



An Optimization Model to Reduce Cooling Energy Consumption in Urban Battery Energy Storage Systems

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ABSTRACT

The increasing deployment of battery energy storage systems in urban areas necessitates advanced thermal management to ensure efficiency and prolong battery lifespan. This paper presents an integrated optimization model designed to minimize the energy consumption of cooling systems. By accounting for energy and heat balances alongside temperature-dependent calendar aging, this model evaluates two cooling strategies: an air-conditioning-only system and a hybrid system that combines forced ventilation and air conditioning. A case study in the metropolitan region of São Paulo, Brazil, was conducted to show the gains of the proposed model. The results show that the hybrid approach significantly reduces cooling energy consumption and operational costs, particularly under milder conditions where ventilation alone is adequate. These findings highlight the model's potential to support the design of controllers and implementation studies for effective thermal management, demonstrating the importance of balancing energy efficiency and battery longevity for sustainable operation of energy storage systems.

Keywords: Battery energy storage system; Battery Degradation; Thermal Management; Hybrid Cooling System.

1 INTRODUCTION

Battery Energy Storage Systems (BESS) have evolved rapidly since the beginning of the last decade, driven by the growing demand for technologies that support grid operation and stability. BESS has become an indispensable component of the energy transition, providing services ranging from frequency regulation and fast demand response to the integration of intermittent renewable sources (HASAN et al., 2017; GUANGMING et al., 2014).

The increasing penetration of solar and wind power has intensified the reliance on storage systems to absorb excess generation and supply deficits, thereby enhancing resource utilization and improving system stability (WANG et al., 2018).

The safe and cost-effective operation of battery systems strongly depends on thermal management and degradation control, as elevated temperatures and deep depth-of-discharge (DoD) accelerate capacity fade and internal resistance growth (APRIBOWO et al., 2022; RAHMAN et al., 2024).

Although Heating, Ventilation, and Air Conditioning (HVAC) systems and State of Charge (SoC) management strategies mitigate these effects, continuous cooling in containerized systems—particularly under hot climates—increases internal energy consumption and operational costs, ultimately undermining energy autonomy (ENGELHARDT et al., 2022; HE; LI; MA, 2014).

In this context, this work proposes an integrated energy and thermal management model for containerized BESS, aiming to reduce reliance on cooling systems without compromising thermal safety or battery lifespan. The model combines the thermal balance of internal air, walls, and battery, calendar degradation dependent on temperature and SoC, and energy management



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considering the electricity market and photovoltaic generation. The cooling system is hybrid, combining forced ventilation and air conditioning. The formulation yields a Mixed-Integer Nonlinear Programming (MINLP) problem, which is solved offline over a daily horizon to inform the operational decisions for the following day. The main contributions are the integration of thermal dynamics and energy management, the inclusion of calendar degradation in the objective function, and an analysis of two levels of cooling system modeling in terms of energy consumption and battery aging.

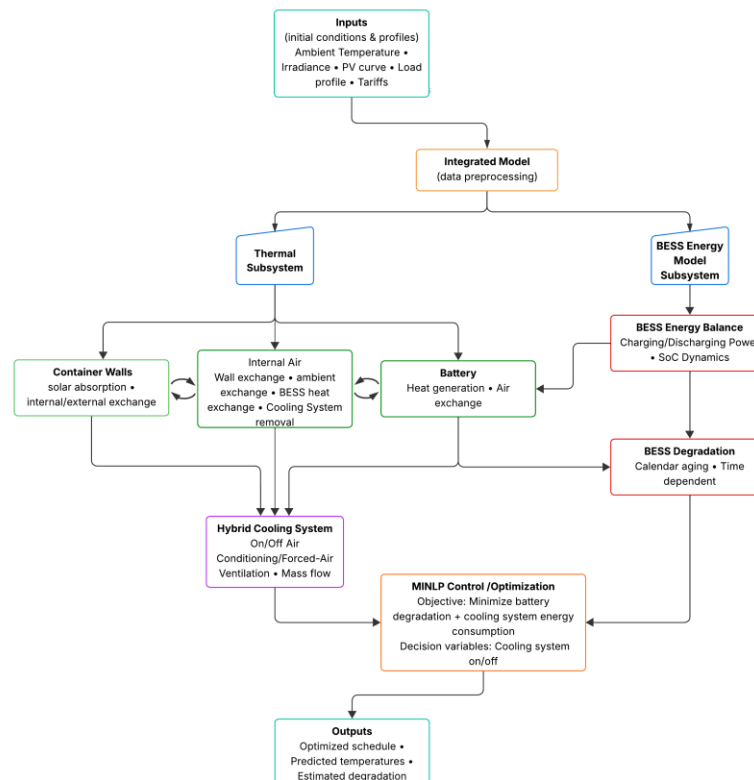
2 PROPOSED METHODOLOGY

Figure 1 illustrates the proposed methodology for the multi-criteria optimization model for thermal and energy management of containerized BESS. The model considers input parameters such as ambient temperature, solar irradiance, PV generation profile, and consumer demand, integrating the system's thermal, energy, and degradation modeling.

In the thermal subsystem, heat generation by the BESS, solar absorption by the container walls, heat exchanges with the environment, and heat removal by the hybrid cooling system are considered. The energy balance is calculated based on the SoC and charge/discharge power, while battery degradation is represented by calendar aging, accounting for time, temperature, and state of energy.

The control strategy is formulated as a MINLP problem, aiming to simultaneously minimize the cooling system's energy consumption and BESS degradation while satisfying operational constraints. The model provides optimized operation strategies, internal temperature predictions, and estimates of battery degradation.

Figure 1 - Flowchart of the Proposed Methodology.





The objective function of the model simultaneously minimizes the energy cost of the hybrid cooling system and the loss of BESS lifetime through a calendar degradation term:

$$\text{Min } z = \sum_{t \in \mathcal{T}} (P_t^{\text{Grid}} \cdot \tau \cdot C_t^{\text{rate}} + \Delta E_t^{\text{cal}} \cdot C^{\text{BESS}}) \quad (1)$$

The first term ($P_t^{\text{Grid}} \cdot \tau \cdot C_t^{\text{rate}}$) represents the cost of grid electricity (R\$), i.e., the power drawn from the grid multiplied by the time step τ and the electricity tariff. The second term ($\Delta E_t^{\text{cal}} \cdot C^{\text{BESS}}$) accounts for the cost of calendar degradation of the BESS (R\$). The degradation increment, ΔE_t^{cal} , is computed on an hourly basis using an empirical expression that depends on elapsed time, stored energy, and battery temperature (AMINI et al., 2024):

$$\Delta E_t^{\text{cal}} = \left[\left(\frac{t}{720} \right)^{0.8} - \left(\frac{t-1}{720} \right)^{0.8} \right] \cdot (0.0081 \cdot E_t^{\text{BESS}} + 0.005764 \cdot E_{\text{rate}}^{\text{BESS}}) \cdot (3.258 \times 10^{-19} \cdot T_t^{b, 5.087} + 0.295) \quad (2)$$

The energy stored in the BESS evolves according to the following balance, which accounts for self-discharge losses (δ^{sd}), charging, and discharging:

$$E_t^{\text{BESS}} = E_{t-1}^{\text{BESS}} \cdot (1 - \delta^{\text{sd}}) + P_{t-1}^{\text{BESS}, \text{chr}} \cdot \tau \cdot \eta^{\text{chr}} - \frac{P_{t-1}^{\text{BESS}, \text{dis}}}{\eta^{\text{chr}}} \cdot \tau \quad (3)$$

The BESS operating mode is defined by three mutually exclusive binary variables: charging (u_t^{chr}), discharging (u_t^{dis}) and idle (u_t^{idle}).

Thermal dynamics of the BESS-container system is discretized by Euler's method with time step τ . The following equations describe the temperature evolution of the internal air (T_t^r), the container walls (T_t^w), and the batteries (T_t^b):

$$T_t^r = T_{t-1}^r + \frac{\tau}{M^r \cdot c^{\text{air}}} \left[\frac{T_{t-1}^{\text{amb}} - T_{t-1}^r}{R^{\text{amb}, r}} + \frac{T_{t-1}^w - T_{t-1}^r}{R^{\text{win}, r}} + N^{\text{racks}} \cdot h^b \cdot A^{\text{racks}} \cdot (T_{t-1}^b - T_{t-1}^r) \right. \\ \left. + u_t^{\text{fans}} \cdot N^{\text{racks}} \cdot \dot{m}_{t-1}^{\text{fans}} \cdot c^{\text{air}} \cdot (T_{t-1}^{\text{amb}} - T_{t-1}^r) + u_t^{\text{arc}} \cdot \dot{m}_{t-1}^{\text{arc}} \cdot c^{\text{air}} \cdot (T_{t-1}^c - T_{t-1}^r) + \delta \right] \quad (4)$$

$$T_t^w = T_{t-1}^w + \frac{\tau}{M^w \cdot c^w} \left[\frac{T_{t-1}^{\text{amb}} - T_{t-1}^w}{R^{\text{wex}, r}} + \frac{T_{t-1}^r - T_{t-1}^w}{R^{\text{win}, r}} + \alpha^w \cdot G_t \cdot A^w \right] \quad (5)$$

$$T_t^b = T_{t-1}^b + \frac{\tau}{C^{\text{th}, \text{tot}}} [I^2 \cdot R_{t-1}^{\text{int}} - I \cdot V_{t-1} - N^{\text{racks}} \cdot h^b \cdot A^{\text{racks}} \cdot (T_{t-1}^b - T_{t-1}^r)] \quad (6)$$

The parameters are defined as follows:

- Internal air: M^r (mass of air in the container), c^{air} (specific heat of air), $R^{\text{amb}, r}$ (thermal resistance between ambient and container), $R^{\text{win}, r}$ (thermal resistance between walls and container interior), N^{racks} (number of racks), h^b (heat transfer coefficient between battery and air), A^{racks} (rack surface area), $\dot{m}_{t-1}^{\text{fans}}$ and $\dot{m}_{t-1}^{\text{arc}}$ (air mass flow rates of forced ventilation and air-conditioning), δ (heat released by auxiliary equipment), T_t^c (air-conditioning supply air temperature), and T_t^{amb} (ambient temperature);
- Walls: M^w (thermal mass of walls), c^w (specific heat of walls), $R^{\text{wex}, r}$ (thermal resistance between ambient and walls), α^w (solar absorptivity), G_t (solar irradiance), and A^w (wall surface area);
- Batteries: $C^{\text{th}, \text{tot}}$ (thermal capacitance of the battery bank), I (cell current), R^{int} (internal resistance), and V (entropic potential of the cells).



The electrical consumption of the hybrid cooling system is modeled as the sum of forced ventilation and air-conditioning power:

$$P_t^{HVAC} = u_t^{fans} \cdot P_{rated} \cdot f_t^{fans^3} + u_t^{arc} \cdot \left(P_{rated} \cdot f_t^{arc^3} + \frac{c^{air} \cdot m_t^{arc} \cdot [k \cdot T_t^r + (1-k) \cdot T_t^{amb} - T_t^c]}{\eta^{arc} \cdot COP} \right) \quad (7)$$

Here, P_{rated} is the rated fan power, f_t^{fans} and f_t^{arc} are normalized air-flow ratios (with cubic dependence for fan laws), k is the recirculation factor, η^{arc} is the sensible heat ratio, and COP is the coefficient of performance. The binary variables u_t^{fans} and u_t^{arc} enforce exclusive operation of the two subsystems (no simultaneous operation).

Finally, the system-level power balance is given by:

$$P_t^{grid} + P_t^{PV} + P_t^{BESS,dis} = P_t^{demand} + P_t^{HVAC} + P_t^{BESS,chr} + P_t^{sell} \quad (8)$$

Where P_t^{PV} and P_t^{demand} represent known PV generation and demand profiles. Additional operational constraints can be included, such as prohibiting BESS charging during nighttime hours and limiting energy sales, P_t^{sell} , to periods when PV generation exceeds total demand.

3 RESULTS AND DISCUSSION

The model was applied to a containerized BESS with external dimensions of 400 cm × 244 cm × 259 cm. The system has a nominal capacity of 250 kWh / 250 kW and consists of 5 battery racks, each containing 16 modules. Each module houses 14 cell blocks, with each block having a capacity of 3.91 V and 57 Ah. The cell blocks are connected in series, as are the modules, while the racks are connected in parallel. For BESS parameterization, a lithium-ion technology with lithium iron phosphate (LiFePO₄) chemistry was considered.

The demand profile was constructed based on the estimated consumption of 15 households, with an average demand of 1.9024 kVA, resulting in a total monthly consumption of 1,277.66 kWh. The photovoltaic generation profile was based on a 10 kWp system.

In the study, the BESS model equipped with a hybrid cooling system (forced ventilation combined with air conditioning) was compared to a model using air conditioning exclusively. The considered temperature ranges were: 20–28 °C for the internal air of the container, 25–35 °C for the batteries, and 15–35 °C for the container walls. The initial conditions adopted were: 22 °C for the internal air, 28 °C for the batteries, and 15 °C for the walls.

The analysis was conducted over a one-year period, from November 2023 to October 2024, with results presented for two representative months: November 2023 (hotter) and July 2024 (colder). Historical data on ambient temperature and solar irradiance were obtained from three meteorological stations located in Santo André, SP, Brazil, with records at 15-minute intervals. These data underwent statistical preprocessing, including outlier removal, imputation of missing values via multiple linear regression, and smoothing using a moving average filter.

Table I presents the daily results of grid energy purchases and the battery calendar degradation rate for both cooling strategies. The results correspond to a selection of days from each analyzed month. The data indicate that the hybrid cooling system significantly reduces both grid energy consumption and associated costs compared to the exclusive use of air conditioning, with this effect being more pronounced in the hotter month than in the cooler month. On hotter days, the fans alone help mitigate the



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thermal load, reducing the need for continuous air conditioning operation and thereby providing immediate energy and cost savings. However, on some days, the degradation term exhibits slightly higher values under the hybrid scenario, reflecting a marginal increase in battery aging due to temperature variations that enable energy savings. For the entire months, total degradation in the hybrid system was 1.168 kWh in November 2023, compared to 1.138 kWh for the air conditioning-only system; for July 2024, degradation was identical in both scenarios, amounting to 1.191 kWh.

Table 1 - Optimization of grid energy purchase cost and BESS degradation.

Day	Hybrid Cooling System								Air Conditioning System							
	November 2023				July 2024				November 2023				July 2024			
	BD	BDC	EC	CC	BD	BDC	EC	CC	BD	BDC	EC	CC	BD	BDC	EC	CC
01	0.077	0.021	47.23	3.23	0.084	0.023	50.671	5.605	0.067	0.0182	82.19	5.67	0.075	0.020	83.63	9.26
03	0.052	0.014	60.57	4.17	0.056	0.015	50.704	5.746	0.047	0.0128	84.88	5.86	0.051	0.014	84.76	9.26
05	0.042	0.011	27.65	2.08	0.045	0.012	47.606	5.269	0.043	0.0117	67.24	4.64	0.048	0.013	73.52	8.15
07	0.038	0.010	56.59	3.91	0.041	0.011	43.911	3.434	0.039	0.0106	77.76	5.37	0.042	0.012	68.61	4.19
09	0.041	0.011	72.18	5.02	0.044	0.012	41.016	3.960	0.037	0.0100	87.96	6.07	0.041	0.011	86.85	8.38
11	0.038	0.010	75.60	5.22	0.038	0.010	40.883	3.859	0.037	0.0100	84.14	5.81	0.039	0.011	75.19	7.09
13	0.041	0.011	82.61	5.70	0.035	0.009	42.179	3.279	0.038	0.0103	89.38	9.51	0.033	0.009	75.67	5.88
15	0.033	0.009	82.62	5.70	0.039	0.010	31.146	2.532	0.036	0.0098	82.10	5.67	0.035	0.009	69.96	5.31
17	0.040	0.011	76.12	5.26	0.033	0.009	43.752	3.371	0.041	0.0111	86.15	5.95	0.037	0.010	63.03	4.86
19	0.038	0.010	44.60	3.08	0.035	0.009	32.575	2.513	0.038	0.0103	84.91	5.86	0.036	0.010	66.86	5.18
21	0.035	0.010	60.98	4.21	0.032	0.009	41.230	2.525	0.028	0.0076	87.41	6.03	0.033	0.009	63.86	3.91
23	0.036	0.010	63.20	4.64	0.032	0.009	36.882	2.550	0.028	0.0076	90.47	6.25	0.035	0.010	72.53	5.02
25	0.028	0.008	46.44	3.09	0.031	0.008	37.206	2.596	0.033	0.0090	74.67	5.16	0.034	0.009	63.84	4.45
27	0.032	0.009	55.26	3.82	0.030	0.008	40.284	2.776	0.034	0.0092	83.17	5.74	0.034	0.009	66.45	4.60
29	0.033	0.009	57.57	3.97	0.034	0.009	30.518	2.413	0.035	0.0095	81.05	5.60	0.035	0.010	74.47	5.48

Note: BD – Battery degradation (kWh); BDC – Cost of battery degradation (R\$); EC – Energy purchased from the grid (kWh); CC – Cost of purchased energy (R\$).

By aggregating the daily results (Table II) on a monthly basis, it was observed that the hybrid configuration reduced grid energy consumption by 24.91% in November 2023 and by 43.9% in July 2024. In monetary terms, the gross energy savings amounted to R\$ 44.36 in the hottest month and R\$ 78.89 in the coldest month. However, the increase in degradation observed in September resulted in an additional cost of R\$ 0.008.

Table 2 - Aggregated Metrics: Hybrid vs Air Conditioning.

Month	EC_ARC	EC_H	EC_R	CC_ARC	CC_H	CC_R	BDC_ARC	BDC_H	BDC_R
November 2023	2478.56	1861.11	24,91%	174.46	130.1	44.36	0.308	0.317	-0.008
July 2024	2181.65	1223.85	43.9%	182.5	103.60	78.89	0.324	0.321	0.003

Note: EC_AC – Energy consumption of the grid due to the air conditioning system (kWh); EC_H – Energy consumption of the grid due to the hybrid cooling system (kWh); EC_R - Percentage reduction in energy consumption (%); CC_AC – Energy cost of the grid due to the air conditioning system (R\$); CC_H – Energy cost of the grid due to the hybrid cooling system (R\$); CC_R – Gross energy savings due to the hybrid cooling system (R\$); BDC_ARC – Battery degradation cost associated with the air conditioning system (R\$); BDC_H – Battery degradation cost associated with the hybrid cooling system (R\$); BDC_R – Variation in degradation cost due to the hybrid cooling system (R\$).

Figure 2 illustrates the daily energy consumption of the cooling system under the two tested scenarios. In both months, the hybrid system consistently consumes less energy, highlighting the ability of forced ventilation to reduce the thermal load on the cooling system. The difference between scenarios is particularly pronounced in July, when the Hybrid Cooling System achieves a 73.84% reduction compared to the Air Conditioning System. In September, the reduction remains significant, reaching 39.56%.



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Figure 2. Optimized energy consumption of the cooling system.

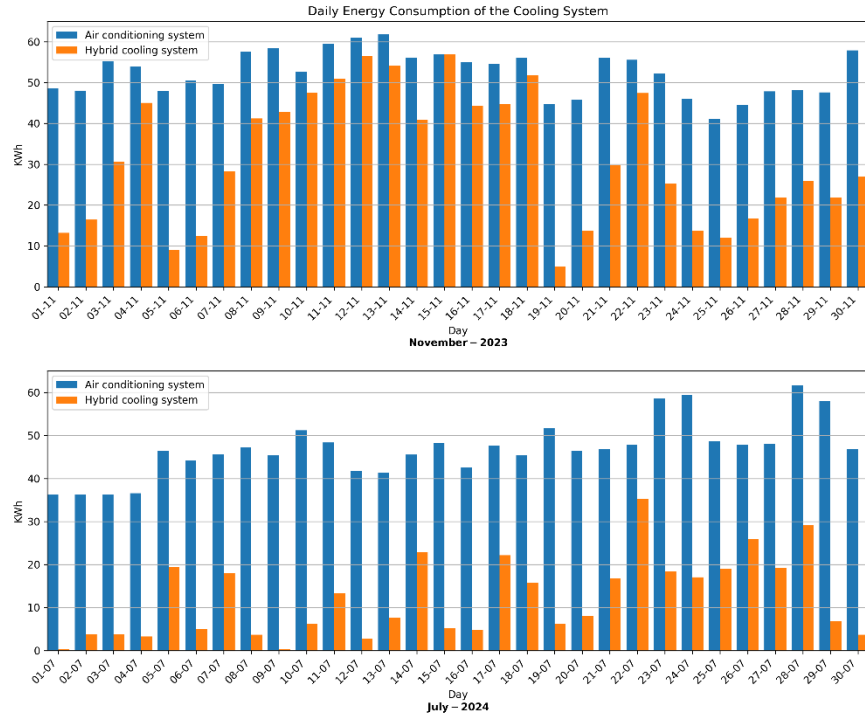
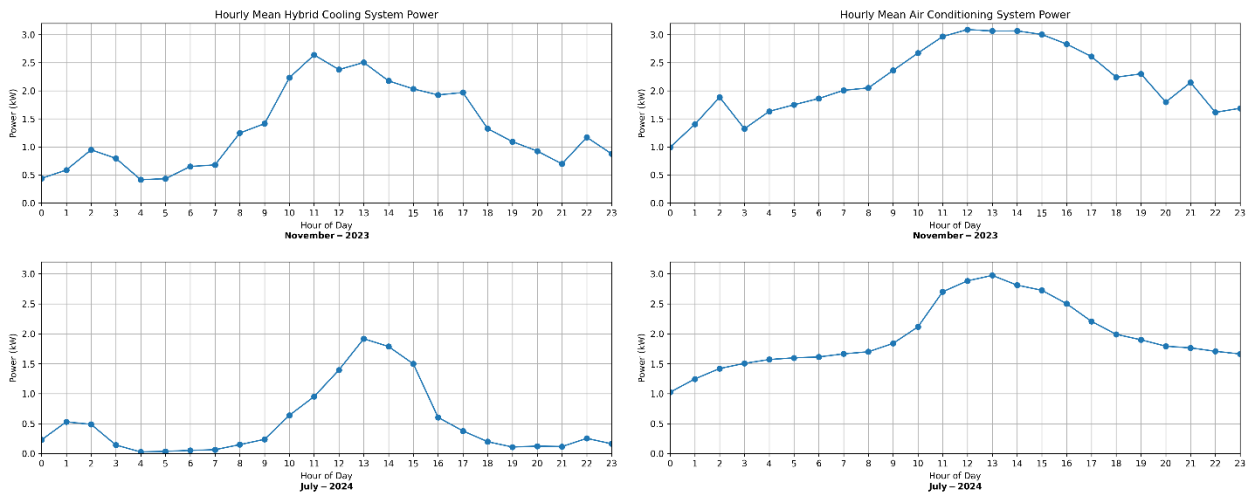


Figure 3, in turn, shows the average hourly power of the cooling system for the two scenarios. In all four subplots, it can be observed that the configuration with an exclusive air-conditioning system maintains a higher baseline power throughout the day, with pronounced peaks between 11:00 and 14:00 (around 3 kW), whereas the hybrid system exhibits a much lower baseline power during the night and smaller, more intermittent peaks—particularly in July, when the difference between the scenarios is most evident. In November, the values are higher in both cases, with smaller advantages for the hybrid system. In summary, the profiles confirm that the forced ventilation of the hybrid system significantly alleviates the load on the cooling cycle, reducing both energy consumption and power peaks, which leads to lower electricity costs and reduced peak demand.

Figure 3. Optimized cooling system power.





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Figure 4 presents the hourly average temperature values of the system. The results show that, in November 2023, under the hybrid scheme, the batteries experienced continuous fluctuations exceeding 32.5°C compared to the scenario with air-conditioning-only operation over the same period. This thermal difference explains why calendar aging was slightly higher in the hybrid case, since this type of degradation depends on both the battery temperature and the state of charge — that is, both the intensity of thermal peaks and the duration during which the battery remains at high temperatures increase the aging rate.

Furthermore, as shown in Figure 5, the SOC trajectory under hybrid operation remained, on average, higher than in the air-conditioning-only operation, indicating that the BESS prioritized higher charging during the day to discharge at night. In summary, the hybrid scheme reduces HVAC energy consumption but allows for higher thermal exposures and different SOC profiles. These conditions — in terms of both amplitude and duration — are the direct cause of the observed increase in calendar aging.

Figure 4. Optimized system temperatures.

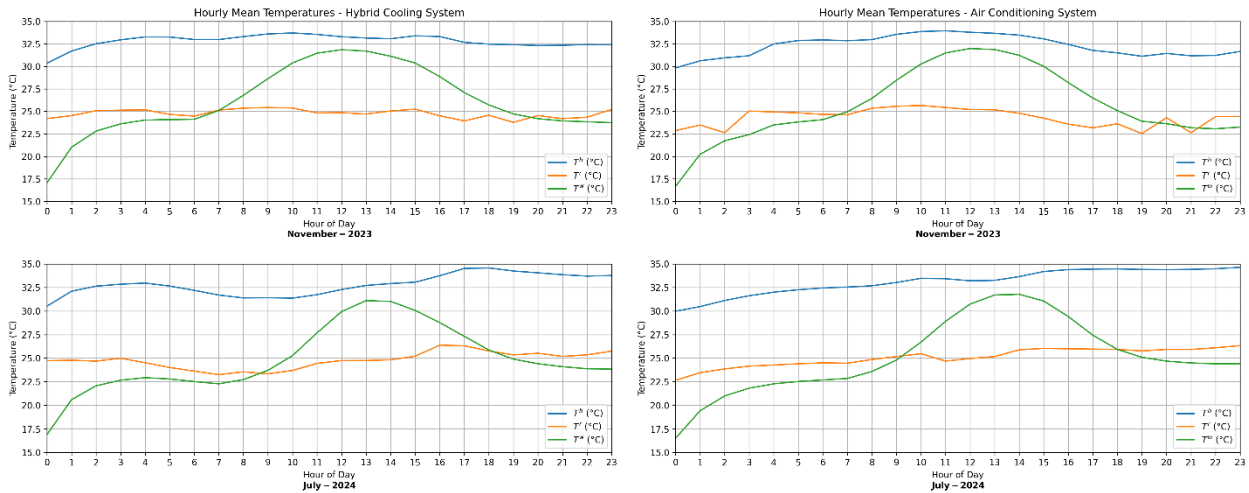
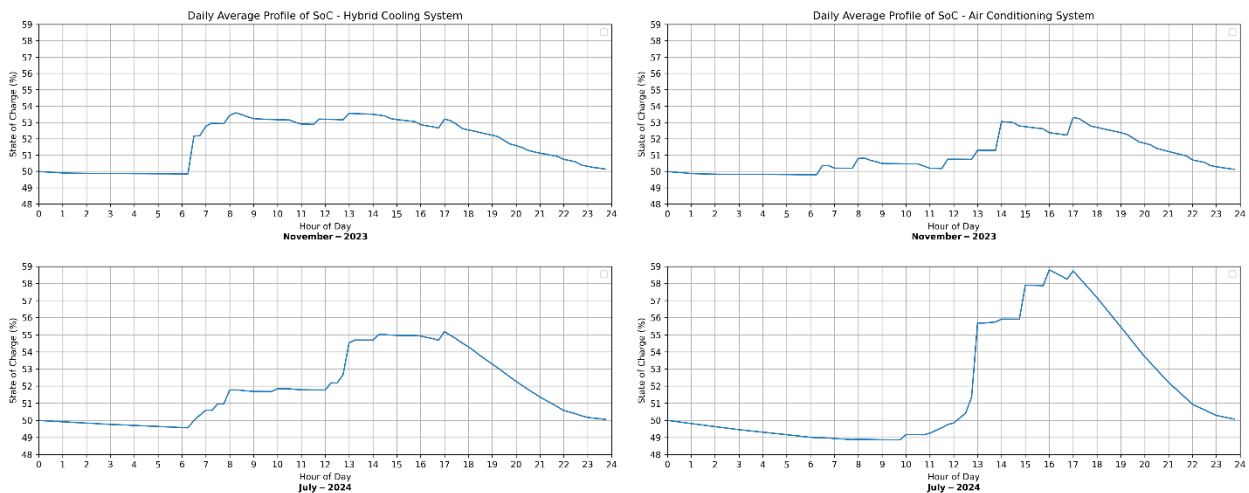


Figure 5. Optimized BESS State of Charge.





4 CONCLUSIONS

The results indicate that the cooling strategy affects both the energy performance and the degradation of the storage system. The hybrid system proved effective in reducing air-conditioning power consumption. However, this configuration resulted in higher battery temperatures, which increased calendar aging. In contrast, the exclusive air-conditioning system required higher energy consumption but maintained more stable battery temperatures, thereby reducing degradation.

In summary, the findings suggest a relationship of exchange: lowering energy consumption comes at the expense of higher battery temperatures, whereas ensuring tighter thermal control requires increased energy use. This implies that the choice of the optimal cooling strategy should take into account not only the immediate energy efficiency benefits but also the long-term effects on BESS lifetime and thermal stability.

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REFERENCES

- AMINI, Mohammad; SANJAREH, Mehrdad Bagheri; NAZARI, Mohammad Hassan; et al. A Novel Model for Battery Optimal Sizing in Microgrid Planning Considering Battery Capacity Degradation Process and Thermal Impact. *IEEE Transactions on Sustainable Energy*, v. 15, n. 3, p. 1435–1449, 2024. Available at: < <https://ieeexplore.ieee.org/document/10379842/>>. Accessed on: Aug. 2025.
- APRIBOWO, Chico Hermanu Brillianto; SARJIYA, Sarjiya; HADI, Sasongko Pramono; et al. Optimal Planning of Battery Energy Storage Systems by Considering Battery Degradation due to Ambient Temperature: A Review, Challenges, and New Perspective. *Batteries*, v. 8, n. 12, p. 290, 2022. Available at: < <https://www.mdpi.com/2313-0105/8/12/290>>. Accessed on: Aug. 2025.
- ENGELHARDT, J.; ZEPETTER, J. M.; GABDERAKHMANOVA, T.; MARINELLI, M. Energy management of a multi-battery system for renewable-based high power EV charging. *Preprint eTransportation*, 2022. Accessed on: Feb. 2025.
- GUANGMING, L. et al. Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors. *Journal of Thermal Analysis and Calorimetry*, v. 116, n. 2, p. 1001–1010, 2014. Accessed on: Feb. 2025.
- HASAN, M. M.; POURMOUSAVI, S. A.; BAI, F.; SAHA, T. K. The impact of temperature on battery degradation for large-scale BESS in PV plant. In: *Proceedings of the Australasian Universities Power Engineering Conference (AUPEC)*, 2017. Accessed on: Feb. 2025.
- HE, F.; LI, X.; MA, L. Combined experimental and numerical study of thermal management of battery module consisting of multiple li-ion cells. *International Journal of Heat and Mass Transfer*, v. 72, p. 622–629, 2014. Accessed on: Feb. 2025.
- RAHMAN, Tuhibur; ALHARBI, Talal. Exploring Lithium-Ion Battery Degradation: A Concise Review of Critical Factors, Impacts, Data-Driven Degradation Estimation Techniques, and Sustainable Directions for Energy Storage Systems. *Batteries*, v. 10, n. 7, p. 220, 2024. Available at: < <https://www.mdpi.com/2313-0105/10/7/220>>. Accessed on: Aug. 2025.