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Off-Grid Systems With Reused Notebook Batteries – A Cost Analysis

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Abstract
Technologies that fall under alternative energy generation methods are currently among the main topics discussed in many environmental and sustainability debates. Among the most commonly used generation methods, on-grid and off-grid photovoltaic systems are prominent, mainly due to the abundance of the energy source. Off-grid, or autonomous, systems rely on energy storage, which requires the use of batteries. The construction of a battery generally involves the combination of cells. In this article, a cost analysis will be carried out to economically demonstrate the viability of a simulated battery assembled from reused cells compared to a new battery with the same characteristics. In this work, batteries are designed using 18650 cells, which are cylindrical cells with a diameter of 18 mm and a length of 65 mm. These cells power many devices, such as laptops and power banks, and were chosen due to the abundance of raw material in discarded equipment. The main result of this analysis is that the use of batteries made from reused cells can make the installation of an off-grid system economically viable, while the installation of such a system with a battery made from new cells is unfeasible. A reused cell can cost about 15% of the price of an equivalent new cell. In an initial analysis, the payback period of an off-grid photovoltaic system can be reduced by approximately 70% when using reused cells, compared to the payback period for a system with new cells.
Keywords**:** *18650 cells; Off-grid Photovoltaic Systems; Reuse of cells from discarded equipment - notebook.*

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I. Introduction

In the contemporary global context, it is widely recognized that natural resources are not inexhaustible. Faced with the growing demand for raw materials in various processes, from production to energy generation and disposal, the search for alternatives (HEATH et al., 2022) that can meet human needs within the environmental sphere becomes a matter of paramount importance. Additionally, the importance of balanced coexistence between human exploitation and the preservation of natural resources is emphasized, which defines sustainability.

In the context of sustainability, energy represents one of the most important aspects, where electricity is one of the most widely used globally, due to its flexibility of use, ease of transport, and installed infrastructure. Sustainable development is one of the main challenges in the search for alternative forms of electricity generation. In view of this, photovoltaic energy is one of the main alternative means of obtaining clean energy today. It is generated through the absorption of light rays by photovoltaic panels and has great potential in terms of the amount of energy captured due to the abundance of its source. However, this type of energy production (photovoltaic) still lacks technological maturity. As with any other form of energy production, the economic factor is one of the biggest obstacles to its development and application. It is worth noting that economic aspects are currently linked to environmental factors, as the economic appeal of green technologies increasingly becomes a decisive factor in global negotiations (DANTAS, 2014).

An economic barrier to be overcome for the use of solar energy is related to the specificity of its production, as it is exclusively diurnal and more intense on sunny, cloudless days. In this way, it is impossible for a region's energy matrix to rely solely on solar energy without storage or interruptions in supply. Therefore, the solution for the effective use of photovoltaic energy lies in storage or the supply of a complementary source, such as hydroelectric power or transfers of surplus production. These characteristics define the type of photovoltaic installation.

There are two types of photovoltaic energy production systems, known as on-grid and off-grid, as well as hybrid systems (BASARAN, 2017). Each of these systems is characterized by how electricity is distributed and stored. On-grid systems do not store energy in any means within the user's residence. The surplus generated during periods of higher production is transmitted to the distribution grid, resulting in credits, which are compensated during times when generation is insufficient or nonexistent. In short, the distribution grid connected to the on-grid system performs a function similar to that of a battery. Effectively, the battery can be compared, for example, to the reservoir of a hydroelectric plant, which reduces energy production when solar power enters the system (CAZZANIGA et al., 2019). This comparison is entirely valid, as the reservoir of a hydroelectric plant stores energy in the form of potential energy in the water mass. Therefore, the on-grid system is dependent, as it relies on an external means, outside of the photovoltaic plant, to store energy and/or manage the instantaneous load consumed.

On the other hand, the off-grid or autonomous system is defined as one in which photovoltaic energy, converted into electricity, is used for immediate consumption, and its surplus is stored in one or more batteries for use during non-illuminated periods or when generation is insufficient. Unlike an on-grid system, the autonomous system is characterized by not being connected to the distribution grid (FALK et al., 2020). The battery in an off-grid system can also act as a regulator of the power supplied by the system, for instance, when a cloud partially blocks the sunlight.

In most installations, the batteries are composed of groups of devices called cells. Typically, a cell is the smallest charge unit within a battery. In this work, the object of study will be a theoretical battery composed of 18650 cells, which are cylindrical batteries with a diameter of 18 mm and an axial length of 65 mm. These cells are found in various everyday devices, such as flashlights and laptops, for example.

An off-grid system is composed of several components, such as a charge controller, capture panels, a battery management system, and the battery itself. The battery is the component that weighs the most in the total cost of this system; in other words, what increases or makes the implementation of an off-grid system feasible is its battery. Thus, a battery composed of reused 18650 cells can represent a cost-saving alternative compared to a battery with new cells. Based on this, the aim of this work is to conduct a comparative cost analysis between a theoretical off-grid battery made from reused 18650 cells and a theoretical battery made from new cells, in order to prove the economic viability of applying reused cells.

When it comes to reuse, giving a "second life" to these devices not only reduces costs for their application but also enhances their environmental importance for two major reasons. First, it reduces the disposal of materials that could potentially be harmful to the environment (ISLAM, 2022). Second, their use as storage for energy generated from a renewable source facilitates the viability of using this type of energy source.

The disposal of batteries and cells encompasses everything from the appropriate location for initial disposal to where the final disposal of the waste will take place. This involves the current regulations regarding the procedure in question. In Brazil, the National Environment Council (CONAMA, 2023) regulates everything from definitions and terminologies to the final disposal of energy storage devices. Regarding the latter, the Council defines in Article 22, Chapter VI, the improper forms of final disposal, which include: open-air dumping and/or burning without properly licensed equipment, and dumping into bodies of water or areas prone to flooding. Although disposal is legally established, it is still a procedure that faces various obstacles today, both in terms of appropriate disposal itself and in the number of specialized facilities that actually carry out the extraction and recovery of elements from batteries. This demonstrates that the reuse of cells can provide significant value and extend the useful life of these devices, enabling a reduction in disposal. According to Chen and Shen (2017), there are three reasons supporting reuse to reduce disposal:

a) A shortage of facilities dedicated to recovering elements from cells;
b) The cost of recovering elements from cells is higher than obtaining and mining these elements;
c) When cells are designated for destruction, no selection process is carried out, resulting in the loss of both reusable and unusable units.

The objective of this work is the reuse of cells exclusively from notebook batteries, given the abundance of this material, the ease of finding these items in electronic waste companies and consequently a standardization in the cost of these batteries.

II. Energy Consumption Simulation Of A Residence – Archetype House

The simulated application presented below aims to demonstrate the feasibility of a battery made from reused cells as a means of storage for an off-grid system that provides electricity to a sample residence, referred to as the archetype house. To conceptualize the model house, we initially defined the number of residents and the main devices in a residence, as outlined in Table (1).

Table 1 – Aspects considered for the formulation of the archetype house.

Aspect Considered	Description
Number of Residents	A standard family was considered, consisting of 4 (four) residents: 2 (two) adults and 2 (two) children.
Individual Power Consumption	Along with the number of residents, the devices and appliances powered in the residence are key factors regarding the consumption and peak current of each household. According to the sizing premise, a residence is minimally composed of 1 (one) shower, 1 (one) refrigerator, 1 (one) washing machine, 2 (two) TVs, lighting, and general appliances. Among these, the shower has the highest consumption.
Usage Period	The daily operating time of an appliance or lighting device is another factor that works in synergy with power consumption and the number of residents in terms of overall consumption.

An inference was also made regarding the specifications of the appliances, as well as the habits of the fictitious residents of the archetype house, in order to estimate the average monthly and daily consumption of this residence. For consumption, the main specification of the devices is their power rating. The residents' habits directly influence the usage time. The electric shower has the highest power rating and the highest consumption. The daily usage time is 32 minutes, considering 8 minutes per day for each resident. The refrigerator remains connected to the electrical grid 24 hours a day, but its operation is intermittent, so we considered 5 hours of daily use, during which it consumes its nominal power, summed with its peak power. A similar procedure was followed for the washing machine, which has the second highest peak power consumption, but a small daily usage period was considered to result in a compatible consumption value, given that the washing machine's power varies widely during operation. For the other appliances, nominal power, usage time, and the number of days of use per month were considered (PROCELINFO, 2023), as shown in Table (2).

Table 2 – List of equipment in the archetypal house (PROCELINFO, 2023).

Device	Nd	Pd	t-d	kWh-d	t-m	kWh-m
Shower (5500 kW)	1	5500	0.53	2.93	30	88.00
Refrigerator (1 door)	1	150	5.00	0.75	30	22.50
Washing machine	1	400	0.37	0.15	12	1.76
TV 21"	2	90	4.00	0.72	30	21.60
Lighting	4	15	5.00	0.30	30	9.00
Sum	9	6155	14.90	4.85	132	142.86

Nd = Number of devices.
Pd = Maximum power of the device(s) (W).
t-d = Uninterrupted time of daily use (h).
kWh-d = Maximum daily consumption (kWh).
t-m = Monthly usage time (d).
kWh-m = Monthly consumption (kWh).

Obviously, the parameters presented in Tables (1) and (2) can change depending on the number of residents, their habits, and the electrical appliances in the residence. However, the main goal, which is to obtain an estimate of the battery size required to power an off-grid system for a residence, as well as the economic viability of this system, will remain unchanged. Therefore, the values presented here can be used as parameters for quick comparisons through simple proportional relationships or even for more in-depth studies through more complex relationships.

III. Cost Analysis

Using the data from Table (3) and following the methodology of Baziotti (2023), we can find a set of numerical results presented in Table (3).

Table 3: Values related to the battery required to power the photovoltaic system of the archetype house.

Greatness	Value
Number of required cells	3327
Value of each reused cell	US$ 0.46
Value of each new cell	US$ 3.04
Battery energy	24,62 kWh

For a feasibility analysis, a price quote was obtained for new 18650 cells with a minimum capacity of 2000mAh. The quote was gathered from marketplace websites, excluding products that clearly present incorrect information in the listing, such as 18650 cells with 9900mAh, as it is impossible for a cell of this size to have such a capacity with current lithium-ion technology.

The lowest price found was US$ 3.04 per cell when purchasing a batch of 20 units of 2200mAh cells. We have no reference for the seller, nor any guarantee of the quality of these cells, so it is possible that purchasing from a supplier with certified quality assurance could result in an even higher unit price than the one found in this online quote.

A preliminary feasibility analysis consists of a simple comparison between the price of a new cell (US$ 3.04) and the price of a reused cell (US$ 0.46), as found in a previous study (BAZIOTTI, 2023). This results in a ratio of 6.67 times, meaning that the reused cell costs about 15% of the price of a new cell.

The analysis of the cell price is only part of the evaluation, as an on-grid photovoltaic system to power the house in our case study would cost around US$ 2,256.00. Assuming initially that the cost of an off-grid system is the cost of the on-grid system plus the cost of the battery (which is quite reasonable), an off-grid system with reused cells would cost around US$ 3,334.00, while the same system with a new cell battery would cost approximately US$ 12,3650.00.

An on-grid system of this size, installed before January 6, 2023 (the expected date for the start of taxation in Brazil on the use of the grid as a battery), has an estimated payback period of 5 years. Using a simple proportional relationship, an off-grid system with reused cells would have a minimum payback period of around 8 years, while the same system with new cells would have a minimum investment payback period of around 27 years.

In a quick analysis, we see that the system in this case study with new cells would be unfeasible, as the expected lifespan of a photovoltaic system is 25 years. It is worth considering that a more detailed analysis could either accentuate or mitigate the results of this study.

To estimate how long the sized battery could power the archetype house, simply divide the total energy stored in the battery (Table 3) by the maximum daily consumption of the residence (Table 1). This calculation results in an autonomy of about 5 days. This means that, once fully charged, the sized battery would be able to keep the house running for 5 days without any sunlight. Thus, even during periods of low solar intensity, such as rainy or cloudy days, this autonomy would tend to increase. How much longer it would last depends on more in-depth studies, some of which are currently being developed by the authors' research group.

IV. Conclusion

Based on the results presented, it can be concluded that, at least for this case study, the use of reused cells in the construction of the battery for the photovoltaic system can make the off-grid system viable. This is because assembling it with new 18650 lithium batteries is economically unfeasible, as the payback period of around 27 years exceeds the system's expected lifespan, which is about 25 years.

When estimating the value of the off-grid system, we simply add the cost of the on-grid system to the cost of the cells for assembling the battery. This approximation is reasonable since these are the main costs of an off-grid system. A more detailed analysis would require a more powerful inverter, as well as a charge controller, a battery management system, cables, and other materials that would further increase the cost of the battery and consequently the off-grid system, making it even more economically unfeasible with new cells. For the off-grid system with reused cells, a more detailed study would be needed to obtain a more reliable payback period. However, it is possible that such a system could be economically viable.

As we have seen, the cost of reused cells (US$ 0.46) is extremely low (BAZIOTTI, 2023) compared to the price of a new cell (US$ 3.04). This difference is certainly due to the fact that no recycling process (RAHMAN, 2017) was performed on the cells, which would undoubtedly consume energy, machinery, and adequate facilities, thereby increasing the cost of the recycled product. In the values presented here, the largest cost involved in the process is labor.

A factor that was not considered in this study, but will certainly be very important for the viability of this project, is the durability of the battery made with reused cells. This analysis is being conducted for future studies. For now, we can report that we have a battery made with reused cells that is operational in a prototype electric vehicle within the research group of the authors of this work.

Finally, we conclude that there is a high likelihood of an off-grid system being viable if its battery is built with reused cells, and little chance of viability if the same battery is assembled with new cells. Although the numbers presented in this work are not sufficient for making a definitive decision, they serve as a test of possibilities. More in-depth studies are being conducted by the research group for future work with a higher degree of certainty.

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