UPCYCLING LITHIUM-ION BATTERIES: A CASE STUDY

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ABSTRACT: The need for cost-effective and flexible solutions to compose the distributed energy storage makes second-life lithium-ion batteries (SLIB) a discussed option. The SLIB is a lithium-ion battery used in an energy/power-intensive first application (automotive) that still retains important performance characteristics to have a second-life application. SLIBs can represent an opportunity to meet this demand and an option for residential and off-grid applications, presenting competitive cost advantages over new batteries. However, their application within the current state of the art still needs to overcome several challenges to become technically and economically viable. In the framework of the POCITYF project (GA 864400), a prototype of a SLIB from the company *betteries AMPS GmbH* has been tested at the University of Évora, connected to the existing experimental microgrid through a commercial inverter. This work aims to contribute to the state of the art of SLIB technology, providing insights into their electrical performance and presenting technical key performance indicators in a real-operational environment. This enables the further finetuning and validation of the product, reaching a higher TRL. This work aims to improve technology acceptance by demonstrating safety and reliability under real operating conditions and promoting the ease of installation and operation of these technologies.

1 INTRODUCTION

The International Energy Agency (IEA) states that the electric automotive industry is expected to increase from 2020 to 2030 with an average annual growth rate of nearly 30% [1]. After their useful life in electric vehicles (EVs), considering the degradation of their energy retention capacity, these batteries retain capacity and power characteristics that make them suitable for applications with lower energy density requirements. The still-useful batteries can create significant value and ultimately increase the sustainability of the battery value chain. In that sense, a secondary market arises for the second application use of the EV batteries before their end of life (EOL) (recyclability, in European Union). Additionally, this second life will also contribute to the world's need for stationary or quasi-stationary energy storage.in the coming decades to meet international climate and decarbonization goals.

Current research on SLIBs still needs to overcome several challenges to become technically and economically viable, achieving the market uptake. Achieving this is currently influenced by the perceived uncertainty associated with their performance and degradation behaviour, where the major research efforts has been focused on understanding the early stages of degradation (first-life lithium-ion batteries).

In the context of the POCITYF project (GA 864400) [2], a SLIB prototype has been built and tested at the University of Évora, in cooperation with the German company *betteries AMPS GmbH* [3]. The specific SLIB, in Figure 1, presented a preliminary power and energy capacity of 2.0 kW/2.3 kWh, a voltage operating range of 45-64 V, and an approximate weight of 35 kg. With an advisable depth of discharge of 80%, the expected lifetime is estimated at 7-10 years [3]. The *betteries AMPS GmbH* solution aims to be applied to off-grid solar photovoltaic (PV) installations. In contrast to other technological approaches, *betteries AMPS GmbH* solution presents a modular design: the modules can be stacked on each other, increasing the usable energy capacity output up to 5 kW/9.2 kWh (with the stacking of 4 modules).

Figure 1: 2.0 kW/ 2.3 kWh second-life lithium-ion battery developed by *betteries AMPS GmbH* and installed in a pilot test as a result of the established cooperation between the University of Évora and *betteries AMPS GmbH*.

In this work, the SLIB and its integrated inverter are subject to performance testing at the stack level, intending to obtain a complete performance characterization of both through the development of a testing control unit. This unit is responsible for communication with the inverter, executing the data acquisition and reading. Within this set-up, the SLIB is evaluated regarding its technical feasibility and electrical performance. The results are analyzed, and key performance indicators (KPIs) are calculated to characterize this second-life technology. The KPIs obtained are relevant data for the state of the art of second-life lithium-ion batteries performance, contributing to further comparisons with other energy storage technologies and allowing further electrical modelling developments.

2 CIRCULAR BUSINESS MODEL AND INNOVATION

2.1 Overview

The global prediction of e-waste is perceived as an obstacle to the increasing future battery volumes for e-mobility. Figure 2 presents the specific global expectation market forecast of the second-life lithium-ion batteries, expected to reach 20 GWh in 2023 and 1552 GWh in 2032 [4].

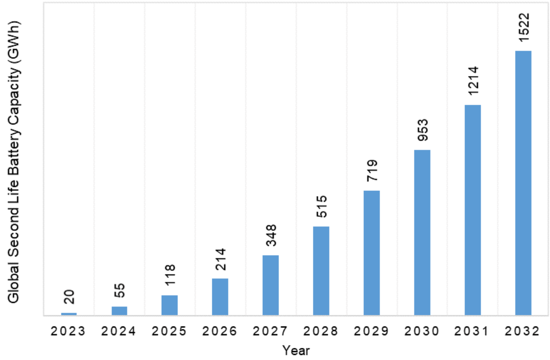


Figure 2: Expected global second life battery capacity from electric vehicle stock. Adapted from [4].

SLIB is expected to contribute to the transition from the current fossil-fuelled model to a sustainable renewable energy sources model, promoting the decentralization of generation and consumption (e.g., increasing the building's PV self-consumption rate) and reducing the carbon footprint of the overall electricity sector.

SLIBs impact the three-dimensional pillars: environmental, social, and economic. Environmentally, the carbon footprint of electric vehicles (EVs) is reduced due to the battery life extension and the second productive lifetime opportunity, minimizing natural resources usage for new batteries. It also reduces the carbon footprint of buildings, allowing a higher penetration of decentralized renewable energy generation. Socially, the SLIBs reduce households' electricity bills and can have a crucial role in energy poverty-fighting. Economically, SLIBs can be managed to provide grid-connected or off-grid competitive business models, with lower costs compared to traditional solutions (e.g., electricity grid or diesel generators). Given the current scarcity of raw materials and difficulties associated with the international logistics of goods, it can present competitive advantages due to the reuse of battery systems. The extension of the battery lifetime can contribute to stabilize high price volatility of the raw materials market. The integration of SLIBs creates a new revenue stream for the car OEMs (Original Equipment Manufacturing), creating additional revenues and job creation for installers and component suppliers.

2.2 Potential social outcomes for citizens and the community

The implementation of SLIBs should bring technology environmental awareness to end users regarding discarded EV batteries' impact on the environment. It can also promote adoption of smart energy management strategies of a household or building, empowering the prosumer. Providing similar characteristics to first life batteries, the prosumer could monitor the power management, benefiting from integration in energy communities or virtual power plants, sharing platforms and bringing awareness to new sustainable life behaviours.

2.3 Circularity and innovation strategies

The circularity of the current business model of *betteries AMPS GmbH* is associated with discarded EV batteries, which are remanufactured into smaller systems fulfilling the needs of households and creating an additional business opportunity for car OEMs. The second aspect of this circular business model is the application of the batteries in a secondary storage application after repurposing, where the batteries are designed to be easy replaced. At the end of the second productive life, optimal recycling technology is required to recover the valuable materials and reintroduce them into the battery value chain (valuable EOL batteries).

Circularity is at the core of these SLIBs. Electric mobility has a crucial contribution to meet global goals on decarbonization. However, if not properly evaluated, one could introduce the issue of how to properly deal with the expected volume of used batteries once they can no longer be applied to EVs. With 145 million EVs predicted to be on the roads by 2030, more than 12 million tons of lithium-ion batteries are expected to be retired until 2030 [5]. With at least 70% of their initial energy capacity left [6] (see Figure 3), the batteries are too valuable to be directly recycled. A productive SLIB application should be encountered so that the e-mobility sector can follow a more sustainable path.

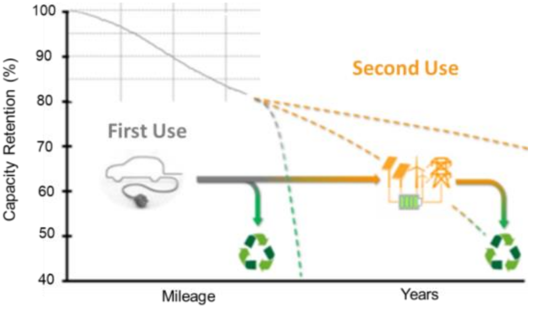


Figure 3: Energy capacity retention (%) during the lifecycle of an EV-lithium-ion battery first application, and the potential second use. Adapted from [7].

betteries AMPS GmbH is committed to supporting the implementation of a genuinely sustainable e-mobility by closing the loop in the energy sector. On the one hand, the company is using discarded EV batteries – which still have up to 70% of their initial capacity – to produce smaller energy storage systems for multiple use cases. On the other hand, deploying home storage systems supports the installation of renewable energy sources in the building sector, thus contributing to the decarbonisation of the grid.

Besides repurposing the battery packs, *betteries AMPS GmbH* reutilises several other components of the battery car pack, such as connectors, fuses, and cables. This action reinforces the business model's circularity principles and minimizes the waste generated from an electric vehicle.

2.4 Costs

The battery acquisition is the critical resource that presents the highest cost in the whole upcycling process.

Public schemes could promote using SLIBs by providing to prosumers a subsidy (similar to what some countries have promoted for other renewable technologies) associated with upcycled batteries. The end users/beneficiaries of the SLIBs will then have a better ROI (Return of Investment) for their household application, enhancing the market uptake, and reducing the higher perceived risks related to a second-life product. With a SLIB, the prosumer could then reduce costs and maximize its renewable electricity self-consumption smartly and flexibly. The primary revenue streams for the end user are the cost savings related to electricity services provided (e.g. self-consumption, ancillary services such as grid stabilization or UPS function, peak curtailment, power ramp rate control, etc.).

2.4 Environmental costs and benefits

The delay of the battery EOL translates into adding a step in the life cycle assessment (LCA). The ecological cost of the technology is related to the carbon footprint associated with the upcycling process and the transportation of storage solutions, reducing the transportation of electricity through decentralized strategies. SLIB could reduce waste generation and EVs' CO_2 footprint by >30%.

3 METHODOLOGY

The SLIB is subjected to testing at its pack level, intending to obtain a performance characterisation. The testing obeyed a protocol specifically designed to operate the batteries at their general operating conditions (presented below), through the development of a dedicated LabVIEW programming in the control unit. The batteries are fully charged and discharged at defined power limits to evaluate their response at the specified typical operating conditions. The control unit is responsible for real-time communication with the inverter to acquire data such as current, voltage or temperature from the sensors. The results are analysed, and key performance indicators (KPIs) such as energy capacity and efficiencies are calculated. This data is relevant for the state-of-the-art of second-life lithium-ion batteries, allowing further comparisons with other energy storage technologies and further modelling development.

The University of Évora tested several battery packs, although this work aims to present the results of the newest version of the product, considering a single battery module. Its preliminary specifications are gathered in Table I below.

Table I: Reference conditions and main characteristics of one pack, made available by *betteries AMPS GmbH*.

Parameter	Battery
Nominal voltage (external) (V)	52.5
Pack voltage range (V)	42.0 to 57.7
Weight (kg)	31.0
Dimensions (height x length x width) (mm)	321 x 558 x 227
Cycle lifetime (cycles)	1500
Calendar lifetime (years)	7.0
Nominal energy capacity (kWh)	2.3
Useful energy capacity (kWh)	1.8 (80% DoD)
Nominal charge power (kW)	1.4
Nominal discharge power (kW)	2.0
Maximum power output (kW)	4.0
Cooling	Passive cooling
Venting	Pressure equalization & overpressure relief
Ambient operating temperature (ºC)	-10 to +40
Non-operating temperature (storage) (ºC)	-20 to +50
Ingress protection	IP67

3.1 Test conditions

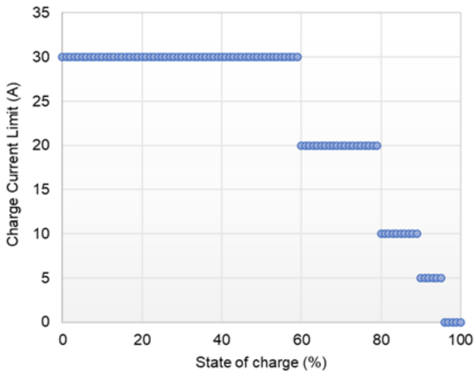
3.1.1. Rates

C-rates are considered reasonable limits to characterise the lithium-ion batteries, in order to normalise and enable different batteries comparison (distinct characteristic among different batteries). Lithium-ion batteries are generally tested with constant current over the voltage range (and state of charge range), resulting in a discharge and charge rate.

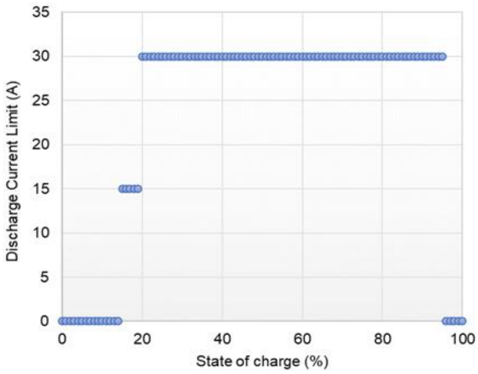
In the battery field, the E-rate is equivalent to C-rate. Nevertheless, it expresses the charge or discharges power in watts. In the absence of a current controller device that effectively sustains the current at a constant value, the controller presented in this work was developed by controlling the AC power setpoint (depending on the connected load), which is the controllable variable on the inverter connected to the battery. This fact conducts to relatively different outputs of these tests to the ones generally presented (if so) by the battery manufacturers. Given the absence of strict standards, the approach of testing with the E-rates is considered as similar as C-rate to describe battery discharge power [8]. Moreover, the testing on these conditions reflects the real operating conditions of the batteries.

3.1.2. Levels of charge and discharge

Lithium-ion batteries' performance and lifetime are mostly affected by charge and discharge conditions, power, and ambient temperature. In this sense, the power setpoint commands of the second-life lithium-ion battery is carefully chosen. Figure 4 (a) and (b) present the charge and discharge maximum limits chosen for current, respectively, and Table II the maximum limits for current, given the number of stacked battery modules.



(a)



(b)

Figure 4: Charge current limits (a) and discharge current limits (b) according to the state of charge of the battery.

Table II: Maximum limits of current, given the stacked number of battery modules, associated to the same inverter.

Number of battery modules	Maximum acceptable current (A)
1	30.0
2	44.3
3	53.6
4	63.0

3.1.3. Reference test conditions

The reference conditions are the storage typical operating conditions in which the characterisation tests occur. The inverter connected to the battery limits the maximum charge and maximum discharge power limits, which in this case, is upper limited to 3.0 kW. The characterisation tests occur at a temperature range from 15 ºC to 25 ºC.

For the case of the tested battery, the tests occurred between the 51.1-57.68 V, representing the newer version pack voltage range (depletion and full-charge states, respectively).

3.2 LabVIEW programming control

The tests entail the development of a programming control which communicates with the inverter unit that ultimately communicates with the battery. The communication is achieved through the Modbus TCP/IP protocol, where the programming was developed within the LabVIEW environment.

The timeframe of the control application was defined as being three seconds, including the sending of requests, executing intermediate measurements, receiving answers from the battery and the inverter, and registering the acquired data (both from the inverter and the external monitoring devices, such as the precision wattmeter).

The desired E-rates were defined in real-time, adapted to the relation current-SOC, given the previously presented limits in Figure 4.

3.3 Battery performance efficiencies’ calculations

A battery-suited evaluation can be achieved by determining performance indicators related to investment and energy perspectives. As the most relevant performance indicators, the analysis relies on the determination of the following indicators: voltage efficiency, coulombic efficiency, energy efficiency and power efficiency, charge and discharge energy capacities (Wh), energy densities (Wh/kg and Wh/L), power densities (W/kg) and fastest/slowest charge and discharge.

The battery performance is characterized by executing tests from the defined range of the state of charge or voltage operation limits (from depletion to full charge). The operating limits of the battery to perform these tests were chosen regarding the safety margins associated with the DOD and degradation, considering the SLIB characteristics. The evaluation KPIs are defined by:

- Voltage efficiency is the ratio of cell voltage during discharge to that during charge [9]:

$$\theta_v = \frac{U_{discharge}}{U_{charge}} \tag{1}$$

- Coulombic (charge) efficiency is the ratio of electrical charge capacity during discharge to that during charge:

$$\theta_q = \frac{q_{discharge}}{q_{charge}} \tag{2}$$

- Energy efficiency is the ratio of electrical energy during discharge to that during charge:

$$\theta_E = \frac{U_{discharge} \times q_{discharge}}{U_{charge} \times q_{charge}} \tag{3}$$

- Power efficiency is the ratio of electrical power during discharge to that during charge:

$$\theta_W = \frac{I \times U_{discharge}}{I \times U_{charge}} \tag{4}$$

The remaining calculated KPIs are defined as follows. The total energy capacity is the sum of the energy used to charge the battery. The useful energy capacity is the sum of the energy drawn from the battery (discharged from the battery). The energy densities are only calculated for discharged energy. They result from averaging the obtained discharged energy from the battery at the different power levels, rated by the weight or volume of the battery.

For the case of the power densities, it was used the averaging of the three maximum discharged power levels (rated at 1300 W AC), rated by the weight and volume of the battery. The slowest and fastest charge and discharge were calculated through the minimum and maximum values, respectively, of the sum of the period whereby the test occurred. The charge-discharge test repetition at each power level allows the averaging of the results, further reducing the associated experimental error. After that, the KPIs for each full charge-discharge of the battery were calculated.

3.4 Inverter efficiency

A dedicated inverter efficiency test was carried out to characterize the inverter input/output influence on the battery performance output. The commercial inverter connected to the SLIB is from the brand Victron, model MultiPlus-II 48/3000/32. The inverter AC-DC (battery operation in the state of charge) and DC-AC (battery operation in the state of discharge) efficiencies are calculated, for charge and discharge states, respectively:

- DC-AC and AC-DC conversion efficiency – Considers energy conversion losses from DC to AC energy and from AC to DC energy, respectively, are presented in Eqs. (5) and (6).

$$\eta_{conv(DC-AC)} = \frac{E_{AC}}{E_{DC}} \tag{5}$$

$$\eta_{conv(AC-DC)} = \frac{E_{DC}}{E_{AC}} \qquad (6)$$

The inverters operates according to an efficiency profile directly related to the power level set and not always at its maximum efficiency. The inverter efficiency used in this work is calculated through Eq. (5) and Eq. (6), considering the different power levels. In this context, a LabVIEW program was developed to operate the inverter at specific power levels (from 150 up to 3000 W) to calculate the efficiency profile and evaluate its performance output. The program was chosen to operate at 15-minute intervals for each power level, regarding its nominal power.

4 RESULTS

4.1 Batteries' KPIs

Each E-rate was averaged for three repeated tests to minimize experimental-related errors. Table III presents the four batteries' efficiencies, calculated with the Equations (1) to (4). The remaining calculated KPIs are shown in Table IV.

Table III: Efficiency results of the studied battery.

	Average efficiency	Standard deviation	Variance
Coulombic efficiency	0.925	0.040	0.002
Energy efficiency	0.830	0.124	0.015
Power efficiency	0.766	0.283	0.080
Voltage efficiency	0.864	0.078	0.006

Table IV: Battery's energy performance main results.

BM / Characteristic	Battery (~50-57 V)
Total energy capacity (charge capacity) (kWh)	2.15 ± 0.11
Useful energy capacity (discharge capacity) (kWh)	2.05 ± 0.60
Energy density (discharge) (Wh/kg)	66.0 ± 10.3
Energy density (discharge) (Wh/L)	49.9 ± 7.76
Power density (discharge) (W/L)	20.4 ± 0.20
Power density (discharge) (W/kg)	27.1 ± 0.27
Slowest/ fastest charge (h)	3.13 / 12.5
Slowest/ fastest discharge (h)	2.46 / 11.8

where ± indicates the percentual error, in comparison with the average of the result.

A more extensive set of battery modules tested would improve the average results found, probably minimizing the STD values of the results. Figure 5 and Figure 6 show an example of the voltage and current-energy capacity curve in the charging operating state, while Figures 7 and 8 show an example of the voltage and current-energy capacity curve in discharging operating state.

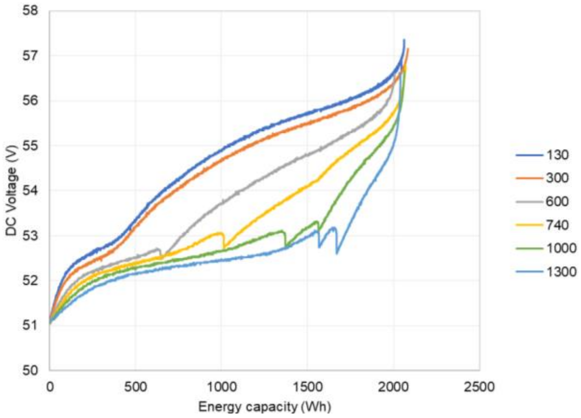


Figure 5:1 Voltage-energy capacity exemplary curve of the battery in charging state.

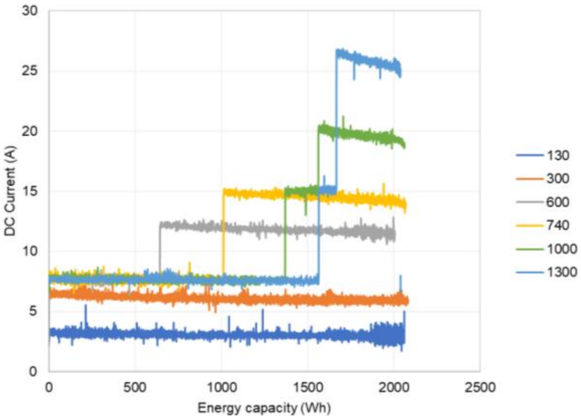


Figure 6: Current-energy capacity exemplary curve of the battery in charging state.

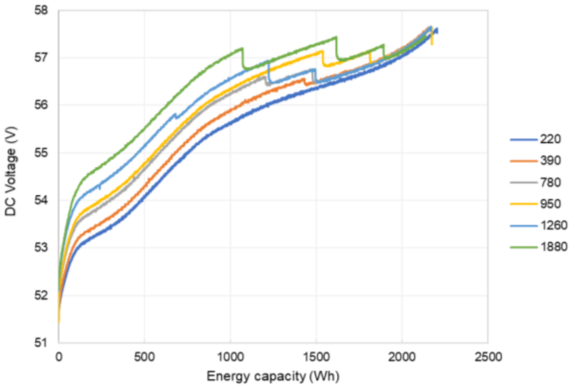


Figure 7: Voltage-energy capacity exemplary curve of the battery in discharging state.

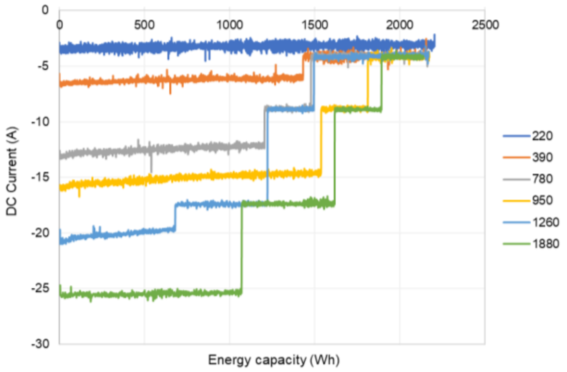


Figure 8: Current-energy capacity exemplary curve of the battery in discharging.

4.2 Inverter efficiency results

The LabVIEW developed control allowed to plot the charge and discharge efficiency curves, Figure 9 and Figure 10. This power-efficiency profile affects the battery's output and should be considered in future modelling of the energy storage system.

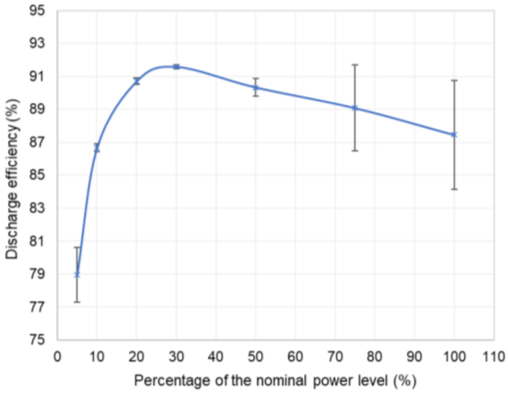


Figure 9: Inverter discharge efficiency in function of the power level.

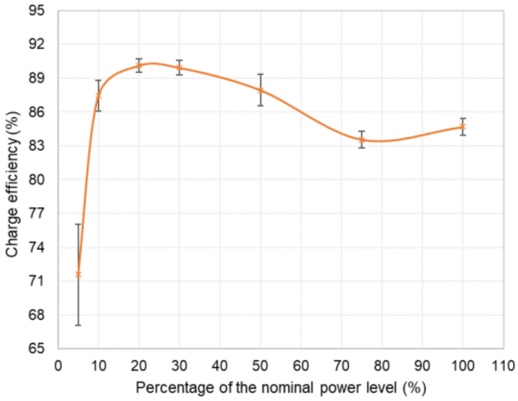
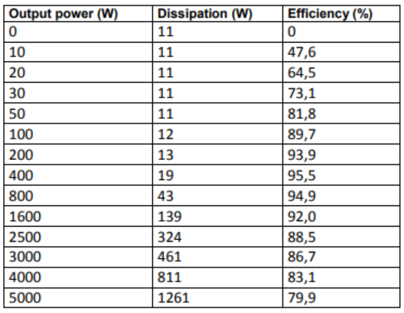


Figure 10: Inverter charge efficiency in function of the power level.

In order to better understand the results obtained of Figure 9 and Figure 10, Figure 11 is depicted below, presenting the inverter efficiency in function of its output power made available by the inverter manufacturer.



Output power (W)	Dissipation (W)	Efficiency (%)
0	11	0
10	11	47,6
20	11	64,5
30	11	73,1
50	11	81,8
100	12	89,7
200	13	93,9
400	19	95,5
800	43	94,9
1600	139	92,0
2500	324	88,5
3000	461	86,7
4000	811	83,1
5000	1261	79,9

Figure 11: Inverter efficiency in function of its output power, made available by the manufacturer [10].

5 DISCUSSION

The SLIB technology was successfully integrated into the University of Évora’s microgrid, where the control with the power conditioning unit was effectively achieved, allowing to proceed with the battery and inverter characterization testing and operation evaluation.

The results in Tables III and IV are congruent to the preliminary results that *betteries AMPS GmbH*, namely the average 2.05 kWh 0.60 %. They can be presented as a reference in the SLIB technology, which facilitates the comparison of the electrical performance of the SLIB with the commercial and documented energy storage technologies. Figure 9 and Figure 10 output results can be related to the inverter available manufacturer data depicted in Figure 11. There, one can observe that for the 400-5000W power levels range, a correspondent increase in energy dissipation is observed (from the low to the highest power level), decreasing the values of efficiency.

The battery presented a controlled performance during the testing, presenting itself as a safe and robust product. In order to have an overall more representative result for this product, a higher number of battery modules are required to execute the characterization tests.

The test setup allowed the implementation of dedicated energy management strategies, producing experimental validation data and contributing to current ageing modelling approaches. In this sense, the product presented suitability for on-grid residential and off-grid applications.

6 CONCLUSION

SLIBs can be applied to improve grid performance and integrate with renewable energy generation or charging EVs. The literature lacks disclosed experiments regarding this recent technology's operation, testing and suitability.

The current work methodology allowed the quantification of the SLIB relevant KPIs, characterising the technology in real operating conditions and opening a path to its electrical modelling with experimental results validation.

The tests allowed the gathering of information that contributed to the improvement of the prior versions of the product for building a more robust solution, reaching a higher TRL. Additional testing with use-case scenarios provides technical key indicators regarding its performance in a real-operational environment under stress conditions, enabling this product's further finetuning and validation.

The integration of the SLIB with energy management strategies testing set presents itself as a suited candidate for inclusion in further project proposals and/or applications.

ACKNOWLEDGEMENTS

The authors would like to thank the support of this work, developed under the European POCITYF project, financed by 2020 Horizon under grant agreement no. 864400. This work was also supported by the PhD. Scholarship (author Ana Foles) of FCT – Fundação para a Ciência e Tecnologia –, Portugal, with the reference SFRH/BD/147087/2019.

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