Design and Performance Analysis of a Residential PV System Integrated with Vanadium Redox Flow Battery (VRFB)

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Abstract

This study presents the design and performance analysis of a residential photovoltaic (PV) system integrated with a Vanadium Redox Flow Battery (VRFB). The primary objective was to evaluate the effectiveness of VRFB as a long-term and safe energy storage solution for residential applications. A typical daily household load profile was used as the basis for system design, with the PV system sized at 13 kWp and the VRFB system providing a nominal capacity of 15 kWh. The simulation was conducted using the Homer Pro program application under NASA prediction solar irradiance data to assess the system's performance in terms of energy self-sufficiency, battery state of charge (SOC), and power flow management. The results indicated that the integrated system can achieve up to 99% energy self-sufficiency under standard conditions, with efficient charge-discharge cycles and minimal overcharging risks. This research highlighted the viability of VRFB in residential renewable energy systems, especially in regions with high solar potential and increasing energy demand.

Keywords: Vanadium Redox Flow Battery (VRFB); Battery Efficiency; Simulation; State of Charge (SOC); Flow Battery; PV-VRFB Integration

1. Introduction

The growing demand for sustainable and reliable energy solutions has accelerated interest in integrating renewable energy sources with advanced energy storage systems, particularly in the residential sector. Among renewable technologies, photovoltaic (PV) systems have emerged as a leading choice due to their scalability, declining costs, and the ability to deliver clean electricity at the point of consumption [1]. However, the intermittent nature of solar irradiation introduces significant challenges for ensuring continuous household power supply, especially during periods of low sunlight or nighttime [2].

Battery energy storage systems (BESS) have been widely implemented to address these intermittency issues. Lithium-ion (Li-ion) batteries, in particular, are commonly used due to their high energy density and round-trip efficiency [3]. Nonetheless, they are constrained by issues such as limited cycle life, risks of thermal runaway, and performance degradation under deep discharge cycles, which can impact long-term reliability and economic performance in residential-scale systems [4].

In contrast, Vanadium Redox Flow Batteries (VRFBs) have emerged as a promising alternative, offering features such as long operational life, high scalability, rapid response, and the ability to decouple power and energy capacities [5, 6]. VRFBs utilize vanadium ions in multiple oxidation states within liquid electrolytes for both half-cells, enabling virtually unlimited charge-discharge cycling without significant capacity degradation [2,7]. These characteristics make VRFBs particularly suited for applications requiring daily cycling and long-duration storage, such as solar-powered residential energy systems [8].

Recent research efforts have explored various hybrid microgrids incorporating PV, wind, and biomass energy with advanced storage systems to enhance reliability and minimize energy costs [4, 5, 9]. However, there remains a gap in comprehensive studies focused specifically on the integration of VRFBs with standalone residential PV systems, particularly in terms of techno-economic feasibility under different demand profiles and reliability constraints [10, 11]. Despite VRFBs' superior durability and operational stability, their relatively high capital cost remains a barrier to widespread adoption. Therefore, a detailed analysis of the Levelized Cost of Energy (LCOE), Net Present Value (NPV) is essential for evaluating their economic viability [12].

This study aims to design, simulate, and evaluate a residential PV system integrated with a VRFB energy storage unit, addressing both technical and economic performance. The system is modeled to meet the energy needs of a typical household while maintaining a near-zero Loss of Power Supply Probability (LPSP), ensuring system reliability as guided by IEEE standards [6, 7]. Optimization of system sizing is conducted using simulation tools such as HOMER and MATLAB to minimize LCOE while maintaining optimal performance. Key performance metrics—such as energy efficiency, battery State of Charge (SOC), and economic indices are assessed to determine the practicality of VRFB integration under real-world operational conditions [13].

2. Methodology

2.1 System Design

This section presents the architecture and design methodology of the proposed residential PV system integrated with a Vanadium Redox Flow Battery (VRFB). The system is intended to meet the electricity demand of

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a typical household, maintain a high reliability level, and optimize long-term energy costs. The design includes key subsystems: the PV array, power converters (DC–DC and inverter), the VRFB storage unit, and the residential load.

2.1.1 System Architecture

The hybrid system architecture is illustrated in Fig 1, which consists of the following components:

- **PV array**: Harvests solar energy and generates DC electricity.
- **DC–DC converter**: Regulates voltage output from the PV system to charge the VRFB stack or supply loads.
- **VRFB system**: Stores excess energy during the day and supplies energy during night or low irradiance periods.
- **Inverter**: Converts DC power to AC for use in residential appliances.
- **Load**: Represents a typical residential daily consumption profile.

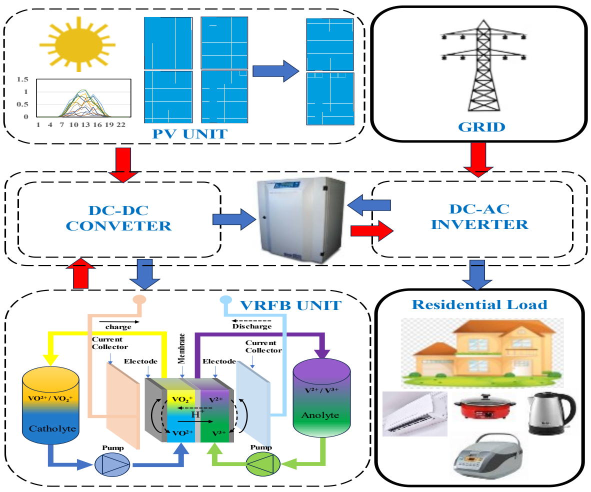

Fig 1: Schematic of Residential PV–VRFB System

2.1.2 Load Profile and Design Assumptions

The system is designed to serve a household with an average daily energy consumption of 11.26 kWh, with a peak load of 2.09 kW. A 24-hour load profile is assumed based on standard residential patterns, with energy usage concentrated in early morning and evening hours from Fig 2.

Design assumptions:

- Autonomy: 1 day (battery should supply full load without PV for 24 hours)
- Solar insolation: 5.0 kWh/m²/day from fig 3. (typical in tropical climates)
- PV efficiency: 18.7%
- VRFB round-trip efficiency: 75-80%
- DC/AC inverter efficiency: 96%

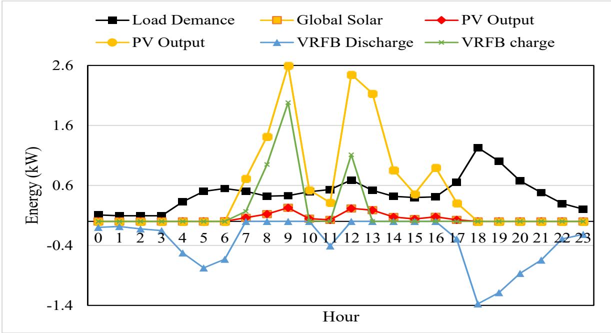

Fig 2: Energy value of the system

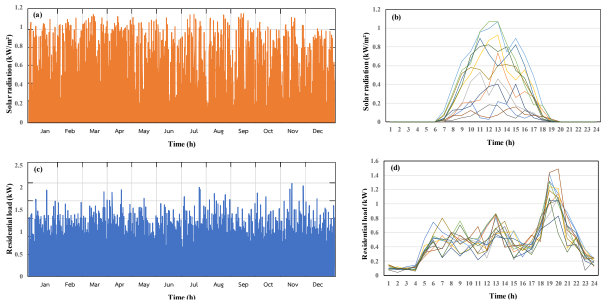

Fig 3: Hourly time series input data for (a) and (b) Solar radiation at Prathum-Thani in Thailand and (c) and (d) Residential load.

2.1.3 PV Array Sizing

The required PV power capacity P_{PV} is calculated to cover both the daily household load and charging the VRFB to full state over sunlight hours

$$P_{\mathrm{PV}} = \frac{E_{\mathrm{load}}}{\eta_{\mathrm{inv}} \cdot H_{\mathrm{solar}} \cdot \eta_{\mathrm{PV}}} \quad (1)$$

Where:

- E_{load} = 11.26 kWh/day
- η_{inv} = inverter efficiency = 0.90
- H_{solar} = average solar insolation = 5 kWh/m²/day
- η_{PV} = PV system efficiency = 0.18

$$P_{\mathrm{PV}} = \frac{11.26}{0.96 \cdot 5 \cdot 0.187} \approx 12.54 \text{ kWp}$$

Hence, a 13 kWp PV system is proposed to ensure both direct supply and storage charging capacity.

2.1.4 VRFB Storage Sizing

The VRFB system must store energy to cover at least one full day of load:

$$E_{\mathrm{VRFB}} = \frac{E_{\mathrm{load}}}{\eta_{VRFB}} \quad (2)$$

where:

- η_{VRFB} = 0.80 (round-trip efficiency)

$$E_{\mathrm{VRFB}} = \frac{11.26}{0.80} \approx 14.078\mathrm{kWh}$$

To ensure margin for degradation and depth of discharge (DoD ≈ 95%), the nominal VRFB capacity is calculated as:

$$E_{\mathrm{VRFB}} = \frac{14.08}{0.95} \approx 14.82 \text{ kWh}$$

A 15 kWh VRFB system is therefore selected.

2.1.5 Power Converter Sizing

- Inverter rating**:** must meet peak load of 2.09 kW with safety margin ⇒ 3 kW inverter
- DC–DC converter: designed based on maximum PV output (13 kW) with charge control logic
- Charge controller: integrated with state-of-charge (SOC) monitoring of the VRFB stack
- Daytime: PV supplies household load. Surplus charges VRFB.
- Nighttime: VRFB discharges to supply the load.
- Excess energy: Can be dumped or used for auxiliary purposes (e.g., water heating)
- Deficit: If present, system allows controlled load shedding or alerts

2.2 Component Modeling

2.2.1 PV system

A Photovoltaic (PV) system is a renewable energy technology that directly converts sunlight into electricity using the photovoltaic effect. It primarily consists of solar panels (modules) made from semiconductor materials such as silicon, which generate direct current (DC) electricity when exposed to solar radiation.

The power output of a PV system at any given time t can be mathematically expressed as:

$$P_{PV}(t) = P_{rated} \cdot \frac{G(t)}{G_{STC}} \cdot \eta_{temp}(t) \quad (3)$$

Where $\boldsymbol{P_{PV}(t)}$ is power output of the PV array at time t (kW), $\boldsymbol{P_{rated}}$ is rated capacity of the PV system under standard test conditions (kW), $\boldsymbol{G(t)}$ is solar irradiance at time t (W/m²), $\boldsymbol{G_{STC}}$ is standard test condition irradiance (1000 W/m²), $\boldsymbol{\eta_{temp}(t)}$ is temperature-adjusted efficiency factor.

2.2.2 Energy storage system

A Vanadium Redox Flow Battery (VRFB) is an electrochemical energy storage system that stores energy in liquid electrolytes containing vanadium ions in different oxidation states. It operates based on reversible redox reactions that occur in separate electrolyte tanks, allowing the system to charge and discharge without degradation of the electrodes.

Key features of VRFBs include:

- Long cycle life due to minimal degradation of materials,
- Decoupled energy and power capacity, allowing flexible scaling,
- High safety and thermal stability, as the electrolytes are non-flammable,
- Suitability for large-scale and long-duration energy storage applications.

The operation of a VRFB can be represented by the following redox reactions:
At the positive electrode (catholyte):

$$VO_2^+ + 2H^+ + e^- \Leftrightarrow VO^{2+} + H_2O \ \ (E^\circ = -0.26 \text{ V}) \quad (4)$$

At the negative electrode (anolyte):

$$V^{3+} + e^- \Leftrightarrow V^{2+} \quad (E^\circ = +1.00\, V) \quad (5)$$

Charging Energy Equation

$$E_{in}(t) = \frac{P_{ch}(t) \cdot \Delta t}{\eta_{ch}} \quad (6)$$

Where $E_{in}(t)$ is electrical energy input to the battery (kWh), $P_{ch}(t)$ is charging power at time t (kW), η_{ch} is charging efficiency (typically 85–95%), Δt is time step (hours)

Discharging Energy Equation

$$E_{out}(t) = P_{dis}(t) \cdot \eta_{dis} \cdot \Delta t \quad (7)$$

Where $E_{out}(t)$ is electrical energy output from the battery (kWh), $P_{dis}(t)$ is discharge power (kW), η_{dis} is discharging efficiency (typically 85–95%)

Energy Balance Equation (Dynamic)
The change in stored energy at each time step:

$$E_{stored}(t + \Delta t) = E_{stored}(t) + E_{in}(t) - E_{out}(t) \quad (8)$$

Or equivalently

$$E_{stored}(t + \Delta t) = E_{stored}(t) + \left(\frac{P_{ch}(t)}{\eta_{ch}} - P_{dis}(t) \cdot \eta_{dis}\right) \cdot \Delta t \quad (9)$$

State of Charge (SOC)

The State of Charge (SOC) represents the ratio of stored energy to the total energy capacity of the battery:

$$SOC(t) = \frac{E_{stored}(t)}{E_{max}} \quad (10)$$

Where $SOC(t)$is state of charge at time t (0–1 or 0–100%), $E_{stored}(t)$ is energy stored in the battery (kWh), E_{max} is maximum energy capacity of the VRFB (kWh)

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (11)$$

2.2.3 Residential load

A residential load (refers to the total electrical energy demand of households or residential buildings. It includes all electricity-consuming devices and appliances used for daily living, such as lighting, refrigeration, air conditioning, cooking, water heating, entertainment electronics, and electric vehicle charging (if applicable).

$$P_{load}(t) = \sum_{i=1}^{n} P_i(t) \tag{12}$$

Where $P_{load}(t)$ is total residential load at time t (kW), $P_i(t)$ is power consumption of appliance iii at time t (kW), n is total number of electrical appliances in the household.

2.3 Energy Balance

At each time step:

$$P_{\mathrm{PV}}(t) + P_{\mathrm{VRFB}}(t) - P_{\mathrm{load}}(t) = 0 \tag{13}$$

Where $P_{\mathrm{VRFB}}(t)$ is positive during discharge and negative during charge.

2.4 Simulation Tools

Two primary software tools are used:

- HOMER Pro – For optimal system sizing, LCOE calculation, and economic feasibility analysis, detailed time-series simulation of PV power, VRFB SOC, and load matching.

Simulation parameters:

- Time step: 1 hour
- Simulation horizon: 1 year
- Load profile: Based on typical residential consumption patterns (peaks in morning and evening).
- Solar irradiance data: Typical Meteorological Year (TMY) for a tropical location.

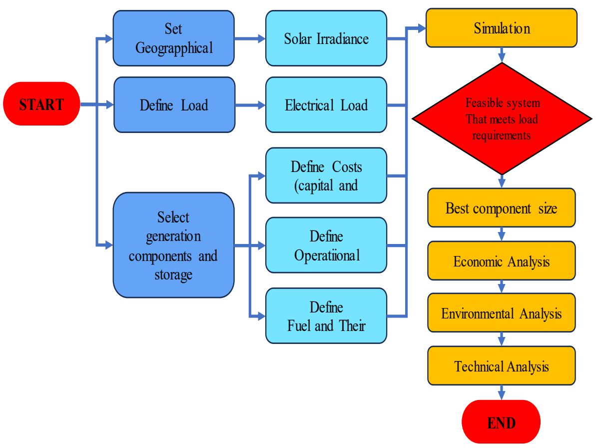

Fig 4: Simulation Process of PV and VRFB Systems for Residential Load Applications

2.5 Techno-Economic Analysis

Key performance indicators (KPIs) include:

1. Loss of Power Supply Probability (LPSP)

$$LPSP = \frac{\sum P_{unsupplied}(t)}{\sum P_{load}(t)} \tag{14}$$

2. Levelized Cost of Energy (LCOE)

$$LCOE = \frac{NPC}{\sum_{t=1}^{T} E_t/(1+r)^t} \tag{15}$$

3. Net Present Value (NPV)

$$NPC = C_{capital} + \sum_{t=1}^{T} \frac{C_{operating} + C_{replacement}}{(1+r)^t} \tag{16}$$

where: $C_{capital}$: Initial capital investment, $C_{operating,t}$: Annual operating cost in year t, $C_{replacement,t}$: Component replacement cost in year t, r: Discount rate and T: Project lifetime (years)

2.5 Case Study Scenarios

- Case A: Grid
- Case B: PV–VRFB sized according to Section 2.
- Sensitivity Analysis
  - Case C-1 to 4: Variation in PV capacity ±10-20%.
  - Case D-1 to 4: Variation VRFB storage ±10-20%.

Simulation outputs include:

- Hourly PV generation, VRFB SOC, and load supply.
- Annual unmet load (to compute LPSP).
- Capacity Shortage (to system Reliability (%) = 1 – Capacity Shortage)
- Financial metrics over a 25-year project life.

3. Result and Discussions

3.1 Technical data Input

TABLE 1 Input Configuration Parameters Used in HOMER Pro

Component	Description	Parameter	Value	Unit	Reference / Remark
PV Array	Main energy source	Rated power 0.30kW/ea.	13	kW	Standard residential scale
		Efficiency	18.7	%	Commercial monocrystalline panel
		Lifetime	25	years	Manufacturer datasheet
		Derating factor	0.9	-	For dust, temp losses
VRFB	Energy storage system	Rated capacity	15	kWh	Based on 4-hour autonomy
		Nominal voltage	50	V	Custom lab prototype
		Efficiency (round-trip)	75–80	%	Lab-scale test result
		SOC limits	20–95	%	Prevent over-discharge
		Lifetime	15	years	Literature-based
Power Converter	Bidirectional inverter	Rated power	3	kW	Matches PV array
	Efficiency	96	%	Typical inverter spec	
Residential Load	Daily demand profile	Peak load	2.09	kW	Based on local residential usage
	Average load	0.47	kW	11.26 kWh/day	
	Load type	Dynamic (hourly)	–	–	Smart meter profile
Location	Solar resource data	Global Horizontal Irradiance (GHI)	5.0–5.5	kWh/m²/day	Based on site (e.g., Pathum Thani)
	Ambient temperature range	24–36	°C	Affects battery & PV efficiency	

3.2 Technical Performance Analysis

3.2.1 SOC of system Analysis

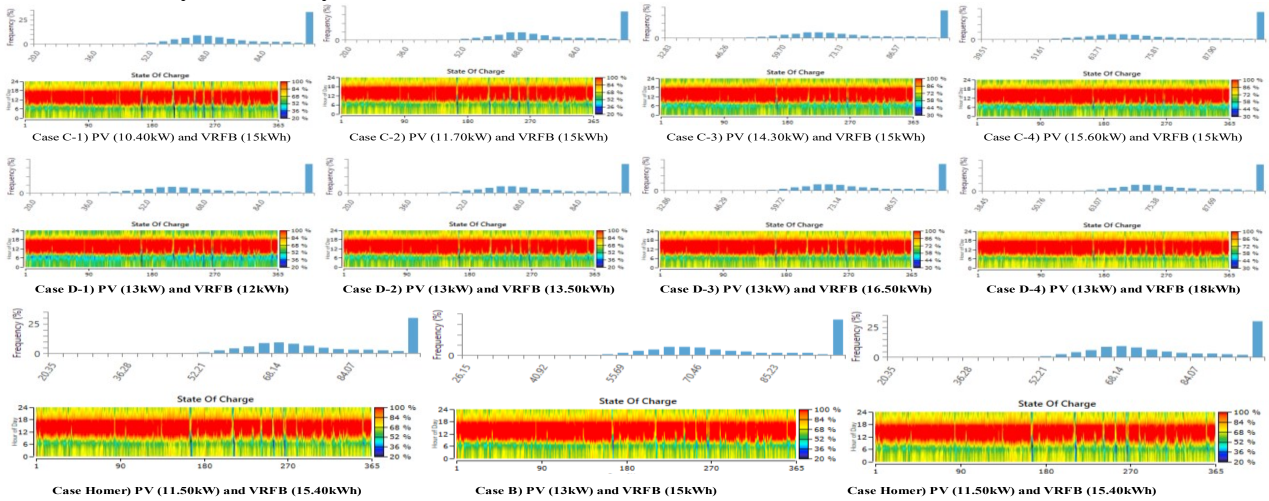

Fig 5: State of Charge and Discharge of PV-VRFB system.

Figure 5 heat map analysis provides a detailed visualization of the hourly performance of a PV-VRFB system over the course of a year, using a gradient color scale to represent varying levels of system efficiency. **Red (100%)** represents peak system performance, typically observed at midday under strong solar radiation, highlighting optimal energy generation and storage. In contrast, **blue (20%)** signifies periods of minimal performance, commonly occurring during nighttime and early morning hours when solar input is absent. Intermediate colors, ranging from yellow to green, reflect gradual transitions between these extremes.

The figure also reveals **seasonal fluctuations** in system performance, with noticeable dips around mid-year. These variations are likely due to changes in solar radiation levels, weather conditions (e.g., cloud cover, monsoons, and reduced sunlight hours during winter), and household energy demand fluctuations. To mitigate these seasonal impacts, strategies such as adjusting VRFB charging cycles to align with seasonal variations, increasing PV panel capacity to enhance solar energy capture, and expanding battery capacity to improve energy storage during low-production periods could be considered.

This analysis underscores a predictable daily performance cycle, peaking during daylight hours, while emphasizing the essential role of VRFBs in maintaining system functionality during periods of low or no solar input. The heat map ultimately demonstrates the PV system's reliability during sunlight hours and the indispensable role of storage solutions in ensuring a consistent energy supply throughout the year.

As illustrated in Figure 5, a system designed using a sizing approach based on the total daily load can accommodate ±20% variations in PV or VRFB capacity while still meeting the power demand. Nevertheless, a reduction in PV generation exceeding 20% (case C-1) leads to a substantial decline in system reliability

3.2.2 Performance and Cost Analysis.

TABLE 2: Performance and Cost of PV and VRFB Systems for Residential Load Applications

Case	System Size				Total Price		Total	PV	VRFB	Excess	LPSP	Capacity Shortage	Storage	Emissions		
	Grid	PV.	VRFB.	INV.	(NPV)	LCOE	Load	Generation	Supplied	Electricity	(Standard <1%)	(standard <0.1%)	Depletion	Carbon Dioxide	Sulfur Dioxide	Nitrogen Oxides
	(kW)	(kW)	(kWh)	(kW)	($)	($/kWh)	(kWh)	(kWh)	(kWh)	(%)	(%)	(%)	(kWh/yr)	(kg/yr)	(kg/yr)	(kg/yr)
Homer		11.50	15.40	1.92	20,684.19	0.3895	4,107	18,554	2,307	74.20	0.0221	0.0995	4.20	0	0	0
A	11.26	-	-	3.00	5,312.07	0.1000	4,107	-	-	-	0.0000	0.0000	-	2,597	11.3	5.51
B	-	13.00	15.00	-	30,766.86	0.5792	4,107	21,014	2,290	77.20	0.0002	0.0157	4.15	0	0	0
C-1	-	10.40	15.00	3.00	30,068.93	0.5664	4,107	16,811	2,321	71.50	0.0558	0.1050	4.27	0	0	0
C-2	-	11.70	15.00	3.00	30,417.87	0.5726	4,107	18,912	2,305	74.70	0.0021	0.0144	4.21	0	0	0
C-3	-	14.30	15.00	3.00	31,116.02	0.5858	4,107	23,115	2,278	79.30	0.0000	0.0000	4.09	0	0	0
C-4	-	15.60	15.00	3.00	31,465.30	0.5923	4,107	25,216	2,268	81.00	0.0000	0.0000	4.07	0	0	0
D-1	-	13.00	12.00	3.00	29,960.09	0.5642	4,107	21,014	2,288	77.20	0.0401	0.0730	4.30	0	0	0
D-2	-	13.00	13.50	3.00	30,363.52	0.5716	4,107	21,014	2,290	77.20	0.0058	0.0216	4.22	0	0	0
D-3	-	13.00	16.50	3.00	31,170.19	0.5868	4,107	21,014	2,290	77.20	0.0000	0.0000	4.07	0	0	0
D-4	-	13.00	18.00	3.00	31,573.52	0.5944	4,107	21,014	2,290	77.20	0.0000	0.0000	4.00	0	0	0

From Table 2, the comparison results, Case A (Grid Only) shows the lowest cost (LCOE = 0.10 \$/kWh) but relies entirely on the grid and produces greenhouse gas emissions. In contrast, Case B (PV 13 kW, VRFB 15 kWh) provides the highest reliability (LPSP ≈ 0) with zero emissions but has the highest overall cost (LCOE = 0.5792 \$/kWh).

Increasing the size of either PV (Case C) or VRFB (Case D) reduces LPSP and capacity shortage to zero but slightly increases the LCOE. Comparing Case C-3 (PV 14.3 kW, VRFB 15 kWh) and Case D-3 (PV 13 kW, VRFB 16.5 kWh), both achieve full reliability (LPSP = 0), but C-3 has a slightly lower overall cost.

Therefore, the optimal system sizing should balance cost (LCOE) and reliability (LPSP). Case C-2 or D-2 appears to provide the best trade-off, achieving near-zero LPSP while keeping costs lower than the largest system configurations.

3.2.3 Techno-economic Analysis of the PV–VRFB System

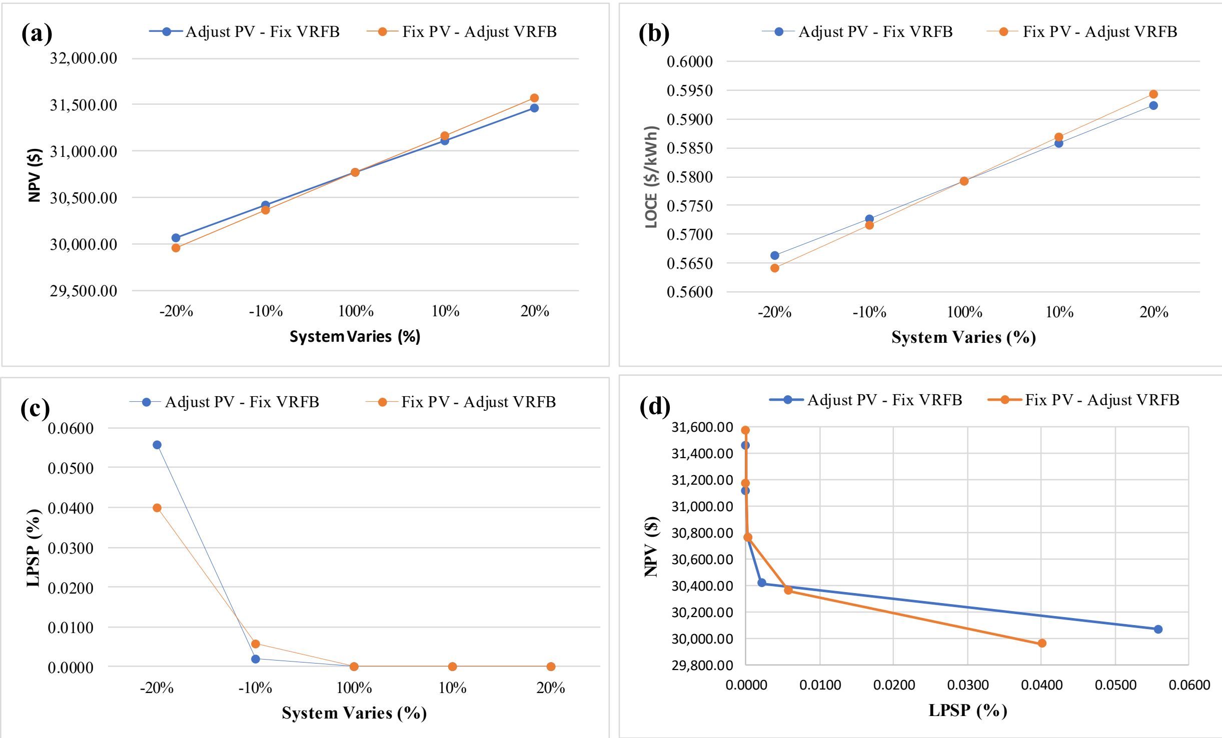

Fig 6: State of Charge and Discharge of PV-VRFB system.

Figure 6 illustrates the techno-economic performance of the PV–VRFB system under two sizing strategies: Adjust PV–Fix VRFB and Fix PV–Adjust VRFB.

(a) For NPV, both strategies show a consistent increase with larger system sizes. Although the trends are nearly identical, the Adjust PV–Fix VRFB approach yields slightly higher NPV at larger capacities, indicating marginally better financial outcomes when PV capacity is adjusted.

(b) The LCOE rises gradually as the system size increases. While the difference between the two strategies is minor, the Fix PV–Adjust VRFB method tends to produce marginally higher LCOE values, suggesting that adjusting VRFB capacity contributes to a slightly greater average cost of electricity compared to adjusting PV.

(c) The LPSP decreases significantly as system size grows. At -20% system variation, Adjust PV–Fix VRFB shows a slightly higher LPSP than Fix PV–Adjust VRFB, implying that PV adjustment alone may provide lower reliability when the system is undersized. However, both strategies achieve zero LPSP from the nominal size onward, ensuring full reliability.

(d) The NPV–LPSP relationship highlights that lower LPSP corresponds to higher NPV for both strategies. The Adjust PV–Fix VRFB approach maintains a higher NPV at comparable LPSP levels, reinforcing its advantage in balancing economic performance with system reliability.

3.2.4 Energy and SOC of System Analysis

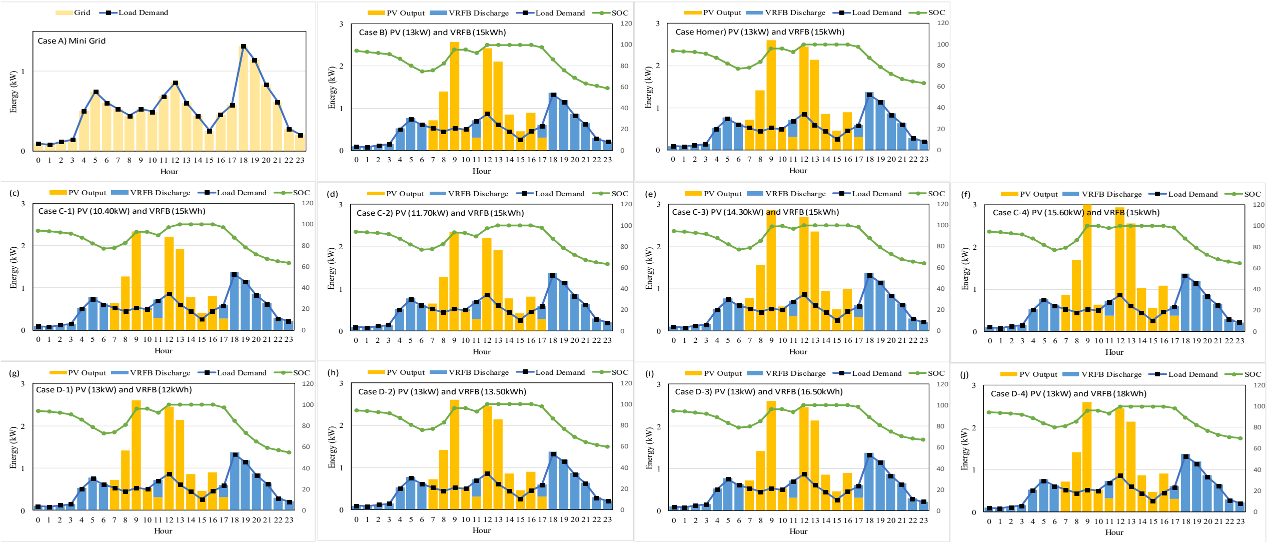

Fig 7: System power delivery performance.

Figure 7, illustrates the energy profiles of various PV-VRFB system configurations across a 24-hour period, highlighting the balance between PV generation, battery storage behavior, and load demand. The system performance is evaluated in terms of PV output, VRFB charging/discharging, and the battery's state of charge (SOC).

Case A (Mini-Grid) serves as the baseline scenario, where the energy demand is entirely met by the grid, with no renewable generation or storage involved.

Case B demonstrates the integration of a 13.40 kW PV array and a 15 kWh VRFB. The PV system sufficiently charges the battery during peak sunlight hours, allowing effective discharging during evening demand peaks, maintaining a balanced SOC profile.

Cases C-1 to C-4 explore the impact of varying PV sizes with a fixed battery capacity (15 kWh). As PV size increases from 10.40 kW to 15.60 kW:

- PV output becomes increasingly sufficient to meet load demands and charge the battery.
- SOC profiles show improved stability, with Case C-4 achieving the most robust energy autonomy and reduced reliance on external sources.

Cases D-1 to D-4 evaluate different VRFB capacities (12 kWh to 18 kWh) under a constant PV size (13 kW). The results indicate:

- Smaller battery capacities lead to faster SOC depletion and limited evening supply (D-1, D-2).
- As the storage size increases, the system can store more excess solar energy and sustain loads longer into the night.

Case D-4 exhibits the most stable SOC, suggesting ample energy storage and reliable load coverage.

Key Insights:

- A well-balanced PV-to-battery ratio is critical for optimal energy self-sufficiency.
- Increasing PV capacity enhances energy harvesting potential during the day.
- Expanding battery size improves energy availability during non-generating hours.
- Cases C-4 and D-4 emerge as the most promising configurations, delivering superior performance in terms of both energy sustainability and system reliability.

4. Conclusions

This study investigates multiple PV-VRFB system configurations to assess their performance in terms of energy autonomy, cost-effectiveness, and battery utilization over an annual cycle. The conclusions are drawn from hourly performance charts, economic evaluation tables, and long-term SOC distribution analysis.

4.1. Energy Performance & Load Matching

- Cases C-4 and D-4 demonstrated the most stable and complete load coverage, showing consistent VRFB discharge during peak demand and sustained SOC levels into the evening.
- As PV capacity increases (C-series), the energy generated becomes more sufficient to cover the demand and maintain battery charge.
- Similarly, increasing VRFB capacity (D-series) improves energy availability throughout the night, ensuring a lower risk of supply shortage.

4.2. Economic Feasibility

- Although Case A (grid-only) has the lowest investment and LCOE, it comes with high emissions and total grid dependency.
- Case B strikes the best balance between cost and clean energy, with a relatively low LCOE ($0.5792/kWh) and full autonomy using solar and storage.
- Higher PV and VRFB capacities (C-4, D-4) improve performance but come with higher Net Present Costs (>$31,000) and increasing LCOE (up to $0.9444/kWh).

4.3. Battery Utilization & SOC Behavior

- The SOC heatmaps indicate frequent fluctuations in charge levels throughout the year.
    - Cases D-3 and D-4 show higher SOC stability with more time spent in the mid-to-high charge zones, minimizing deep discharge cycles and improving battery health.
    - Cases C-1 and D-1 suffer from lower SOC values and more rapid depletion, suggesting undersized PV or storage capacity.
- The histogram distribution supports that, systems with larger storage or PV size reduce low-SOC frequency, increasing reliability.

4.4. Emissions and Environmental Impact

- All PV-VRFB integrated systems (B–D-4) achieved zero emissions, showcasing their effectiveness for clean energy transition.
- Only Case A emitted CO_2 (2,597 kg/yr), emphasizing the environmental benefit of integrating renewable sources.

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