Integration of photovoltaic systems with first- and second-life batteries: A technical-economic case study in Brazil

João Pedro F. Abreu, Vinícius Hirassaki, Helena F. Naspolini and Ricardo Rüther

Solar Energy Research Laboratory/Universidade Federal de Santa Catarina, Florianópolis (Brazil)

Abstract

This study evaluates the technical and financial feasibility of implementing three renewable energy systems on the Universidade Federal de Santa Catarina main campus in Florianópolis, SC. The feasibility was assessed by analyzing Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback, and Levelized Cost of Energy (LCOE). The evaluated configurations included: *i*) a solar photovoltaic (PV) system; *ii*) a system comprising PV coupled with a first-life Battery Energy Storage System (BESS); *iii*) a PV system with a second-life BESS. In order to address uncertainties related to battery pricing and the operational lifespan of second-life batteries, the study first compared IRR across scenarios ranging from 30% to 70% of a first-life BESS cost and one to up to six battery replacements, while assuming a fixed Minimum Attractive Rate of Return (MARR) of 14%. A second analysis compared NPV, IRR, payback, and LCOE for five specific scenarios over a 25-year projection with a variable MARR. Although the standalone PV system demonstrated the lowest LCOE, the PV + BESS first-life system demonstrated superior financial attractiveness due to a higher NPV. PV + BESS second-life systems surpassed the PV + BESS first-life system in financial viability when the second-life battery cost was 50% or less of the first-life battery cost, provided the project required at most three replacements. The PV + BESS second-life (30% cost/1 replacement) scenario presented the best NPV, TIR and payback. Inflation and tariff adjustment indices were not considered for the financial analysis.

Keywords: Second-Life Battery Systems, Hybrid system, Battery energy storage system, Photovoltaic Systems, Financial Feasibility.

1. Introduction

Photovoltaic (PV) energy stands out globally as an efficient solution, driven by technological advancements and cost reductions that have broadened its accessibility. According to Boucar Diouf and Ramchandra Pode (2015), its progress results from the improvement of components for the expansion of grid-connected systems, which are essential factors for its evolution and large-scale adoption. In Brazil, PV sources led the expansion of installed generation capacity in the country in 2024 for the fourth consecutive year, representing 9.3% of all energy generated for the same year (EPE, 2025).

The high levels of solar irradiation in Brazil make PV systems an effective strategy for reducing energy consumption in urban buildings (Rüther and Zilles, 2011). University campuses, characterized by their horizontal architecture and high daytime demand (computers, lighting, and air conditioning), stand out as ideal environments for PV integration, mitigating dependence on the conventional grid (Pinto, 2018; Park and Kwon, 2016).

The global market for energy storage systems registered significant growth in 2024, with installed capacity reaching 175.4 GWh, a 26.5% increase compared to the previous year, driven primarily by China and the United States (InfoLink, 2025). Among the different energy storage technologies, battery energy storage systems (BESS) are a notable example. In Brazil, BESS are still sparsely deployed due to their high cost (MME and EPE, 2023). However, BESS can still be utilized for energy consumption management in both high and low voltage applications (EPE, 2022).

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Second-life Li-ion batteries are batteries retired from primary applications (e.g., electric vehicles) after the end of their lifespan, but still usable in secondary, stationary applications (Hohmann et al., 2024). However, because they are still a recent application of the technology, and are not yet available in large quantities, they present many uncertainties regarding their lifespan and initial investment (CAPEX) (Kampter et al., 2023). This work aims to analyze the technical and economic viability of integrating PV and first-life (1st life) and second-life (2nd life) BESS in university campuses.

2. Methods

This study aims to analyze the financial viability of standalone PV generation systems, PV + 1st life BESS, and PV + 2nd life BESS in a Consumer Unit (CU) located on the campus of the Universidade Federal de Santa Catarina (UFSC), in Florianópolis. This region is noted as having one of the lowest solar irradiation incidences in the country (Pereira et al, 2017), as shown in Figure 1. Despite this, PV systems still demonstrate significant viability (Greener, 2025).

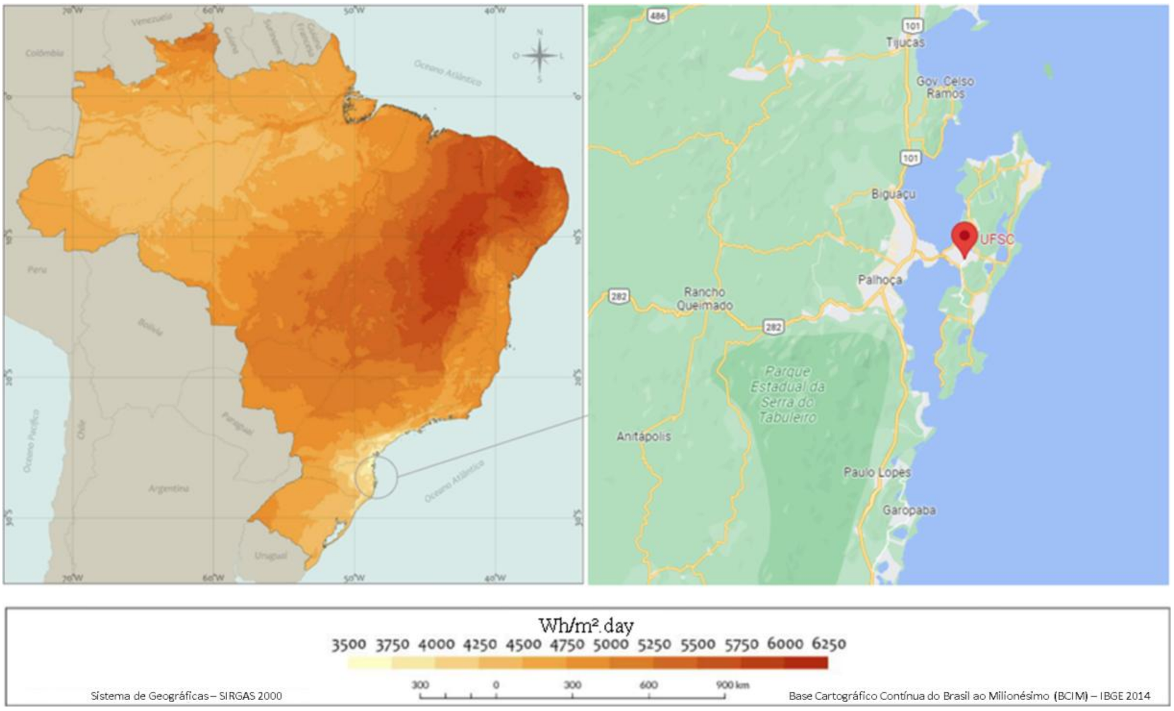

Figure 1 – Daily total Global Horizontal Irradiation (right) and UFSC location (left).

The simulated PV system will be integrated into the arched roof surface of the Swimming pool Complex Gymnasium at UFSCs Sports Centre (CDS) (-48.52° and -27.60°). The total roof area of the CU is approximately 3,400 m². The energy consumption of the building consists mainly of heating the swimming pools during the colder periods of the year and lighting. Figure 2 shows the CU building and its 3D model with PV integration.

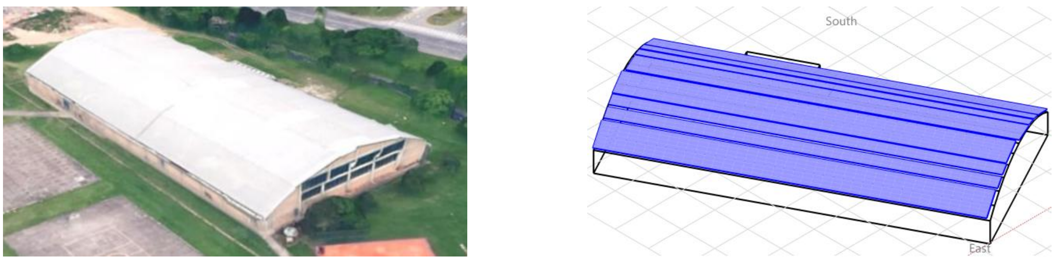

Figure 2 – CU Building (Source: Google Earth) and its 3D model with PV integration.

The PV sizing utilized GCL-M3/78H-445 modules and SUN2000 inverters, simulated using the solar simulation software PVsyst® 7.4.2 (PVsyst, 2023) with meteorological data from Meteonorm 8.1 (Meteonorm, 2021) and the Brazilian Solar Energy Atlas (Pereira et al., 2017). Simulation parameters included thermal loss (29.0 W/m²K), cabling (8.7 m), and specific losses (STC: 0.5%, efficiency: -0.3%, MPP: 2%, LID: 3%, soiling: 3% per year). Table 1 shows the parameters utilized in this study for the PV system.

Table 1 – PV system and inverter parameters.

PV Module		Inverter	
Technology	**Power (Wp)**	**Power CC (kW)**	**Frequency (Hz)**
Si-mono	445	50	50 / 60

For the financial viability, electricity bills for the year 2024 were analyzed. The CU is supplied at 13.8 kV (Subgroup A4) and has an electricity supply contract with Centrais Elétricas de Santa Catarina S.A. (CELESC) under the Green Hourly Tariff contracting modality (ANEEL, 2021).

The BESS represents the largest CAPEX of the system; thus, the BESS was sized to be sufficient to supply the month with the lowest energy consumption during P hours in 2024 (January). The BESS power was sized to meet the highest P (peak) hour demand of the CU during the analyzed period (September). For both 1st and 2nd life batteries, Lithium-Ion technology was adopted (EPE, 2022a), with parameters shown in Table 2. Depth of Discharge (DoD) is the percentage of BESS capacity that can be utilized without damaging the equipment, while Roundtrip is the aggregated charging and discharging efficiency rate of the BESS.

Table 2 – BESS Batteries parameters

Technology	DoD	Roundtrip	Degradation per year
Lithium-Ion	90.00%	89.00%	3.00%

The dispatch policy in this study is modeled to maximize the self-consumption derived from PV generation, and to prevent consumption from the grid during P hours.

During OP (off-peak) hours, the energy generated by the PV system is utilized to supply the CU's consumption, and any surplus is used to charge the BESS. 1 hour before the start of the P period, the BESS is charged utilizing energy from the grid until full charge, if it is not full already.

During P hours, the BESS supplies the CU's consumption until the end of the P period or until it reaches its minimum State of Charge (SOC). This policy is based on the works of Abreu (2023) and Pinto et al. (2024), which demonstrate the technical and economic viability of integrating PV systems with BESS in public buildings. Figure 3 shows this dispatch policy in flowchart form.

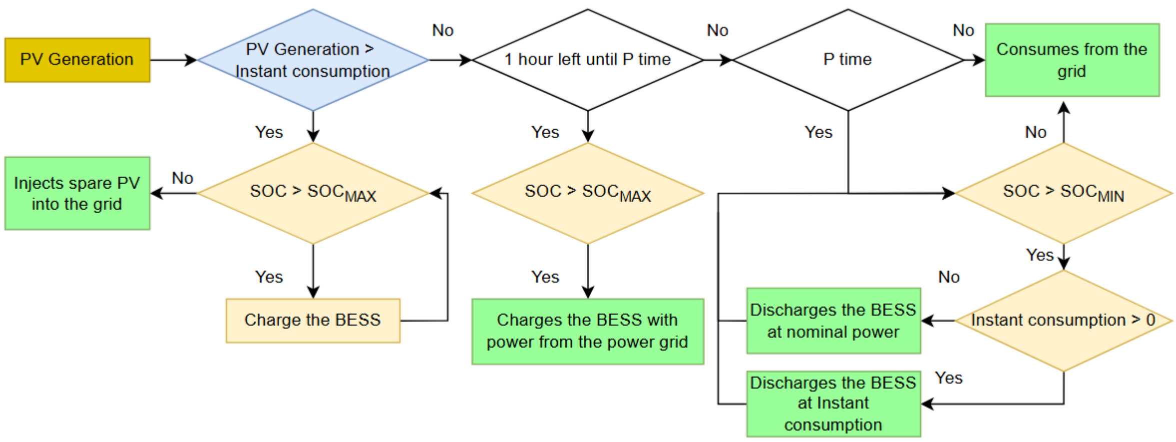

Figure 3 – Dispatch policy flowchart.

The fees adopted by CELESC, under REH Nº 3.511/25 (ANEEL,2025), for the energy and use of distribution system tariffs (TE and TUSD respectively), and for the contracted demand (without taxes), as well as the average 2024 rates for the Tax on Circulation of Goods and Services (ICMS), the Contribution to the Social Integration Program and the Formation of Public Servant Heritage (PIS), and the Contribution for the Financing of Social Security (COFINS) are shown in Table 3.

Table 3 – Values of tariff components and the average value of ICMS, PIS, and COFINS for 2024

Group A4 - Green	Tariff Components (without taxes)			Average Taxes (2024)		
Period	**TUSD ($/MWh)**	**TE ($/MWh)**	**Demand ($/MW)**	**ICMS (%)**	**COFINS (%)**	**PIS (%)**
Peak	$ 194.55	$ 87.27	$ 3,289.09	17.00%	3.07%	0.66%
Off-peak	$ 25.45	$ 18.09	$ 3,289.09	17.00%	3.07%	0.66%

Eq. (1) shows the value of the final tariff including taxes:

$$T_f = (TE + TUSD)/[(1 - ICMS).(1 - (PIS + COFINS))] \quad (1)$$

Where T_f is the final tariff including taxes ($/kWh); TE and $TUSD$ are the Tariff Components ($/MWh); $ICMS$, PIS and $COFINS$ are the aforementioned taxes.

Eq. (2) presents the amount to be billed for green hourly tariff contracting modalities, according to REN N°1000/2021.

$$VF(v)=[(CE(OP).(TE(OP)+TUSD(OP))) + (CE(P).(TE(P)+TUSD(P)))+(DemC.TD)] \quad (2)$$

Where $CE(OP)$ is the energy consumption during OP hours (kWh); $TE(OP)$ is the electric energy consumption tariff during OP hours ($/kWh); $TUSD(OP)$ is the distribution system usage tariff during OP hours ($/kWh); $CE(P)$ is the energy consumption during P hours (kWh); $TE(P)$ is the electric energy consumption tariff during P hours ($/kWh); $TUSD(P)$ is the distribution system usage tariff during peak hours ($/kWh); $DemC$ is the contracted demand (kW); TD is the demand tariff ($/kW); and $VF(v)$ is the billed value of electric energy under the green hourly tariff ($).

The electric energy compensation system (SCEE) is the mechanism that compensates a CU's energy bill consumption using credits generated from injected energy. According to Law 14.300/22, the CU falls under the modality GD II (Brasil, 2022). Therefore, the energy compensation (excluding taxes) for the CU during the P and OP periods is calculated according to Eq. (3) and (4).

$$E_{credOP} = E_{credi,OP} + E_{i,OP} - G_{OP} \quad (3)$$

Where E_{credOP} is the final energy credit quantity at the end of the energy tariff billing cycle for the OP period (kWh); $E_{credi,OP}$ is the energy credit quantity at the start of the energy tariff billing cycle for the OP period(kWh); $E_{i,OP}$ is the injected energy during the OP period (kWh); and G_{OP} is the credit value expended for compensating the energy tariff for the OP period (kWh).

$$E_{credP} = E_{credi,P} + E_{i,P} - G_P \quad (4)$$

Where E_{credP} is the final energy credit quantity at the end of the energy tariff billing cycle during the P period (kWh); $E_{credi,P}$ is the energy credit quantity at the start of the energy tariff billing cycle during the P period (kWh); $E_{i,P}$ is the injected energy during the P period (kWh); and G_P is the credit value expended for compensating the energy tariff during the P period (kWh).

According to Law 13.169/2015 (Brasil, 2015), energy credits can be utilized to offset the amounts charged for PIS and COFINS, pertaining to both the TE and TUSD components. The ICMS portion of the TE is compensated, via RICMS/SC (2002), for energy injected into the grid by photovoltaic systems up to 1 MW. Eq. (5) and (6) illustrate the calculation of the compensation, including taxes, for the OP and P periods, respectively:

$$V_{credOP} = G_{OP}(TUSD_{OP} + TE_{OP} - a.Fio_{B,OP})/((1 - ICMS).(1 - PIS - COFINS)) - G_{OP}(TUSD_{OP} - a.Fio_{B,OP}).ICMS/((1 - ICMS).(1 - PIS - COFINS)) \quad (5)$$

Where V_{credOP} is the compensated value of the energy tariff during the OP period ($); $TUSD_{OP}$ is the rate for the use of the distribution network during the OP period ($/kWh); TE_{OP} is the energy rate during the OP period ($/kWh); a is the percentage charge of Fio B; $Fio_{B,OP}$ is the cost component of Fio B during the OP period ($/kWh); and G_{OP} is the credit value utilized for compensating the energy tariff during the OP period (kWh).

$$V_{credP} = G_P(TUSD_P + TE_P - a.Fio_{B,P})/((1 - ICMS).(1 - PIS - COFINS)) - G_P(TUSD_P - a.Fio_{B,P}).ICMS/((1 - ICMS).(1 - PIS - COFINS)) \quad (6)$$

Where V_{credP} is the compensated value of the energy tariff during the P period ($); $TUSD_P$ is the rate for the use of the distribution network during the P period ($/kWh); TE_P is the energy rate during the P period ($/kWh); $Fio_{B,P}$ is the cost component of Fio B during the P period ($/kWh); and G_P is the credit value utilized for compensating the energy tariff during the P period (kWh).

Table 4 displays the values for the percentage charged for Wire B over the years, according to Law 14.300/22 (Brasil, 2022). This work stipulates that the Wire B charge will be maintained at 90% after the year 2028, given that the current SCEE regulations for the GD II group, established by Law 14.300/22, will be valid to 2025. The value of Fio B is zero (null) for the OP period, whereas it is $ 118.14/MWh during the P period.

Table 4 – Fio B fee progression over the years

Year	2023	2024	2025	2026	2027	2028
Percentage charged of Wire B	15.0%	30.0%	45.0%	60.0%	75.0%	90.0%

For the financial viability study, the financial indicators Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE) were utilized, as shown in Eq. (7) through (10). The discounted payback period was also calculated, defined as the duration required for the sum of costs to equal the revenue generated by the project, accounting for monetary devaluation over time. For this work, the Minimum Acceptable Rate of Return (MARR) ranged from 0 to 15%.

$$PV(i) = -I + \sum_{i=0}^{n} \frac{(R_i - C_i)}{(1 + MARR)^i} \quad (7)$$

Where $PV(i)$ represents the Present Value ($); I is the initial investment ($) R_i is the revenue generated in year i ($); C_i is the cost incurred in year i ($); n is the system's lifespan (years); and $MARR$ is the minimum acceptable rate of return.

$$NPV = PV(n) \quad (8)$$

Where NPV is theis Net Present Value ($); and $PV(n)$ is the Present Value in year n ($).

$$0 = \sum_{i=0}^{n} \frac{CF_i}{(1 + IRR)^i} \tag{9}$$

Where CF_i is the Cash Flow in period i ($); n is the system's lifespan (years); and IRR is the internal rate of return.

$$LCOE = \sum_{i=1}^{n} \left[\frac{I_i + O\&M_i}{(1 + MARR)^i}\right] / \sum_{i=1}^{n} \left[\frac{E_i}{(1 + MARR)^i}\right] \tag{10}$$

Where $LCOE$ is the Levelized Cost of Energy ($/kWh); I_i is the value invested in year i ($); $O\&M_i$ are the operation and maintenance expenses in year i ($); and E_i is the electrical energy generation in year i (kWh).

This study analyzes the financial attractiveness of the return on investment over a 25-year project projection. assuming no inflation or tariff adjustment. The initial investment for the PV system was estimated at $ 2.18/Wp (Greener. 2025), coupled with an annual decrease in generated energy of 0.5% and O&M costs equivalent to 1.0% of the initial investment (Pinho and Galdino. 2014). Inverter replacement is scheduled for the 10th year. with a cost set at 15% of the initial investment (EPE. 2022b).

For the BESS. an annual degradation rate of 3.0%. O&M costs of 0.5%. and replacement after 10 years were adopted (EPE. 2024). The initial BESS investment in 2025 was set at $90/kWh (BloombergNEF. 2024), using an exchange rate of R$5.50/$ (BCB. 2025) and a tariff charge of 70.2% (EPE. 2024). Logistics and project implementation costs (EPC+BOS) accounted for 5% and 13% of the CAPEX. respectively (ABSAE. 2024). The price projection for the BESS until 2050 adhered to the study conducted by Cole and Karmakar (2023). Second-life batteries operate at 70% of their initial capacity.

In order to mitigate the uncertainties surrounding the cost and durability of 2nd life batteries (Kampker et al., 2023), scenarios were defined with prices ranging from 30% to 80% of the value of new batteries, and 1 to 6 replacements over the project's lifetime. Batteries account for 69% of the total BESS cost (Greener. 2025b). The remaining equipment components of the 2nd life BESS are replaced in the tenth year of the project.

The initial analysis compared the financial viability of PV systems with first-life and second-life batteries (30%–70% of the cost of 1st life batteries. 1–6 replacements) using the IRR indicator under a fixed MARR of 14%. The second analysis compares the economic viability using the NPV. IRR. payback. and LCOE indicators over a 25-year perspective across five scenarios with variable MARR (0% - 15%). assuming 50% simultaneity:

i) The Consumer Unit with standalone PV integration;

ii) The Consumer Unit with PV + 1st life BESS integration;

iii) The Consumer Unit with PV + 2nd life BESS integration with 50% of the 1st life battery cost and 6 battery replacements;

iv) The Consumer Unit with PV + 2nd life BESS integration with 40% of the 1st life battery cost and 3 battery replacements; and

v) The Consumer Unit with PV + 2nd life BESS integration with 30% of the 1st life battery cost and 1 battery replacement.

Simultaneity is defined as the percentage of energy generated by the PV system used to meet the Consumer Unit's instantaneous consumption from the consumer's perspective.

3. Results

Table 5 shows the measured power demand and energy consumption during peak hours (P) and off-peak hours (OP) for each month.

Table 5 –Demand and energy consumption of the CU

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P Dem (kW)	259	262	441	475	412	412	403	449	487	415	426	432
P (MWh)	10	12	17	21	19	20	22	19	21	20	18	17
OP (MWh)	116	126	167	178	169	162	175	164	171	172	168	156

The CU exhibits an average monthly consumption of 178.33 MWh. with January recording the lowest consumption (126 MWh) and April the highest (199 MWh). During the P period. the maximum demand occurred in September. reaching 487 kW. and the minimum consumption was observed in January. totaling 10 MWh.

Table 6 presents the values for the performance ratio (PR) and the PV energy generation from the PVsyst® simulation of the analyzed CU over the first year of the PV generation system. The PV system has an installed capacity of 713.6 kWp and 600 kW inverters. featuring four distinct inclinations (18.7°; 13.3°; 8.0°; 24.0°) and an azimuth of 62.1° west. The system requires an initial investment of $ 282,210.91. and the inverter replacement cost is $ 42,331.64. The data for temperature (Temp.) and global horizontal irradiation (GHI) are shown in the same table.

Table 6 - Monthly progression of PR, PV generation, GHI and Temperature for the CU.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PR (%)	79.8	80.5	80.4	81.3	82.2	82.8	83.2	83.3	83.0	82.1	81.2	80.3
PV Generation (MWh)	100.9	85.2	81.4	63.9	54.2	44.3	48.3	61.2	61.5	77.0	93.6	103.7
GHI (kWh/m².month)	177.6	148.7	133.6	110.3	85.3	69.3	75.3	96.3	97.3	123.9	152.8	181.4
Temp. (C°)	25.4	25.0	24.5	21.6	18.3	16.4	14.9	16.6	18.0	21.1	22.5	24.6

The results indicate that during the warmest month of the year (January), the system exhibited the lowest PR values (79.8%), despite also being the month with the highest PV generation (100.9 MWh). The winter months had the lowest PV generation (44.3 MWh in June). The PV system yields an annual generation of 875.3 MWh, an average annual PR of 81.7%, and an annual yield of 1.23 MWh/kWp.year.

Both the 1st life and 2nd life BESS operate at 487 kW of maximum power, but they differ in capacity: 534.34 kWh for the 1st life system and 763.34 kWh for the 2nd life system. Table 7 provides a detailed analysis of the cost evolution for both systems and their equipment. projecting the trajectory of values between the years 2025 and 2050.

Table 7 - 1st and 2nd Life BESS cost progression

Year	2025	2026	2027	2028	2029	2030	2031
1st Life Battery	$66,767.64	$64,294.77	$61,821.89	$60,173.31	$57,700.43	$56,051.85	$55,227.55
2nd Life Battery (70% of 1st Life Battery Cost)	$66,767.64	$64,294.77	$61,821.89	$60,173.31	$57,700.43	$56,051.85	$55,227.55
2nd Life Battery (60% of 1st Life Battery Cost)	$57,229.41	$55,109.80	$52,990.19	$51,577.12	$49,457.51	$48,044.44	$47,337.90
2nd Life Battery (50% of 1st Life Battery Cost)	$47,691.17	$45,924.83	$44,158.49	$42,980.93	$41,214.59	$40,037.03	$39,448.25
2nd Life Battery (40% of 1st Life Battery Cost)	$38,152.94	$36,739.87	$35,326.79	$34,384.75	$32,971.67	$32,029.63	$31,558.60
2nd Life Battery (30% of 1st Life Battery Cost)	$28,614.70	$27,554.90	$26,495.10	$25,788.56	$24,728.76	$24,022.22	$23,668.95
Pack	$42,852.62	$41,265.49	$39,678.36	$38,620.27	$37,033.13	$35,975.04	$35,446.00
Year	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**
1st Life Battery	$ 54,403.26	$ 53,578.97	$ 51,930.39	$ 51,106.10	$ 50,281.80	$ 49,457.51	$ 48,633.22
2nd Life Battery (70% of 1st Life Battery Cost)	$ 54,403.26	$ 53,578.97	$ 51,930.39	$ 51,106.10	$ 50,281.80	$ 49,457.51	$ 48,633.22
2nd Life Battery (60% of 1st Life Battery Cost)	$ 46,631.37	$ 45,924.83	$ 44,511.76	$ 43,805.23	$ 43,098.69	$ 42,392.15	$ 41,685.62
2nd Life Battery (50% of 1st Life Battery Cost)	$ 38,859.47	$ 38,270.69	$ 37,093.13	$ 36,504.35	$ 35,915.57	$ 35,326.79	$ 34,738.01
2nd Life Battery (40% of 1st Life Battery Cost)	$ 31,087.58	$ 30,616.55	$ 29,674.51	$ 29,203.48	$ 28,732.46	$ 28,261.44	$ 27,790.41
2nd Life Battery (30% of 1st Life Battery Cost)	$ 23,315.68	$ 22,962.42	$ 22,255.88	$ 21,902.61	$ 21,549.34	$ 21,196.08	$ 20,842.81
Pack	$ 34,916.95	$ 34,387.91	$ 33,329.82	$ 32,800.77	$ 32,271.73	$ 31,742.68	$ 31,213.64
Year	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**
1st Life Battery	$ 47,808.93	$ 46,984.64	$ 46,160.35	$ 45,336.05	$ 44,511.76	$ 43,687.47	$ 42,863.18
2nd Life Battery (70% of 1st Life Battery Cost)	$ 47,808.93	$ 46,984.64	$ 46,160.35	$ 45,336.05	$ 44,511.76	$ 43,687.47	$ 42,863.18
2nd Life Battery (60% of 1st Life Battery Cost)	$ 40,979.08	$ 40,272.55	$ 39,566.01	$ 38,859.47	$ 38,152.94	$ 37,446.40	$ 36,739.87
2nd Life Battery (50% of 1st Life Battery Cost)	$ 34,149.23	$ 33,560.45	$ 32,971.67	$ 32,382.89	$ 31,794.11	$ 31,205.33	$ 30,616.55
2nd Life Battery (40% of 1st Life Battery Cost)	$ 27,319.39	$ 26,848.36	$ 26,377.34	$ 25,906.32	$ 25,435.29	$ 24,964.27	$ 24,493.24
2nd Life Battery (30% of 1st Life Battery Cost)	$ 20,489.54	$ 20,136.27	$ 19,783.01	$ 19,429.74	$ 19,076.47	$ 18,723.20	$ 18,369.93
Pack	$ 30,684.59	$ 30,155.55	$ 29,626.51	$ 29,097.46	$ 28,568.42	$ 28,039.37	$ 27,510.33
Year	**2046**	**2047**	**2048**	**2049**	**2050**	**-**	**-**
1st Life Battery	$ 42,038.89	$ 41,214.59	$ 40,390.30	$ 39,566.01	$ 38,741.72	-	-
2nd Life Battery (70% of 1st Life Battery Cost)	$ 42,038.89	$ 41,214.59	$ 40,390.30	$ 39,566.01	$ 38,741.72	-	-
2nd Life Battery (60% of 1st Life Battery Cost)	$ 36,033.33	$ 35,326.79	$ 34,620.26	$ 33,913.72	$ 33,207.19	-	-
2nd Life Battery (50% of 1st Life Battery Cost)	$ 30,027.77	$ 29,438.99	$ 28,850.21	$ 28,261.44	$ 27,672.66	-	-
2nd Life Battery (40% of 1st Life Battery Cost)	$ 24,022.22	$ 23,551.20	$ 23,080.17	$ 22,609.15	$ 22,138.12	-	-
2nd Life Battery (30% of 1st Life Battery Cost)	$ 18,016.67	$ 17,663.40	$ 17,310.13	$ 16,956.86	$ 16,603.59	-	-
Pack	$ 26,981.28	$ 26,452.24	$ 25,923.19	$ 25,394.15	$ 24,865.10	-	-

Table 8 illustrates the IRR of the second-life BESS across different scenarios. considering a MARR of 14%. battery costs ranging between 30% and 70% of the first-life values. and 1 to 6 battery replacements throughout the project's lifetime. For comparison. the configuration featuring a first-life BESS exhibits an IRR of 12.44%. Green scenarios denote greater viability for the 2nd life BESS. while red scenarios indicate lower viability. In all analyzed scenarios. the PV system was considered to operate with 50% simultaneity.

Table 8 – Comparison between PV + 2nd-life BESS (30% - 70% of cost. 1 - 6 replacements) and PV + 1st-life BESS (IRR 12.44%) for a Hurdle Rate of 14%

Nº of exchanges		1	2	3	4	5	6
Price of 2nd life batteries	30% 1st Life Price	14.45%	14.36%	14.19%	14.03%	13.79%	13.49%
	40% 1st Life Price	13.66%	13.54%	13.31%	13.11%	12.78%	12.39%
	50% 1st Life Price	12.91%	12.77%	12.48%	12.22%	11.82%	11.34%
	60% 1st Life Price	12.20%	12.02%	11.68%	11.38%	10.90%	10.33%
	70% 1st Life Price	11.52%	11.31%	10.91%	10.56%	10.01%	9.36%

Second-life battery systems begin to demonstrate greater financial attractiveness compared to the first-life system when a cost of 50% of the first-life batteries is considered. coupled with a maximum of three replacements over the project duration. For lower cost values. the system utilizing second-life batteries maintained superior financial attractiveness even with an increased number of replacements.

Figures 4 to 7 illustrate the results for NPV. IRR. discounted payback. and LCOE for a minimum acceptable rate of return ranging from 0% to 15%, considering a 25-year projection and 50% simultaneity. The graphs present the analysis for the scenarios i) through v).

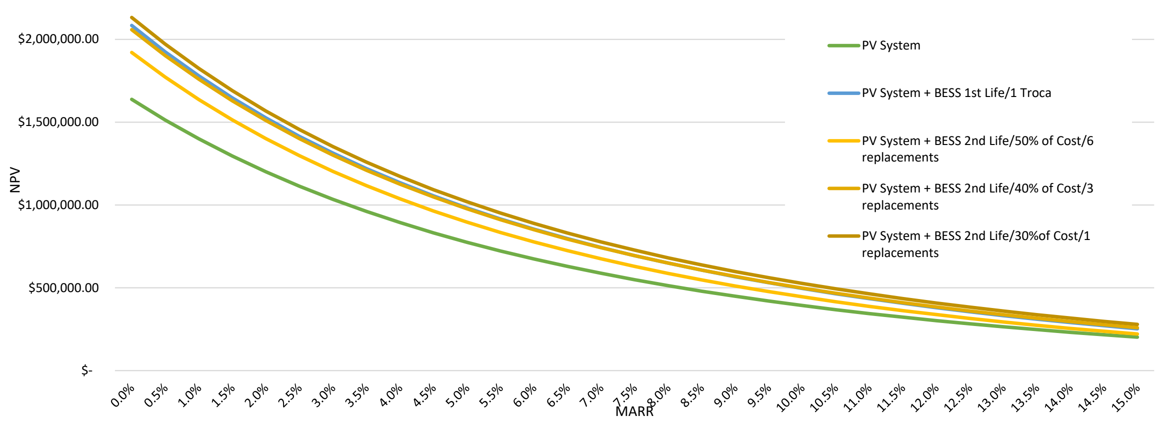

Figure 4 - NPV values for the five scenarios.

Figure 4 demonstrates that across all five scenarios. The initial NPV values decrease as the MARR increases, and the standalone PV system exhibits the lowest NPV compared to the other scenarios. The scenario utilizing PV + 2nd Life BESS (30% cost/1 replacement) yielded the highest NPV, followed by the PV + 1st Life BESS scenario.

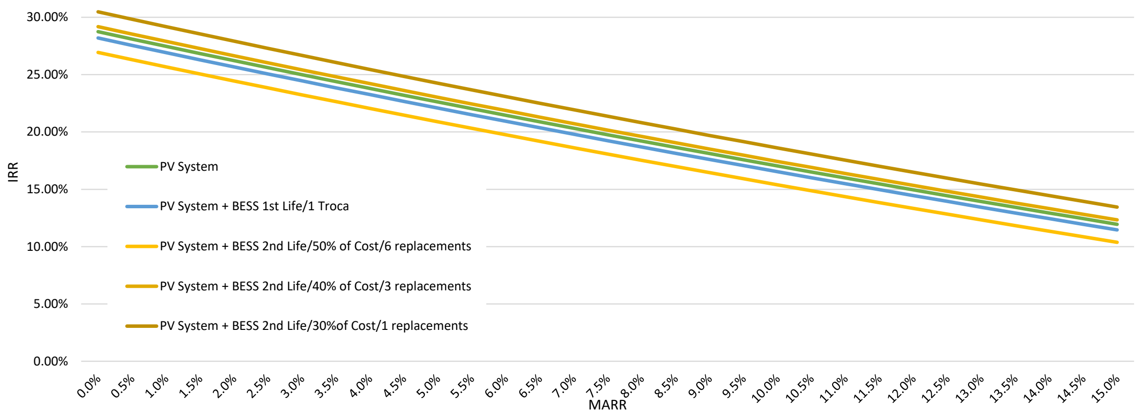

Figure 5 - IRR values for the five scenarios.

Figure 5 shows that IRR values decrease as the MARR increases across all scenarios. and the standalone PV system possesses the third highest IRR compared to the remaining scenarios. Notably, the PV + 2nd Life BESS (30% cost/1 replacement) scenario produced the optimal result, while the standalone PV system and the PV + 1st Life BESS scenario exhibited virtually equivalent performance, with a maximum difference of 0.56% for the same MARR values.

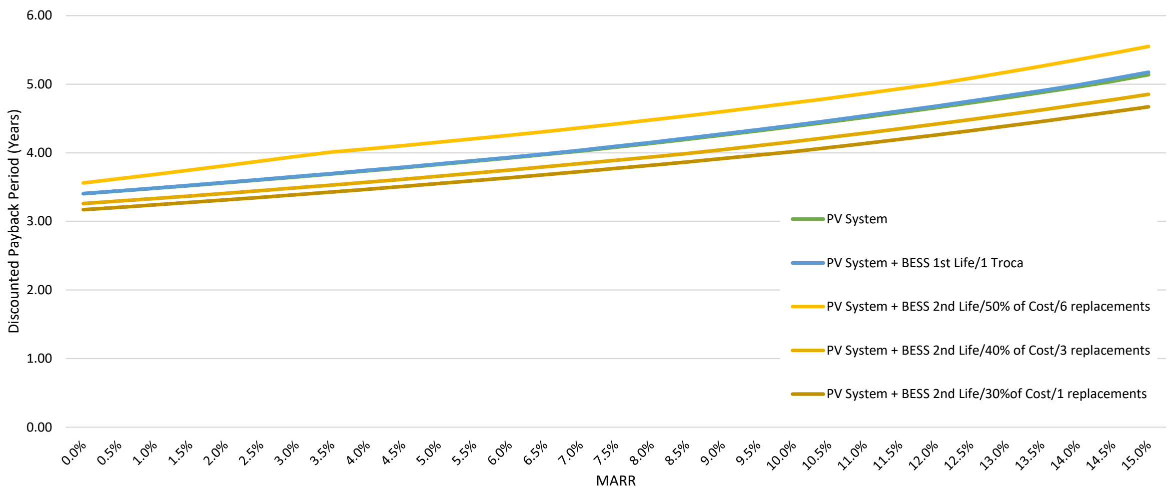

Figure 6 - Discounted payback values for the five scenarios.

Figure 6 demonstrates that payback values increase as the MARR increases in all scenarios. Although the standalone PV system is superior. it exhibits virtually identical behavior to the PV + 1st life BESS system. The PV + 2nd Life BESS (30% cost/1 replacement) scenario yielded the lowest payback value. The PV + 1st life BESS system and the standalone PV system have a maximum difference of 14 days for the same MARR values.

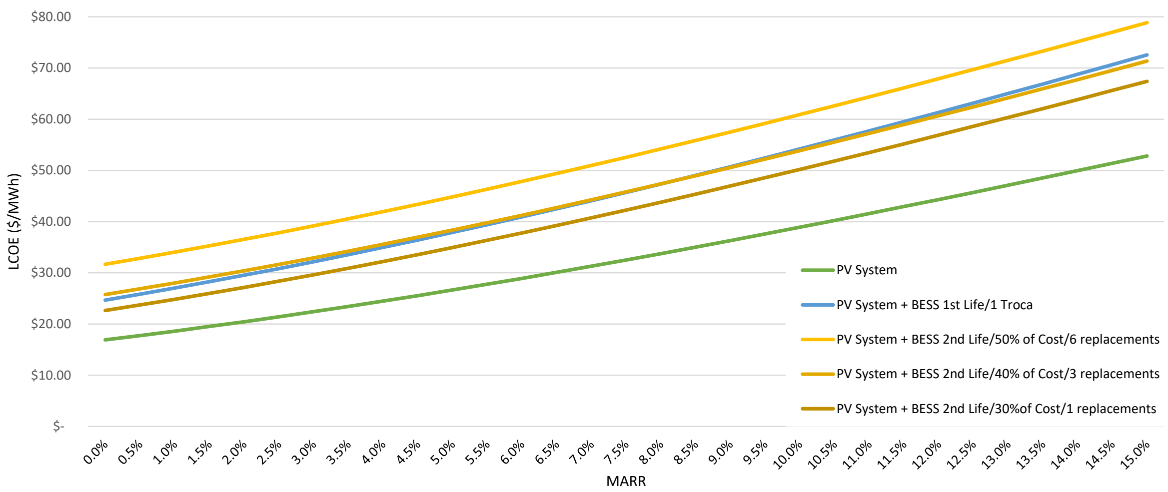

Figure 7 - LCOE values for the five scenarios.

Based on Figure 7. across the five scenarios. it can be primarily observed that LCOE values increase with the growth of the MARR. and the standalone PV system presents the lowest LCOE. The PV + 2nd Life BESS (40% cost/3 replacement) and the PV + 1st life BESS system had very close LCOE values, with a maximum difference of $1.20 for the same MARR value. The standalone PV system shows a difference of $5.74 to $14.57 from the second lowest LCOE (PV + 2nd Life BESS (30% cost/1 replacement)) for the same MARR value.

4. Conclusion

In this study. A detailed analysis was carried out to evaluate the technical and economic viability of integrating PV and 1st life and 2nd life BESS in university campuses.

The primary focus of the analysis was, first, to compare the financial attractiveness of PV systems with 1st life and 2nd life BESS, considering an IRR of 14% across various scenarios where the cost of second-life batteries varied between 30% and 70% in comparison to first-life values, and the number of battery replacements ranged from 1 to 6 over the project's lifetime.

The second analysis compared the economic viability using the NPV. IRR, Payback, and LCOE indicators over a 25-year projection in five scenarios with a variable MARR (0% - 15%), assuming 50% simultaneity: (i) the Consumer Unit with only the PV system; (ii) the Consumer Unit with the PV + 1st Life BESS system; (iii) the Consumer Unit with PV + 2nd life BESS integration with 50% of the 1st life battery cost and 6 battery replacements; (iv) the Consumer Unit with PV + 2nd life BESS integration with 40% of the 1st life battery cost and 3 battery replacements; and (v) the Consumer Unit with PV + 2nd life BESS integration with 30% of the 1st life battery cost and 1 battery replacement.

The PV system exhibits an annual generation of 875.3 MWh with a capacity of 712 kWp, an average annual PR of 81.7%, and an annual yield of 1.23 MWh/kWp.year. The implementation cost for the PV system was $ 282,210 ($ 0.40/Wp), and the cost of replacing the inverter was $ 42,331 scheduled for the tenth year of the project.

The 1st life BESS has a capacity of 534.34 kWh and a power rating of 487 kW, with an initial cost of $ 96,764 ($ 180/kWh) and one replacement over the project duration. The 2nd life BESS has a capacity of 763 kWh and a power rating of 487 kW, with initial costs ranging from $ 109,620 ($ 143/kWh) down to $ 71,467 ($ 93/kWh). involving one to six battery replacements and one replacement of the remaining equipment.

The hybrid PV + 1st life BESS system yielded IRR and discounted payback results very similar to the standalone PV system. However, the 1st life BESS achieved a significantly higher NPV result compared to the standalone PV system. Therefore, the PV + 1st life BESS system demonstrates superior financial attractiveness compared to the standalone PV system.

The hybrid PV + 2nd life BESS systems become more financially attractive than the PV + 1st life BESS systems when the cost of the 2nd life battery is 50% lower than the 1st life battery. provided the project does not exceed three replacements. For even lower second-life battery costs, the financial attractiveness remains superior even with a higher number of replacements. Due to second-life batteries being a recent application of technology, the values assumed for the studied scenarios are inherently linked to market uncertainties (Kampter et al., 2023).

The financial analysis conducted in this study employs the case of a Consumer Unit belonging to CELESC's Group A4 – Green within the UFSC university campus. The CDS UFSC Consumer Unit is situated in one of the regions of Brazil with the lowest solar incidence. thereby operating outside the optimal conditions for PV utilization. and is served by one of the utilities with the lowest energy taxation rates in Brazil. Furthermore. the study examines the cost perspective of first-life and second-life batteries without factoring in changes to tax collection policies or governmental program incentives.

In Brazil, there is still no robust regulatory framework regarding the integration of energy storage systems into the electrical grid, and second-life battery applications remain rare. However, recent public consultations have demonstrated an effort by Brazilian regulatory bodies to develop a regulatory basis for the connection of storage systems to the grid. Moreover, the growth of the national electric vehicle market may represent a promising prospect for the expansion of second-life battery applications.

Additionally, it is important to consider that CELESC is one of the utilities with the smallest tariff differential between peak and off-peak hours (ANEEL, 2025) and is located in one of the regions with the lowest solar irradiance in the country. These factors suggest the relevance of analyzing the feasibility of hybrid systems in other regions of Brazil, where tariff structures and irradiance conditions may be more favorable.

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