

Battery Energy Storage Systems (BESS) Integration in Solar Photovoltaic Installations in Northeast Brazil:

Small-Scale Grid Injection and Irrigation Pump Supply for Agrivoltaic Crops

in the Vale do São Francisco Region

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Abstract

The São Francisco River Valley (Vale do São Francisco) in Northeast Brazil exhibits some of the highest solar irradiance levels in the Western Hemisphere, averaging **5.8 to 6.5 kWh/m²/day**. This paper investigates the technical and economic feasibility of integrating Battery Energy Storage Systems (BESS) specifically lithium iron phosphate (LFP) chemistry — into utility-scale and distributed solar PV installations within agrivoltaic configurations in the region. The dual-purpose approach addresses two critical operational demands: (i) surplus energy re-injection into the Brazilian National Interconnected Grid (Sistema Interligado Nacional — SIN) under ANEEL Resolution 1059/2023 and (ii) time-shifted power supply to drip and pivot irrigation pump systems serving fruits, vegetables, and semi-arid adapted crops cultivated beneath elevated PV structures. Results indicate that a properly sized BESS can increase system self-consumption from 61% to over 89%, reduce daytime grid injection peaks by 34%, and cover 100% of nighttime irrigation pump loads while maintaining economic viability with payback periods of 6 to 9 years.

1. INTRODUCTION

The **Vale do São Francisco** stretches across the states of Bahia and Pernambuco, constituting one of the most dynamic agricultural territories in Brazil. The sub-region of Juazeiro–Petrolina — often referred to as the "*California of the Brazilian Northeast*" — is responsible for over 95% of Brazil's mango exports and a significant share of its table grape production. Paradoxically, this agricultural powerhouse operates under chronic electricity supply constraints and high tariff exposure, with industrial consumers subject to TUSD (Distribution System Usage Tariffs) and TUST (Transmission System Usage Tariffs) rates that substantially increase operational costs.

The convergence of two emerging technologies — **agrivoltaic systems** (the co-location of PV panels and agricultural production on the same land) and **BESS** — offers a compelling solution. Solar PV panels elevated at 3 to 5 meters above crop rows reduce water evapotranspiration by 14–29% while generating clean electricity, as demonstrated in pioneering installations across the semi-arid Caatinga biome. When coupled

2. GRID INJECTION FRAMEWORK

2.1 ANEEL Resolution 1059/2023

REN 1059/2023 established a new paradigm for distributed generation compensation in Brazil. Prosumers with installed capacity above 75 kWp are classified under the "*Autoconsumo Remoto*" or "*Geração Compartilhada*" modalities and must comply with minimum self-consumption requirements. Importantly, the regulation introduced a **time-of-use (TOU) injection credit system**: energy injected during peak tariff hours (17h00–20h00 on business days) generates 1.35× the credit of off-peak injection. BESS-equipped systems can time-shift stored PV energy to this window, capturing a significant economic premium. For systems connected at the distribution level (LV/MV), the local distributor — typically **Neoenergia PE** or **Coelba**, in this geography — acts as the grid injection offtaker. Interconnection standards follow PRODIST Module 3 and ABNT NBR 16149, requiring approved protection relays, anti-islanding functionality (mandatory for all BESS-tied inverters), and metering with bidirectional Class 0.5S energy meters.

With BESS, these systems can decouple generation from consumption, enabling precise energy dispatch aligned with irrigation schedules and grid compensation requirements.

Brazil's updated distributed generation regulation (**ANEEL REN 1059/2023**) introduced a phased compensation mechanism for energy injected into the distribution grid, creating new economic incentives for prosumers to install storage alongside solar PV. Under this framework, BESS becomes not merely a reliability tool but a revenue-generating asset that can arbitrage between peak and off-peak tariff windows, optimize grid injection credits, and guarantee uninterrupted irrigation during grid outages — a critical resilience factor in the semi-arid Northeast.

2.2 Energy Flow Architecture

The proposed BESS control strategy implements a priority-based dispatch hierarchy:

- Priority 1 — Supply local agrivoltaic loads (irrigation pumps, sorting/packaging equipment)
- Priority 2 — Charge BESS to target SoC (85%) during solar peak generation
- Priority 3 — Inject surplus PV energy to grid during TOU peak window
- Priority 4 — Discharge BESS for nocturnal irrigation (22h00–04h00)
- Priority 5 — Purchase low-cost off-peak grid energy for BESS top-up (optional arbitrage)

3. SOLAR RESOURCE & AGRIVOLTAIC CONTEXT

3.1 Irradiance Characterization

The Petrolina–Juazeiro sub-region receives annual global horizontal irradiance (GHI) values between **2,050 and 2,300 kWh/m²/year**, monthly peak irradiance 7.2 kWh/m²/day during the dry season (June–September). The region records over 3,000 sunshine hours annually, with cloud cover accounting for losses below 8% of available solar resource — substantially lower than coastal and southeastern Brazilian sites. PVGIS data confirm a capacity factor of 22–26% for fixed-tilt south-facing bifacial modules at optimal inclination angles of 10–14°.

3.2 Agrivoltaic System Architecture

Typical agrivoltaic configurations in the Vale do São Francisco employ **elevated east-west bifacial tracker arrays**

or fixed south-facing structures at 3.0–4.5 m hub height, preserving mechanized access for irrigation and harvesting equipment. Panel spacing is designed to achieve **35–50% ground coverage ratio (GCR)**, balancing shading benefits for heat-sensitive crops (e.g., bell peppers, passion fruit, guava) with sufficient energy yield. Under these configurations, annual PV production per hectare ranges from **480 to 720 MWh/ha**, depending on installed density and module efficiency. Drip and micro-sprinkler irrigation systems in the region typically operate at pump motor ratings of **15 to 110 kW**, with daily energy consumption of 80–350 kWh/day per hectare depending on crop water demand, soil type, and ambient temperature. Traditional diesel-powered backup pumps are progressively being replaced by grid-tied electric pump systems, creating a direct opportunity for BESS-powered supply during off-peak and nocturnal irrigation windows.

Table 1 — Reference BESS System Parameters for 250 kWp Agrivoltaic System

| Parameter | Value |
|---------------------------|-----------------|
| PV Installed Power | 250 kWp |
| BESS Usable Capacity | 200 kWh |
| BESS Peak Power | 100 kW |
| Battery Chemistry | LFP |
| Cycle Life (80% DoD) | > 4,000 cycles |
| Self-consumption Rate | 89% |
| Annual Grid Injection | ~87 MWh/yr |
| Irrigation Supply (daily) | 180-320 kWh/day |
| System Efficiency (AC→AC) | 91% |
| Estimated CAPEX (BESS) | BRL 680–820k |

4. ECONOMIC ANALYSIS

4.1 Financial Performance Indicators

Under current Neoenergia Pernambuco tariff structure (Group A4, 2024: R\$ 0.72/kWh peak, R\$ 0.41/kWh off-peak), BESS integration adds a net annual benefit of approximately **BRL 85,000 to BRL 140,000** per 250 kWp agrivoltaic system through combined mechanisms: avoided diesel costs for backup irrigation, TOU injection premium capture, and reactive power compensation incentives.

With BESS CAPEX estimated at BRL 680,000–820,000 (including installation, BMS, and protection systems) and available financing through **BNDES Finame/FNE Solar** at 8.5–10.5% p.a. over 12 years, simple payback periods range from **6 to 9 years**, with IRR of 14–19% and NPV (25-year horizon, 10% discount rate) of BRL 320,000–580,000. The investment thesis strengthens further when agrivoltaic crop yield premiums (estimated 15–30% reduction in water consumption and associated irrigation costs) are incorporated into the cash flow model.

5. BESS TECHNICAL ARCHITECTURE

5.1 Chemistry Selection

For agrivoltaic applications in the semi-arid Northeast, **Lithium Iron Phosphate (LFP)** chemistry is the preferred choice due to its superior thermal stability (critical given ambient temperatures of 35–45°C), cycle life exceeding 4,000 full cycles at 80% Depth of Discharge (DoD), and compliance with Brazilian fire safety standards (ABNT NBR IEC 62619). LFP cells maintain over 80% capacity retention after 10 years of operation in tropical climates, as demonstrated by installations in Sobral (CE) and Casa Nova (BA).

5.2 Sizing Methodology

BESS sizing in the agrivoltaic context must simultaneously satisfy three competing objectives:

- Maximize self-consumption of PV generation during peak daytime hours
- Store surplus energy for nighttime irrigation pump supply (peak demand: 18h00–22h00 local)
- Optimize the volume and timing of grid injection to maximize compensation credits under REN 1059/2023

For a representative 250 kWp agrivoltaic system, energy balance modeling indicates an optimal BESS capacity of **200 kWh (usable)** with a **100-kW bidirectional inverter**. This configuration supports a C/2 charge rate during solar peak hours (10h00–15h00) and enables 4-hour full discharge to supply irrigation loads without grid dependency. The State of Charge (SoC) management algorithm maintains a minimum SoC of 15% as reserve against grid outage events.

6. CONCLUSIONS

The integration of BESS into agrivoltaic solar PV systems in the Vale do São Francisco region represents a technically robust and economically viable pathway for the Brazilian semi-arid agricultural sector. The combination of exceptional solar resource, chronic grid unreliability, high diesel dependency for irrigation backup, and the revised regulatory framework under **ANEEL REN 1059/2023** creates a uniquely favorable environment for BESS deployment.

LFP-based systems sized at 0.8 kWh/kWp demonstrated the best balance between capital cost and operational benefit, achieving self-consumption rates above 89% and enabling full decarbonization of nighttime irrigation loads. Future work should focus on *AI-driven energy management systems* that integrate crop water demand forecasting, weather prediction, and real-time tariff signals to further optimize BESS dispatch and maximize economic return for family and commercial agrivoltaic farmers across the Caatinga biome.

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