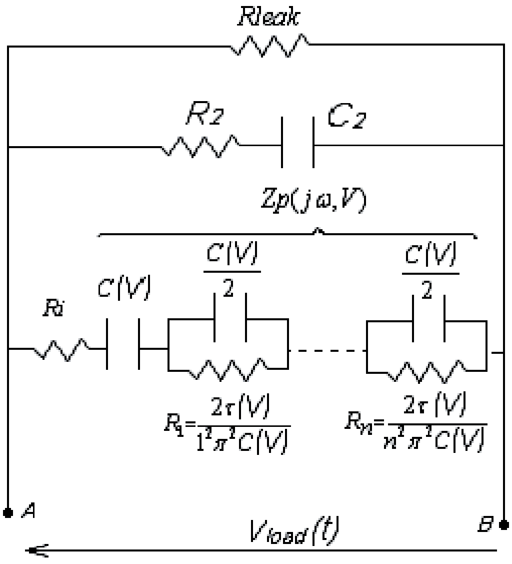

Fig. 1: Complete model of supercapacitor introduced in [14].

This model will be used to make considerations on the experimental results obtained.

B. High Power Lithium Battery

The battery under test, to be fairly compared with a supercapacitor, has been chosen to be one of the lithium batteries capable of the highest power on the market.

It is a battery composed by eight cells in series, and a nominal, two-hour capacity of 7.2 Ah, manufactured by Kokam (SLPB 45205130P).

Performance data for this battery are available for full discharges to up to $15{*}C_n$, while pulse discharges may be performed to up to $20\ {*}C_n$, where C_n represents the nominal battery capacitance, reported in manufacture's datasheet, expressed in Ah.

From manufacturer's graphical documentation the following significant numerical data can be inferred:

TABLE II

HIGH POWER LITHIUM BATTERY DATA

Discharge regime (A)	I=C_n	2*C_n	5*C_n	10*C_n	15*C_n
Delivered charge (%)	102	98	97	96	96
Average voltage (V)	3.85	3.80	3.70	3.60	3.50

According to this manufacturer's data, therefore, a single cell, whose mass is 226g, should be able to deliver (at $15C_n$ regime, for about 230 s) around 1673 W/kg, (or 1460 W/kg if a overhead of 13% for case and BMS -Battery Management System- is taken into account) that is difficult to compare with the value of 13587 W/kg of the considered supercapacitor, much higher, but available for only a split second.

This preliminary analysis on the two systems considered shows that differences in performances between supercapacitors and high power lithium battery are due to different technology: supercapacitors, as that one considered for our study and based on activate carbon, store energy in an electrostatic field and no electrochemical reaction takes place during the charging and discharging processes, while high power lithium battery are characterized by electrochemical reactions during the charging and discharging processes. It's clear that the dynamic of the electrostatic process is faster than an electrochemical reaction.

This implies the interest to make a direct comparison of the two systems by means of specific lab tests to better focus the interest of each technology according to the application. These have been carried out and will be discussed in the following sections.

III. STRESS DEFINITION

The stress to which the considered storage devices were subject in [5] were mainly create to reproduce, in an idealised way, stresses that are encountered in hybrid vehicle drive trains.

However, since they are composed by idealised parts (constant current charges/discharges and pauses), the results are useful for other applications as well.

In particular the following stress types are used:

- a specific power test. It is constituted by a full I-U charge followed by full constant-I discharge at different regimes
- an efficiency test. It is constituted by repeated charge-discharge cycles

When testing supercapacitors, discharge started at maximum capacitor voltage (i.e. from fully charged capacitor) and terminated when the terminal voltage was half the initial value; with this technique, normally suggested by supercapacitor manufacturers, the energy delivered should be, especially at small currents, around 0.75 times the energy initially stored inside.

When testing batteries, discharge ended when the minimum voltage of 2.7V/cell was reached, considering the lowest voltage cell, to avoid battery damage.

IV. RESULTS

A. *Supercapacitor Module Tests*

In this section the main results of tests carried out on supercapacitors are given.

The considered supercapacitor has been subjected to constant-current discharge tests using current chosen so to have roughly the following discharge times: 5s, 10s, 20s, and 40s: these times are significant of every-day vehicle usage, e.g. during urban-drive accelerations. Fig. 2 shows, as an example, one cycle of the test result obtained when discharge current was 30A, corresponding to an expected discharge duration of around 5 s. Ambient temperature during test was 20°C. The corresponding power delivered by the device is reported in Fig. 3.

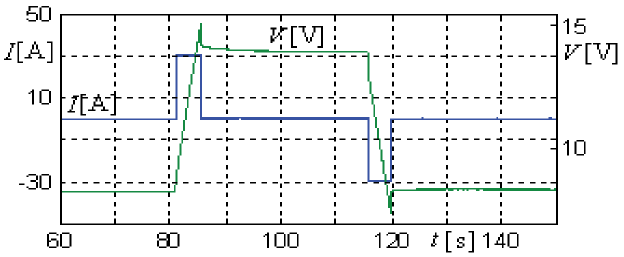

Fig. 2: Supercapacitor charge-discharge cycles using a charge/discharge current of 30A – voltage and current.

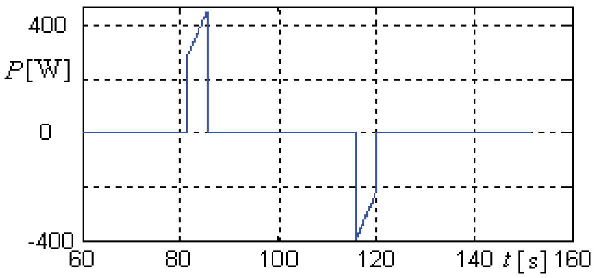

Fig. 3 : Supercapacitor charge-discharge cycles using a discharge current of 30A – power delivered.

To ease comparison with Lithium batteries, in case of short discharge durations, also tests with "asymmetric" currents were performed, limiting charge currents to a value comparable to that obtainable using batteries, and I-U charge.

For instance, Fig. 4 shows current and voltage for asymmetric test referring to a discharge of around 10 s. The corresponding temperatures are reported in Fig. 5

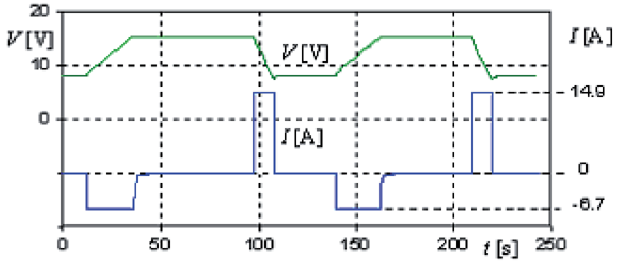

Fig. 4: Supercapacitor cycles using I_U charge and discharge current of 14.9A – voltage and current.

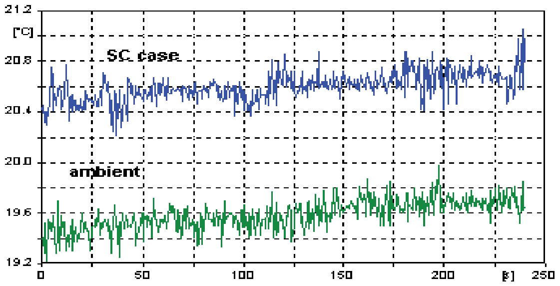

Fig. 5: Temperatures measured on the supercap case and its ambient during the tests reported in Fig. .

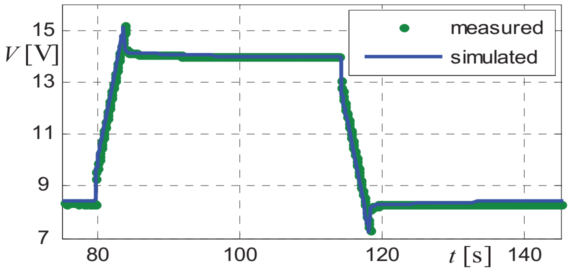

Fig. 6: Measured and simulated voltage profile of the supercapacitor module when the current profile of Fig. 1 is imposed.

In addition, the experimental data were used to validate the supercapacitor model presented in a previous work in [14]. In Fig 6 is reported the simulated and measured voltage profiles when the current of Fig 2 is imposed.

It can be seen how the simulated data fits very well the experimental ones. As shown in next session, this model will be used to simulate the supercapacitor efficiency of a cell different than tested ones.

B. High Power Lithium Battery Tests

In this section the main results of tests carried out on batteries are given.

The considered battery has been subjected to constant-current discharge tests. In this case the discharge current values cannot be chosen in the same way used for supercapacitors, since safety limits exist on the maximum current deliverable by the battery.

Taking into account manufacturer's data, tests were made at the highest range available for the battery: full tests at a current of 5*Cn and 10*Cn, and short duration tests at highest currents, up to the maximum allowable pulse current, equal to 20*Cn= 144A.

Since in these tests attention was mainly devoted to discharge phase, charging was made in a way that could mainly fully charge the battery, i.e. a I-U charge; nevertheless, since the I for the constant current part of the charge was as high as 3*Cn, the results are to a somewhat extent useful also for efficiency evaluations. Fig.7 shows, as an example, two cycles of the test results obtained when discharge current was 10*Cn=72A. The corresponding power delivered by the device is reported in Fig. 8, from where it is apparent that the battery, at this regime, is able to deliver an average power of 1kW/kg for durations of around 510s.

Because of its great importance in the management of lithium battery, Fig. 9 shows the battery case temperature, as compared to the ambient temperature. It is noticeable that this current is very stressful for the battery, causing the temperature to reach the maximum limit of 60°C (dashed in figure) when the current is shut off at the end of second discharge period: the current is shut-off by reaching nearly simultaneously the minimum cell voltage, and maximum temperature; after zeroing the current the battery temperature continues to rise for a while before starting to decline.

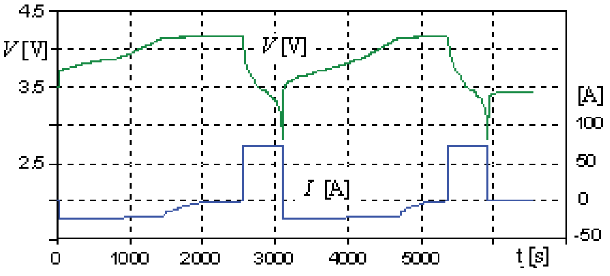

Fig. 7:Battery charge-discharge cycles
using a discharge current of 10*C_n – voltage and current.

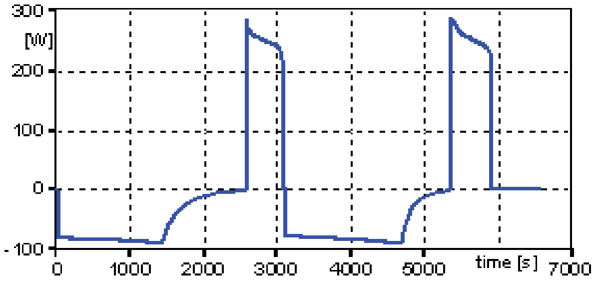

Fig. 8: Battery charge-discharge cycles
using a discharge current of 10*C_n – power delivered.

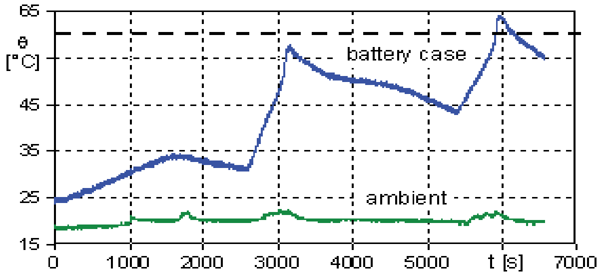

Fig. 9: Battery charge-discharge cycles
using a discharge current of 10*C_n – temperatures

Considering shorter discharges, Fig.10 shows the battery thermal behaviors in case of 10s discharge for a 20 C current, i.e. the maximum pulsed current allowed by the manufacturer for the considered battery. Here the temperature rise, much smaller, is well compatible with the battery usage.

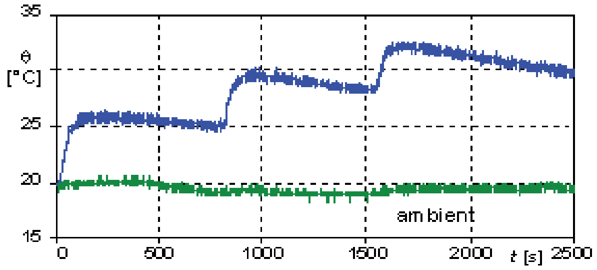

Fig. 10: Battery charge-discharge cycles, with
20s discharge time – Temperatures (I=20*Cn).

V. COMPARISON

The full results of the tests carried out in the performed tests are reported in paper [5]. They are summarised in Tables III. and IV.

In the case of the lithium battery the charge power was limited by the manufacturer constraint for the current to be not more than 3 A per Ah of nominal capacity.

Indeed, new tests are under way showing that this limit, for short charge durations, can be well overcome, giving more competitiveness to lithium batteries. This means that it is expected that, at least for durations up to 30 s, the discharge power reported in Table I can be effectively used also during charge.

The battery charge/discharge efficiencies were forcedly computed for the case of asymmetrical charging, since, as noted the maximum charge current was smaller than the maximum discharge current. For a fair comparison, therefore, supercapacitor efficiencies were reported both with symmetrical and asymmetrical charging; in the latter case the charging power was limited to the value used for lithium batteries.

TABLE III

SPECIFIC POWERS (W/KG) FOR THE TWO DEVICES
(CONSIDERED MASS REFERS TO MODULES, INCLUDING CASES)

discharge duration (s)	Supercap Power (W/kg)	Li battery Power (W/kg)	
		charge	disch
5	1417	330	2100
10	717	330	2070
20	361	330	2030
40	175	330	1980
60	116	330	1910
240	25	330	1450

TABLE IIV

MEASURED CHARGE/DISCHARGE EFFICIENCIES (%)
(CONSIDERED MASS REFERS TO MODULES, INCLUDING CASES)

discharge duration (s)	Supercap Efficiency (%)		Li battery Efficiency (%)
	symmetric charging	asymmetric charging	
5	79.3	84.7	87.6
10	87.4	89.5	84.8
20	91.8	94.5	83.7
40	94.7	97.5	83.0
60	96.5		82.5
240	99.0		87

The powers reported in Table I are indeed average powers during the discharges that, as stated earlier, are performed at constant current. However it is felt that constant-power discharges would have not brought very different results.

Moreover, since the discharges were performed at pre-defined constant currents, and the end-of discharge conditions referred to the final cell voltage, the discharge durations were not under control; the values reported in Table IV are therefore the consequence of a interpolation of actual measured data.

Collected data show how the supercap is advantaged from having nearly symmetrical charge and discharge powers while the limitation introduced to charging to $I_{ch}=3*C_n$ is a major lithium battery disadvantage. When only discharge power is considered the battery has a definite vantage on all the considered range, with the advantage being one order of magnitude at useful times of 40s. This aspect has to be matched with the overtemperature of both systems according to the operative conditions. As shown in Fig. 9, at high power density, lithium batteries can deliver only a small amount of the total stored energy to avoid quick temperature increasing until the maximum allowable. Supercapacitors are no affected by this criticality.

The tables do not take into account cycle lives; in principle, just to give some hints, it may be quoted that the considered systems show about 10.000 cycles with a depth of discharge of 20% for batteries [16] and 500000 full discharge cycles for supercapacitors discharged at nominal current between nominal voltage and half of it [15]; in the considered tests the capacitor was nearly fully discharged while the battery was discharged from 2.7% for 5s discharge up to 33% for the 60 s discharge. In both cases the end-of life criterion is a residual energy delivery capacity equal to 80% the rated value.

Despite of the two devices under test have been compared in terms of power and energy density, the two systems are characterized by cell mass different one order of magnitude. Supercapacitor module consists of 6 cells of 35g/cell while high power lithium battery is a 8 cells of 226g/cell. This aspect has made it necessary to compare the two technologies with cells of similar mass. The attention has been focused on a supercapacitor cell of 650F @ 2.7 V manufactured by Maxwell Technologies (BCAP0650 P270) with 200g/cell mass. As the unavailability to test this cell, the supercapacitor model presented in [14] has been used to simulate the supercapacitor efficiency considering the same operative charge and discharge conditions used in testing the small cells. The results are reported in Table V and VI.

TABLE V

MEASURED (ON LITHIUM BATTERY) AND SIMULATED (ON 650F SUPERCAPACITOR CELL) EFFICIENCIES (%)

Power in Discharge (W/kg)	Power in Charge (W/kg)	Measured Li-Battery efficiency (%)	Simulated Supercap efficiency (%)
2100	330	87.6	90.3
2070	330	84.8	90.8
2030	330	83.7	90.8
1980	330	83.0	91
1910	330	82.5	91.2
1450	330	87	93.1

TABLE VI

SIMULATED (ON 650F SUPERCAPACITOR CELL) EFFICIENCIES (%) CONSIDERING SYMMETRIC CYCLES.

Power in Discharge (W/kg)	Power in Charge (W/kg)	Simulated Supercap efficiency (%)
2100	2100	84.3
2070	2070	84.5
2030	2030	84.8
1980	1980	85.1
1910	1910	85.6
1450	1450	88.8

As shown in Table V and VI, when the two devices are compared with similar cell mass, the supercapacitor efficiencies is greater than high power lithium batteries in all operative conditions. Furthermore the supercapacitor efficiency is very high in symmetrical cycles characterized by high power density both in charging and discharging.

Considering the supercapacitor model reported in Fig.1 it can be noticed that power losses are due not only to dissipative elements of the first branch of the model, but also those of second and third branch. Dissipative elements of first branch and of the third branch take in account respectively the internal resistance (R_{dc}) and the leakage current (I_{leak}) declared on manufacture's datasheet (the losses due to the leakage resistance are negligible in cycle of 100s of period). No information are declared regarding the parameters of the second branch responsible of redistribution phenomena. As explained in [14], [17] the second branch is characterized by a time constant of about 100 - 400s and by a capacitance C_2 about one tenth of the capacitance of the first branch. The efficiency values reported in Table II-VI will be greater if charge and discharge take place without any interval at 0 power. In this case no redistribution takes place and the efficiency could arise about 2-3% respect to the value reported.

Besides the technical data analyzed, a system designer has to take into account the cost data of the two storage systems. Although a detailed analysis of present-day and forecasted market costs is beyond the scope of this paper; a cost estimate can be made considering that:

- around 3.3 c€/F, that means a cost of 50€/Wh, is the cost often quoted for today's SC cells for prototype application (including overheads for monitoring and equalization systems), in terms of industrial volume the cost is about one third, [cf. 6-7].
- the considered battery is sold at around 1 €/nominal Wh that implies, considering an overhead of 20% due to Battery Management System a cost of 1.2 €/nominal Wh; nominal Wh is obtained multiplying the nominal Ah per the nominal voltage (3.7 V per cell).
- considering the same number of life cycles the high power lithium battery cost is about 200 €/Wh.

VI. CONCLUSION

In the two cases considered (a state-of-the art supercapacitor and a state-of-the-art ultra high power lithium battery) the battery specific power available both in charge and discharge overcomes the SC one starting from 30 s discharge times. If only discharge powers are considered, the battery advantage in terms of specific power over SCs starts from 5s discharges. As far as charge/discharge efficiency comparison is concerned, at equal discharge time a significant advantage is seen for SCs in all operative conditions when the two technologies are compared at same cell mass. In addition the supercapacitor devices in all operative conditions don't show thermal management criticality.

The results proposed open a full field of investigation that can be explored in further studies, in particular further analysis will be conducted using different specimens of the two technologies to verify differences in terms of performances and efficiency between modules and equivalent cells, and cycle life of different products should be investigated in depth (only a few hints were given above).

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