PERFORMANCE TESTING OF ADAPTED NI-MH BATTERIES FOR SECOND-LIFE USE IN AMAZONIAN ISOLATED MICROGRID

Lucas dos Santos Bulhosa[1], Anderson Amoras Vieiras[1], Marcos André Barros Galhardo[1], Gilberto Figueiredo Pinto Filho[2], Daniel Henrique Nogueira Dias[2] and Wilson Negrão Macêdo[1]

[1] UFPA - Universidade Federal Do Pará, Belém (Brazil)

[2] UFF - Universidade Federal Fluminense, Niterói (Brazil)

Abstract

With the expansion of the electric and hybrid vehicle market, due to incentives to tackle the problem of greenhouse gas emissions, a directive should be considered for the disposal of batteries remaining in these vehicles after the end of their service life. A viable solution is to reuse these storage devices with remaining capacity in second-life applications. Although they are no longer useful for their initial purpose, they can be used to form battery banks for off-grid systems that serve remote communities (isolated from the conventional power grid) that suffer from a lack of access to energy. Given this scenario, this study aims to provide an analysis of tests carried out on batteries removed from hybrid vehicles sold in Brazil, in order to promote their second life use, with the aim of enabling their application for connecting the battery bank to a direct current distribution microgrid supplied by photovoltaic energy implemented in a remote community. It has been found that, depending on the storage technology, the energy capacity may be insufficient for second-life applications due to factors such as wear and tear in the original application, time, and storage conditions. However, there are promising technologies for this application.

Keywords: second-life batteries, off-grid systems, electric vehicles, hybrid vehicles, photovoltaic energy.

1. Introduction

The electric vehicle (EV) market has expanded rapidly worldwide (IEA, 2024). It drives by the need for sustainable alternatives in the energy and transport sectors. Batteries, as a core component of electric vehicles, have seen an increase in demand, with usage expected to grow 4.5 times by 2030 and more than 7 times by 2035 (IEA, 2024).

Although batteries for electric vehicles are increasingly common, their service life is limited. When the capacity of the battery drops below 80% of its nominal capacity, it is typically considered unfit for use in vehicles (Cantú et al., 2022). However, these batteries often retain significant residual capacity that can be repurposed for less demanding applications, such as stationary energy storage. Studies indicate that the use of second life in Battery Energy Storage Systems (BESS) can offer environmental and economic advantages (Haasis et al., 2024; Spindlegger et al., 2025).

When applied in off-grid systems, particularly whit intermittent renewable sources, such as solar or wind, second life batteries can help extend the life of energy storage assets. The photovoltaic stands out among renewables due to its scalability, modularity and decreasing costs, already exceeding 2.2 TW of installed capacity globally, up from 1.6 TW in 2023 (IEA, 2025).

Solar photovoltaic energy is particularly relevant in regions where expanding the electrical grid is economically or technically unfeasible. This is the case of isolated or riverside communities in the Amazon, where solar generation can serve as a viable and sustainable alternative. According to the Brazilian National Electric Energy Agency (ANEEL), these locations are among the priorities for access to energy, although conventional expansion of the distribution network is not a viable solution (Vieira Filho et al., 2024).

An economical and sustainable solution for these contexts is the implementation of direct current (DC) microgrids using locally generated photovoltaic energy and storage systems using second-life batteries. This configuration increases system efficiency by eliminating the need for conversion to alternating current (AC), offering greater flexibility and reducing system complexity (Turan et al., 2025).

In this context, the present study evaluates the behavior of second-life nickel-metal hydride (NI-MH) batteries removed from hybrid vehicles for reuse in DC microgrids. The objective is to characterize degradation due to manufacturing and usage time, evaluate its performance and operational viability for second-life applications, and

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compare it with the application in a DC microgrid of second-life batteries of another technology, such as Lithium Nickel Manganese Cobalt (Li NMC).

2. Methodology

The battery modules tested were the NP2 Ni-MH models, obtained from the second generation of Toyota Prius vehicles sold in Brazil between 2013 and 2015. The study of these batteries becomes of interest given the time this technology has been used, which allows us to verify the wear and tears that have occurred on the cells, given the time of manufacture and use in vehicles.

The bank used was provided to Grupo de Estudo e Desenvolvimento de Alternativas Energéticas (GEDAE - in English: Study and Development Group of Energy Alternatives) through a partnership with professors from the Universidade Federal Fluminense (UFF), which made it possible to carry out the tests.

Two test procedures were performed on the battery bank, where the battery modules were initially tested individually to determine their capacity. These tests are relevant because there was little information related to the modules such as actual time of use, capacity and storage conditions, which can significantly reduce the remaining capacity (Haasis et al., 2024). In a second step, after defining the individual capacities, another battery with a smaller capacity was produced with the modules that had performed best in the tests. This battery was tested on the bench and in a system with a photovoltaic generator and charge controller.

Each battery bank consists of 28 NP2 modules connected in series, generating a nominal voltage of 201.6 V and output of 1.35 kW. The module parameters are described in table 1. Each module passed for individual tests to evaluate its residual capacity.

Table 1: NP2 Module Information.

Product Name	**NP2 Battery Module**
Nominal Voltage	7.2 V (6 cells)
Nominal Capacity	6.5 Ah
Output	1,350 W
Energy Density	46 Wh/kg
Mass	1,040g
External Dimensions (mm)	19.6 (W) x 106 (H) x 285 (L)

The equipment used in the tests was:

- Bidirectional DC Source ITECH model IT-M3432 – 800 W/30 A/60 V.
- Multichannel Digital Power Meter Chroma 66204.
- Program developed on LabView Platform, for acquisition of electrical quantities.
- Circuit breakers and copper cables for protection and connections.

The arrangement of the equipment used in the test is shown in figure 1, where using the bidirectional DC source it was possible to charge and discharge the modules individually. The electrical quantities were measured by the power meter and saved by a LabView developer program on the computer. A shunt resistor with a capacity of 50 A and a voltage of 75 mV comprises the circuit arrangement for measuring current using a power meter. Figure 2 illustrates the test bench with the equipment used.

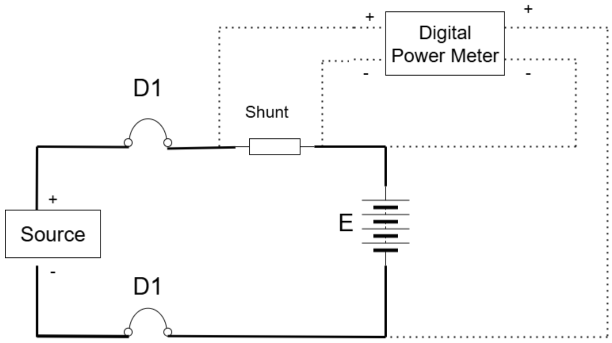

Figure 1: NI-HM module test diagram.

Figure 2: Test bench.

Initially, the voltage of the modules was measured, and it was found that they were all discharged, with voltage below 7 V. Thus, the modules were charged with a voltage of 8.7 V, aiming for each module to absorb approximately 6 Ah of capacity. According to Haasis et al. (2024), it is estimated that vehicle batteries have around 70% to 80% of their nominal capacity, close to 4.785Ah (75% of the original 6.5Ah).

Therefore, considering the wear and tear of the batteries, the value of 6 Ah for charging was determined, which represents a value close to 120% of the expected remaining capacity. This value is in accordance with the charging recommendation range described by Linden and Reddy (2002), which suggests that the battery be charged to approximately 120% to 150% of the nominal capacity, under constant voltage conditions.

Thus, a charge-discharge cycle was performed using a constant voltage of 8.7 V and a current of 0.5 C (3.25 A), with the goal of providing 6 Ah (120%–150% of the expected residual capacity), in line with the methodology of Linden and Reddy (2002). The energy delivered during discharge quantified the usable capacity. A second cycle adjusted the charging process to 140% of the first cycle result, followed by discharging for confirmation. Figure 3 summarizes the test procedure. After individual tests, the modules were grouped by similar capabilities in order to assemble a battery of modules that could be reused. Sixteen modules were selected from 28. The defined arrangement was 4 modules in series to achieve a voltage close to 24 V, the voltage at which the battery is planned to operate, with 4 subgroups in parallel.

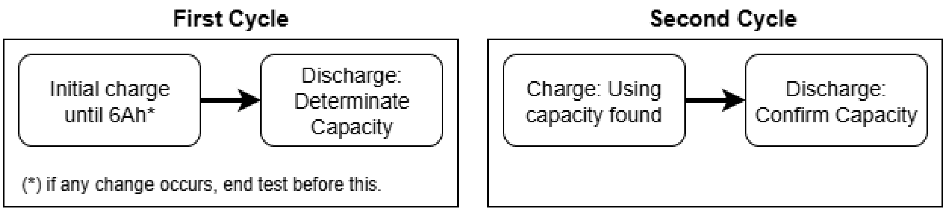

Figure 3: Flowchart of tests performed by module.

For the test under real conditions, two photovoltaic modules were used in series, these were detached from a larger generator already assembled with orientation to the geographic north and inclination of 10º, the parameters of the modules shown in table 2. Figure 4 shows the complete generator. A charge controller model XTRA 3210N from the manufacturer Epever was also used, with features such as MPPT (Maximum Power Point Tracking), battery charging current of up to 30 A, and operation at voltages of 12/24 V, besides circuit breakers, in a panel made for the tests. The IT-M3432 bidirectional power supply was used as the load again.

Figure 4: Battery produced, PV generator and panel made for tests.

Table 2: Parameters PV module.

Model	**JAP6-60-265 – JA SOLAR**
Peak Power	265 W
Open Circuit Voltage (Voc)	38.14 V
Max Power Voltage (Vmp)	30.96 V
Short Circuit Current (Isc)	9.10 A
Max Power Current (Imp)	8.56 A

3. Results and Discussions

3.1. Individual tests results

Figure 5 shows the residual capacity measured for each of the 28 modules tested, presented in Ampere-hour and remaining percentage relative to nominal capacity. The average capacity obtained from the modules was 2.45Ah and is represented by the red dotted line. The median of the results was 2.085 Ah, with a variance of 1.35Ah², and a standard deviation of 1.16 Ah. With this result, and as expressed in figure 5, it is noted that 16 of the 28 modules showed degradation equal to or greater than 50% in relation to the initial one, this data is consistent due to the estimated age of more than 10 years of manufacture, and the fact that they were removed from the vehicles. Most batteries had a capacity result between 1 and 3.5 Ah (about 20% to 70% of the total capacity), with only 6 modules having more than 60% of the initial capacity. Given that the numbering adopted follows the assembly layout of the vehicle's battery pack, a significant decrease in capacity can be seen in the batteries in the central region of the pack, a factor that can be associated with the higher temperature level to which these modules were exposed during operation.

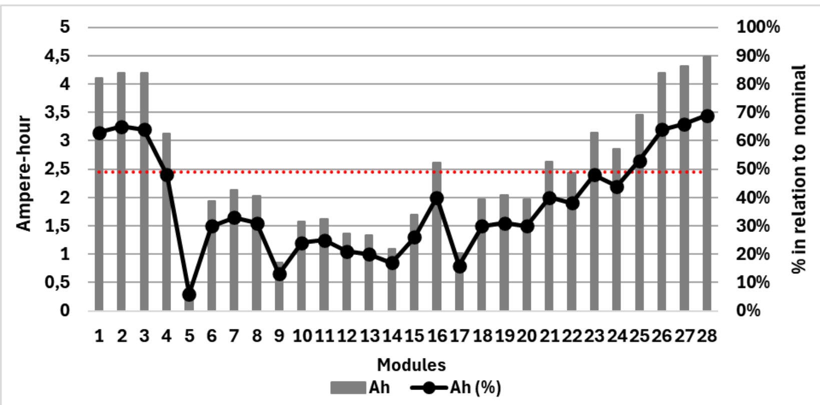

Figure 5: Results of individual tests of the NiMH modules.

In general, wear was predominantly equal to or greater than 50%. Of all of them, only six had a capacity greater than 60% and would have the potential to perform better than the others, for a second-life application with sufficient capacity to justify reuse in low-demand applications. Additionally, some modules show critical signs of degradation, such as rapid current drop during charging, excessive heat buildup, or voltage collapse after prolonged constant current charging. For safety reasons, such testing cycles were terminated early.

As the objective was to produce a storage device that could be used, given the results, the 16 modules with the highest capacity tested were selected, as shown in table 3. In theory, the battery formed would have approximately 394Wh of capacity, given the sum of the individual capacities. The selected modules were mounted in a battery bank and charged in a bench test with a constant voltage of 34 V and a current of 13 A (equivalent to 2C), as illustrated in figure 6. This test aimed to verify the voltage and current profile of the modules for both charging and discharging, as well as to verify whether the predicted values for field charging would be sufficient to charge the bank.

During the test, the battery bank showed stable behavior, with current reduction over time and no significant increase in temperature even after a long charging time and with a continuous voltage profile without abrupt drops. The current did not reach zero during this test, which may be associated with the fact that some of the modules were already worn, causing an increase in internal resistance. After approximately 5 hours of testing, the system stored 394.4 Wh with an approximate charging efficiency of 65%, requiring 605 Wh to charge it. The test was terminated as the current tended to rise again after hours of being practically stable, this, in turn, caused a small voltage drop, indicating that the battery was no longer charging and was only heating up with the charging current.

Despite the loss in nominal capacity, in this test the assembled battery bank demonstrated technical viability for applications in microgrids, being an option for low-power loads, such as lighting or cell phone charging. However, temperature regulation remains a critical consideration, with active controls being of interest in cases where safe operating limits are exceeded.

Table 3: Capacity and energy of the modules used in the battery made.

Module	Ah	Wh	
3	4.19	31.02	Group 1
26	4.19	31.78	
27	4.32	32.52	
28	4.48	34.62	
1	4,11	30.82	Group 2
2	4.19	31.38	
23	3.14	24.05	
25	3.46	26.5	
4	3.12	22.81	Group 3
21	2.63	20.13	
22	2,44	18.93	
24	2.85	21.97	
7	2.13	16.4	Group 4
8	2.03	15.72	
16	2.61	20.03	
19	2.04	15.67	

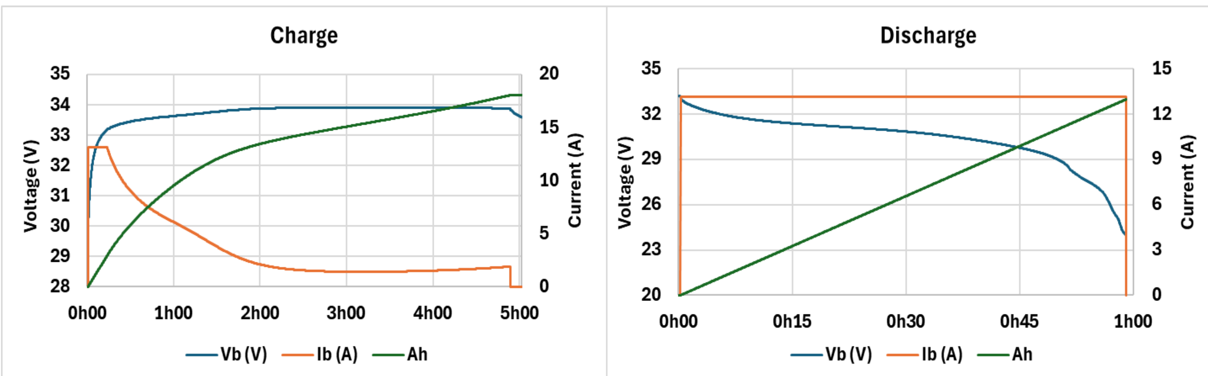

Figure 6: Operational performance of the battery composed of 16 modules.

3.2. Results of testing the battery assembled for operation in a photovoltaic system.

In tests of the battery operating in a photovoltaic system, a different capacity was recorded from that obtained on the test bench. The test followed the order of placing the bank completely discharged in the system to verify the energy needed to charge it reaching determined voltage values and how much energy would be available afterwards. The charge was made using the generator and controller mentioned above, and for the discharge the bidirectional source was used in charge mode with a constant current of 6 A. The controller programming is shown in Table 4. These values were defined considering the controller's capacity and limits for operation in a 24V DC system and considering the nominal voltage of the 28.8 V bank.

Table 4: Voltage parameters setup.

Setup	Voltage (V)
OVD - Over Voltage Disconnect Volt	34
OVR - Over Voltage Reconnect Volt	33.8
ECV - Equalization Charge Volt. (V)	33.5
BCV - Boost Charging Volt. (V)	33.5
FCV - Float Charging Volt. (V)	30.6
BRC - Boost Reconnect Charge Volt. (V)	30
CLV - Charge Limit Voltage (V)	33.5
DLV - Discharge Limit Voltage (V)	24.2
LVD - Low Volt. Disconnect Volt. (V)	25.2
LVR - Low Volt. Reconnect Volt. (V)	28.5
UVW-Under Volt. Warming Volt. (V)	25
UVWR-Under Volt. War. Reconnect Volt. (V)	25.4

The charging result using the charge controller was different from that presented using the bench source, mainly because the current goes to zero after reaching the voltage level stipulated in the controller, unlike what happened in the bench test where the battery did not reach the charge value and did not go to zero the current. This difference makes the charge last less time with the controller. This limitation can be explained by the controller's operating voltage range for 24 V, which is from 17 V to 34 V, so the programming values must be in this range. Therefore, it was necessary to use a lower BCV than in the previous test, contributing to this differentiation in the test. As shown in figure 7, for charging using a solar generator, the energy supplied to the bank was 149.9 Wh and 4.6 Ah, less than half of what was achieved in bench tests.

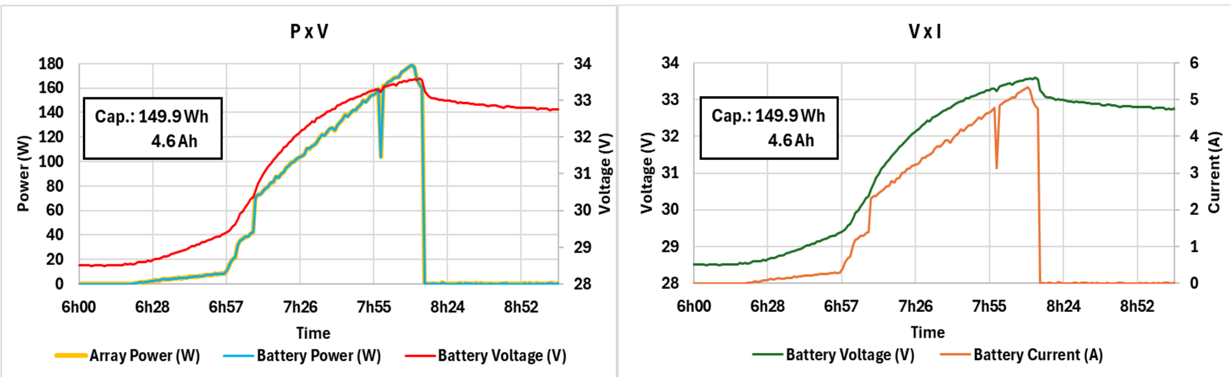

Figure 7: Operational performance of the battery, using PV generator - Charge.

After charging, the bank was discharged with a continuous current of 6 A, without the photovoltaic generator connected, in order to verify the stored energy. The result is shown in figure 8. The stored energy, as expected, is lower than the capacity previously calculated for the bank. Thus, despite showing a capacity that could be exploited in bench tests, in the field such a battery would have a very low energy contribution, which might not justify its implementation given its low capacity.

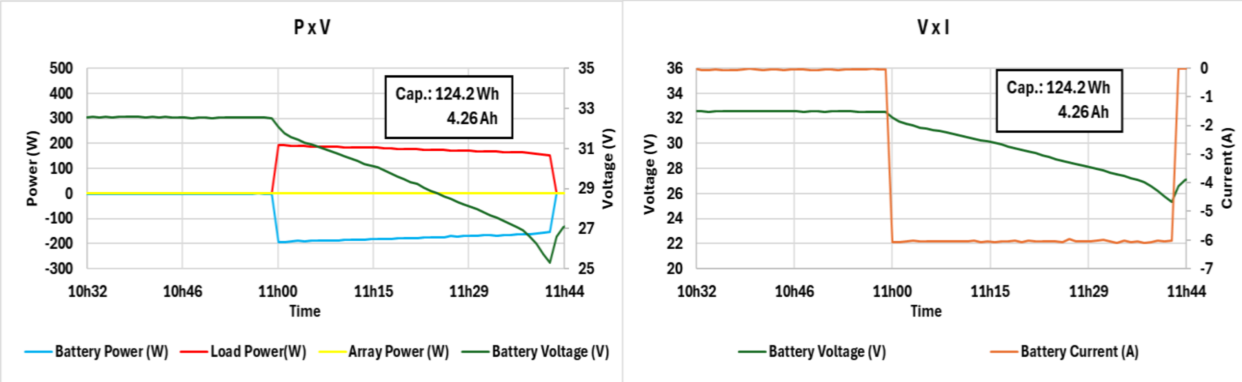

Figure 8: Operational performance of the battery, using PV generator - Discharge.

3.3. Comparison with other second-life technologies.

After the results of bench tests and tests with equipment simulating field operation, it was found that the NI-MH batteries tested would have low efficiency if used in a microgrid. Although it is an option, its energy capacity is limited due to wear and tear, which reduces energy density and may make the investment unattractive. The stored energy could only be used for low demand loads or as a backup in times of shortage, but only for a short period of time.

As a comparison for the use of second-life storage, GEDAE has explored the use of second-life Li NMC storage, also removed from electric vehicles, applying them to a microgrid in a remote community just a few minutes from Belém, the state capital, composed of approximately 15 predominantly residential buildings, also counting on a charging station for electric boats.

In initial tests in one of the residences, a Li NMC battery was added with dimensions and weight similar to those made with NI-MH modules, with superior capacity and energy density. Replicating bench tests, where the manufactured NI-MH battery provided approximately 394 Wh, the second-life Li NMC technology battery was able to provide approximately 3,450 Wh, almost 9 times more energy, as shown in figure 9. In addition to energy density, these batteries have the advantage of a longer service life with more cycles, a lower self-discharge rate, and more modern technology (Almadani, 2024).

The capacity obtained is significantly higher than that achieved with NI-MH. As it is a more recent technology, this type of battery shows promise for supplying remote consumers in terms of energy capacity and cost, since, compared to commercial solutions, it can provide more energy at a lower cost. However, it obviously has limitations, such as a shorter service life and greater wear and tear, and depending on the module classification tests, may have an even shorter service life than expected due to failures, also suffering from the short warranty period provided, given that in general the suppliers of this equipment tend not to provide long warranty periods.

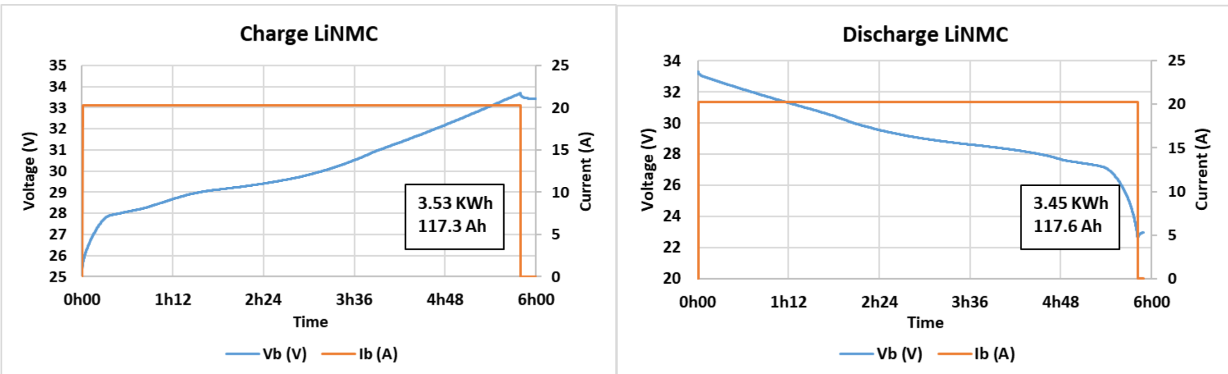

Figure 9: Li NMC Battery test.

Thus, the results of applying a second-life Li NMC battery in a direct current microgrid are presented below, verifying its performance in a real situation. The experimental results are shown in Figures 10 and 11, over a day of operation. Initially, it should be noted that this bank makes good use of solar resources, even with the high variability of irradiance during the day. At dawn, the system's priority is to supply the controller's load output. As soon as the power generated by the photovoltaic array exceeds the load demand, the charge controller directs the excess energy flow to the battery bank, initiating the charging stage with the MPPT acting, characterized by positive power in the battery and Raising Charge status (pink line).

During peak generation, around midday, the system demonstrates its ability to cope with the intermittency of the resource, reflecting local weather conditions, with marked fluctuations in the power generated (Array Power – orange line). Even during these moments of variation in power generation and consumption, the charge controller recharges the battery, ensuring a continuous power supply.

In the late afternoon, the system reaches a point where generation is no longer sufficient to meet demand and charge the battery simultaneously. From that moment on, the battery supplements the photovoltaic generation to ensure that the load continues to be powered without interruption.

Finally, when photovoltaic generation is unavailable, the battery takes over the power supply for the load. The battery bank is in discharge mode (negative power), supplying the demand of users, with a gradual reduction in demand during the night.

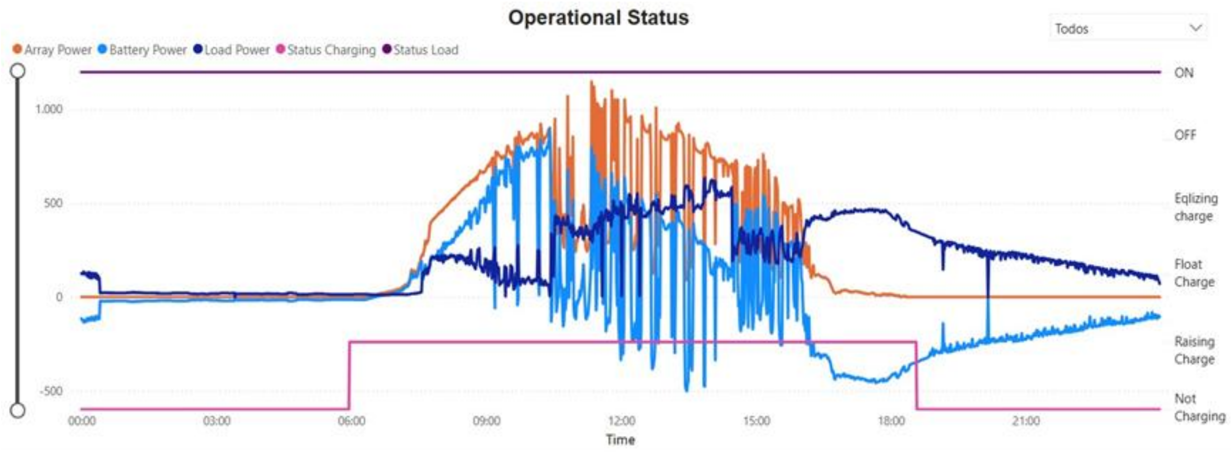

Figure 10: Operational performance of a Li-NMC battery, using PV generator at a microgrid.

Figure 11 shows the energy profile for the day considered above, where the energy accumulated by the battery was 2.59 kWh and the energy supplied by it to the load was 2.55 kWh. In addition, the total energy generated during the day, 5.07 kWh, was able to supply virtually all the load consumption, 5.03 kWh, demonstrating the self-sufficiency of the system during the period analyzed, where the battery was responsible for supplying approximately 49.31% of the load demand, while the remainder was supplied by photovoltaic generation.

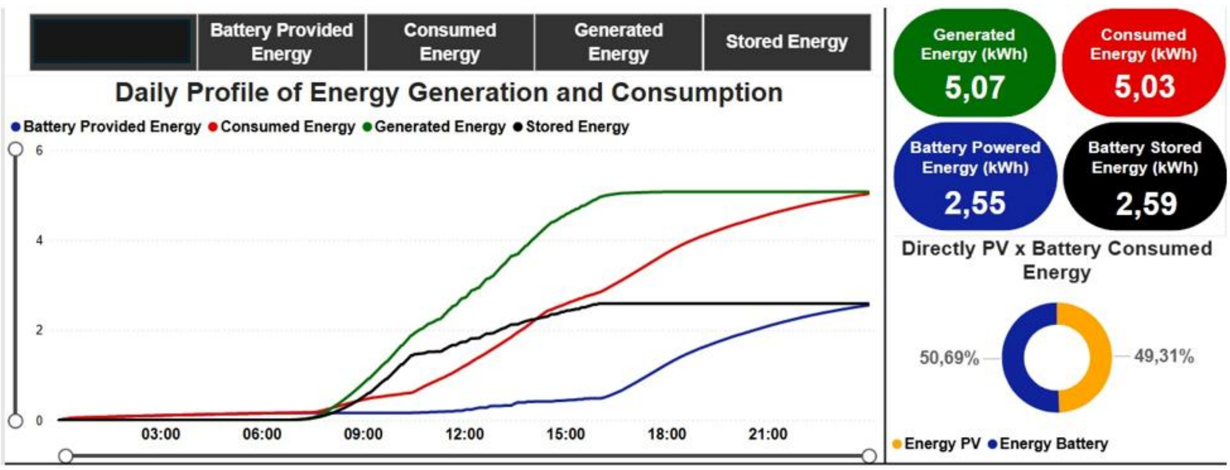

Figure 11: Daily Energy Profile Analysis.

4. Conclusion

NI-MH batteries used in electric vehicles are characterized as a robust technology, less polluting when compared to other technologies such as NiCd (Nickel Cadmium), which they replaced, and, if properly tested and inspected, can have a second life application. However, depending on their level of wear, their application may be limited or unfeasible, as they may have low reuse potential due to their low residual capacity, as was the case presented in this study, with such wear being justified by use in primary applications, manufacturing time, and uncertain storage conditions.

Other technologies with higher energy density, such as Li NMC batteries, offer significant technical advantages over NI-MH batteries and may be a good alternative for use in isolated DC microgrids operating at extra-low voltage. Thus, evaluating the performance and impacts of using second-life batteries becomes particularly relevant, since this approach allows extending the service life of storage systems, reducing the demand for extraction of new materials, and mitigating the environmental impacts associated with the manufacture of new storage devices. Furthermore, their application in isolated systems can mitigate problems related to lack of access to electricity.

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