Optimal Sizing of Vanadium Redox Flow Battery Used for PV System Energy Storage

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Abstract : This study introduced a novel approach to design an optimal sizing of a vanadium redox flow battery (VRFB) for a PV system with a sample load of 4,109.12 kWh/year or 11.26 kWh/day. Initially, the analysis involved evaluating various sizes of PV systems relative to the maximum load demand (2.06 kW) and VRFB sizes, which are also relative to the daily load (11.26 kWh/day). The tested sizes ranged from 1 to 8 times of the maximum load demand for solar panels and from 1 to 7 times of the daily load for VRFBs. Based on the analysis, the most suitable configuration was a PV system with 3 times of the maximum load demand and a VRFB sized at 3 times the daily load. These findings provide crucial insights for determining the system size and estimating associated costs. The study results can be used as a fundamental key for further refinement and optimization in order to ensure accuracy and precision in system sizing, which are important to achieve optimal performance and cost-effectiveness in integrating PV systems with VRFBs for reliable energy supply.

Keywords— Redox Flow Battery, Battery Backup Energy Storage, Energy Storage, Vanadium Redox Flow Battery

I. INTRODUCTION

Today, industries around the world are growing fast, causing the demand for energy to increase. The primary raw materials used to produce energy are fossil fuels. A survey of global energy usage from 2013 to 2016 [1] found that fossil fuel consumption decreased from 78.3% to 75.5% because energy produced from alternative sources increased from 19.1% to 24.5%. Alternative energies used around the world [2] include wind energy (4%), biomass energy (2%), and solar energy (1.5%). The Thai government recognizes the importance of this shift. Therefore, the use of alternative and renewable energy must increase. This is evident as the Ministry of Energy has driven the Energy 4.0 policy, hastening the development of energy storage systems and emphasizing technology and innovation to reduce risks and create stability for electricity production from alternative and renewable energy [3]. It also creates energy stability and increases energy efficiency within the country. Moreover, the mechanism driving the economy for the future includes ten target industries, consisting of five traditional industries (the first S-curve) and five future industries (the new S-curve) [4]. Renewable energy technology, or alternative energy, can be applied and used in various industries, including the modern automotive industry, the intelligent electronics industry, industrial robots, and more.

The manuscript received Sept. 10, 2024; revised Dec. 10, 2024; accepted Dec. 20, 2024; Date of publication Dec. 30, 2024.

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Energy storage technology is crucial for supporting energy storage, particularly for electrical energy produced from alternative energy sources such as the sun, wind, and water. However, the electricity produced from these alternative energy sources is unstable because it depends on the weather conditions of the location where they are installed. To ensure that these alternative energies are stable for future use, there is a need for an energy storage system in conjunction with the production of electricity from alternative energy sources (wind and solar cells). These systems store excess electrical energy and distribute it when the electrical energy in the system is insufficient.

II. MATERIALS AND METHOD

A. The Batteries Storage Energy

The optimization framework employed considers factors such as cost, energy efficiency, and load variability, using a combination of empirical data and predictive modeling techniques. The batteries are the most popular electrical energy storage device (Figure 1 [5]). Statistical data shows Let's see that in 2014. The demand for lead-acid batteries was approximately 64.5%. However, it is forecast the demand for lead-acid batteries will drop to 19.2% due to the limitations of this type of battery life.

The Batteries are gaining attention as replacements for lead-acid batteries in the industry. Especially the automotive industry and the electronics industry are Lithium-ion batteries. The forecast for 2025 lithium-ion batteries will have a market share of approximately 70% (Figure 1) due to the high energy density (100-200 Wh/kg) of this type of battery. Works up to 95% and has a cycle life of approximately 4,000-8,000 cycles [6].

However, the amount of lithium available in the world market (approximately 35,000 tons per year) is not sufficient for the production of batteries [7]. Based on this information, redox flow batteries are the industry's choice. It increases market share from 0.4% to 6.6% (Figure 1). This type of battery is considered the most attractive option in terms of unlimited capacity, flexible security design, and responsiveness. Quickly (Fast response) [8].

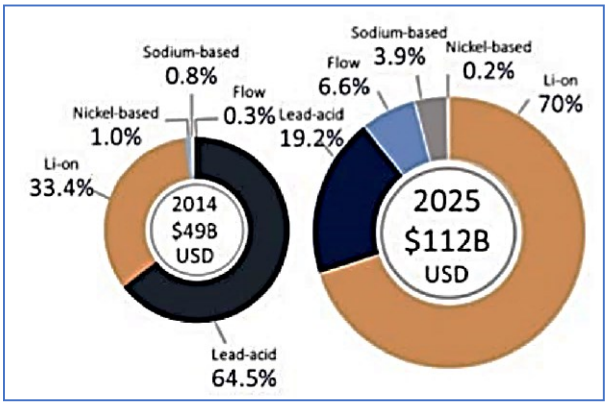

Fig 1. Market share of different kinds of batteries in 2014 and forecast in 2025 [5]

B. *Vanadium redox Flow Batteries*

The vanadium redox flow batteries (VRFBs) show in figure 2 are the most commercially available flow batteries today. Because it has many advantages over other battery chemistries. Even though it has limited energy and energy density. The use of vanadium on both electrodes prevents cross-contamination. However, the limited solubility of vanadium salts compensates for this advantage in practice. The most important for VRFB's commercial success is the near-perfect matching of the voltage window of the carbon acid/water interface with the operating voltage range of the vanadium redox couple. This guarantees the durability of the low-cost carbon electrode and low impact from side reactions. Such as H2 and O2 evolution, resulting in a record-long service life (several years) and cycle life (15,000–20,000 cycles). This has consequences at a low cost of energy (LCOE, i.e. The system cost is divided by available power, cycle life, and round-trip efficiency). The battery's long service life allows it to offset relatively high distribution costs. (Minimizes the cost of vanadium, carbon felt, bipolar plates, and membranes.) Total energy costs are about twenty to thirty dollars or euros per kWh, which is much lower than solid-state batteries and not far from the targets of approximately 0.05 dollars and 0.05 euros stated by the United States and EC government agencies.

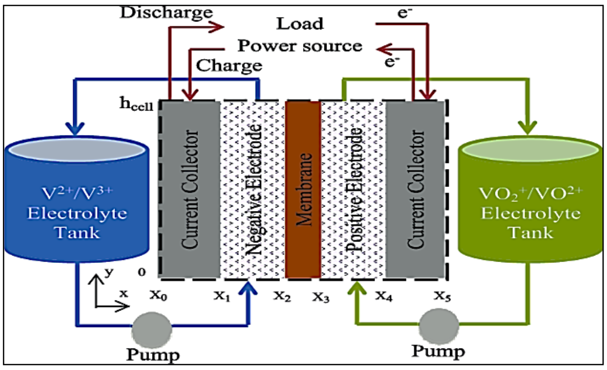

Fig. 2. A Vanadium redox flow battery [9]

Considering the investment cost of installing equipment energy storage (Capital cost) [10]. The investment cost in installing energy storage using redox flow batteries in units of energy cost (Energy cost) is approximately 150-1,000 $/kWh, which is less than the investment cost of installing energy storage equipment for lithium-ion batteries. It has a value equal to 500-2,500 $/kWh. Considering the power cost of a redox flow battery, it is about (600$-1,500$/kW), which is more than a lithium-ion battery (175-400 $/kW). The investment cost of installing a redox flow battery comes mainly from the electrolyte solution, accounting for 37%, and the series cell set (Stack cell) represents 31% of the total installation investment. As shown in Figure 3.

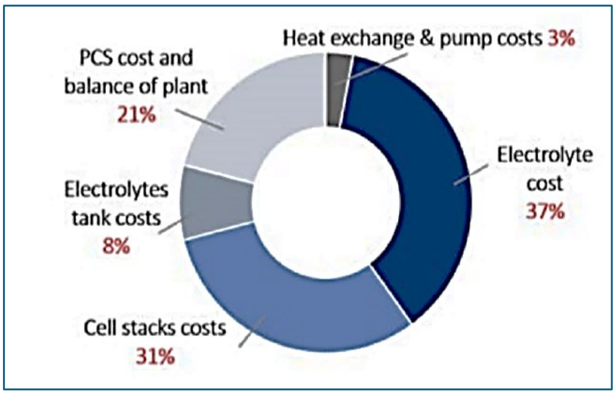

Fig 3. Installation cost of Vanadium Redox Flow Battery [11].

The type of battery uses vanadium solution as the electrolyte for both the anode and cathode. The vanadium solution used in vanadium redox flow batteries contains four oxidation states of vanadium: V2+ [V(II)], V3+ [V(III)], VO2+ [V(IV)] and VO2+ [V(V)] charging and discharging reactions and combined reactions Shown as Equation (1-3) [12] (Note: The forward reaction is a discharge process and the reverse reaction is a charging reaction.

Negative (-) Oxidation

$$V^{2+} \leftrightarrow V^{3+} + e \qquad E^0 = -0.26\ V \qquad (1)$$

Positive (+): reduction

$$VO_2^+ + 2H^+ + e \leftrightarrow VO^{2+} + H_2O \qquad E^0 = 1.00\ V \qquad (2)$$

Overall:

$$V^{2+} + VO_2^+ + 2H^+ \leftrightarrow V^{3+} + VO^{2+} + H_2O \qquad E^0 = 1.26\ V \qquad (3)$$

C. Methodology and Tools Used in Optimization

The optimization process for determining the appropriate size of the VRFB involves several key steps. First, HOMER Pro was used to simulate various configurations of PV and VRFB systems. The tool allowed for the modeling of different system sizes, ranging from small-scale residential applications to larger installations. Factors such as local solar irradiance, residential load profiles, and system cost parameters were input into the model. The simulation then optimized the PV and VRFB sizes based on minimizing the Levelized Cost of Energy (LCOE) and ensuring that energy demand was met reliably throughout the year.

For each configuration, the daily and yearly energy production, storage, and consumption were analyzed. The system sizes were adjusted iteratively to find the most cost-effective combination that provided reliable energy storage and supply. Sensitivity analyses were also conducted to understand the impact of varying parameters such as battery efficiency, energy loss rates, and cost fluctuations. This comprehensive approach ensured that the selected VRFB size was not only optimal in terms of performance but also economically viable.

III. Discussions & Experiment

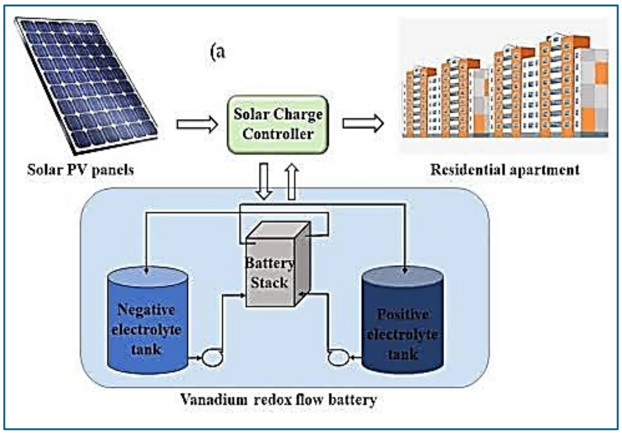

Fig. 4 Diagram of a vanadium redox flow battery for the storage of electricity produced by PV system [13]

The analysis of the optimal PV with VRFB system for supplying residential loads was conducted using the Homer Pro application. Initially, annual residential load profiles and solar irradiance values were input into the system, as depicted in Figures 5 ,6 and 7. Subsequently, PV capacities ranging from 2 to 16 kW (1 to 8 times the maximum load demand) and VRFB capacities from 10 to 70 kWh (1 to 7 times the daily load) were set, as shown in Figure 4. The system's operation was then simulated, and the energy outputs were recorded in Table 1, detailing electricity generation from PV systems of different sizes and the utilization of VRFB energy. Increasing the PV size results in higher energy production, leading to increased surplus energy. However, the energy stored in VRFBs decreases as shown in Figure 8.

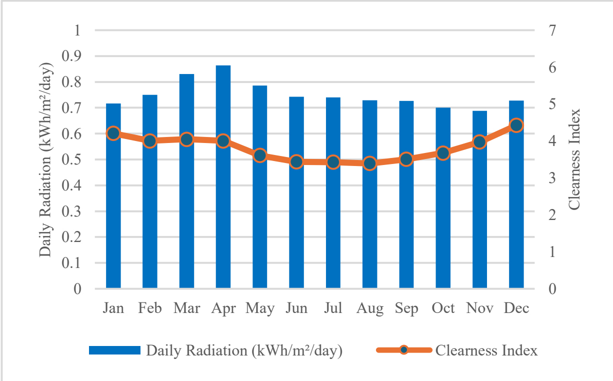

Fig. 5 Solar irradiation at RMUTT, Pathum Thani

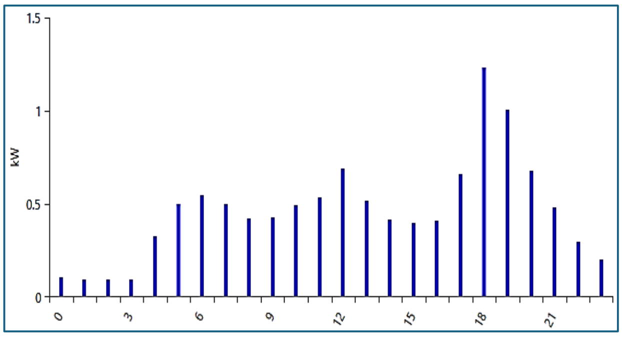

Fig. 6 Daily resident load profile

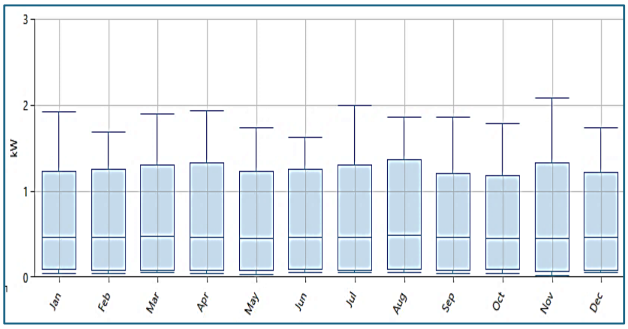

Fig. 7 Yearly resident load profile

In Figure 8 and Table 1, it is illustrated that increasing the size of the PV system enhances power production and surplus energy. Surplus energy refers to the energy that exceeds demand and is thus wasted, making the system larger than necessary. The energy supplied to the load is a combination of PV and VRFB energy; as PV size increases, the demand for VRFB decreases. Therefore, the optimal system should efficiently meet the annual energy demand of 4,109.12 kWh. To achieve this, a thorough analysis of the energy supply across the entire PV and VRFB systems, as depicted in Figure 9, is essential.

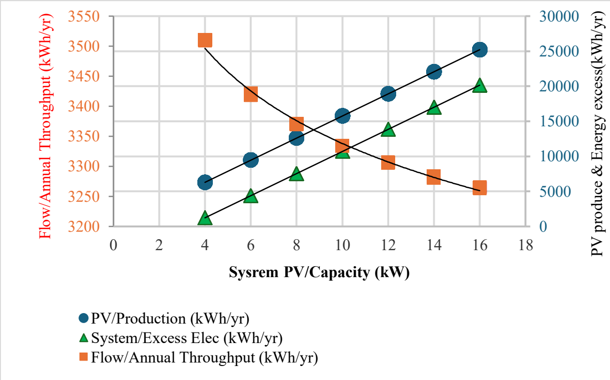

Fig. 8 Status of Energy produced, Energy excess and VRFB's energy.

In Figure 9, the PV systems paired with VRFB are depicted. Each PV size can be paired with VRFBs ranging from 15 kWh to 70 kWh. However, the optimal system must prioritize factors such as cost-effectiveness, surplus energy availability, and efficient load distribution.

Table 1 Amount of energy of the equipment in the system

PV Size		VRFB Size		Residential Load (kWh/yr.)	Excess Power (kWh/yr.)
Cap. (kW)	Produced (kWh/yr.)	Cap. (kWh)	Throughput (kWh/yr.)		
4	6,306.348	50	3,509.167	4,109.120	1,405.468
6	9,459.521	35	3,418.600	4,109.120	4,585.483
8	12,612.700	30	3,369.821	4,109.120	7,753.438
10	15,765.870	25	3,334.025	4,109.120	10,916.240
12	18,919.040	20	3,305.914	4,109.120	10,476.320
14	22,072.220	15	3,280.541	4,109.120	17,017.120
16	25,225.390	15	3,263.455	4,109.120	20,175.480

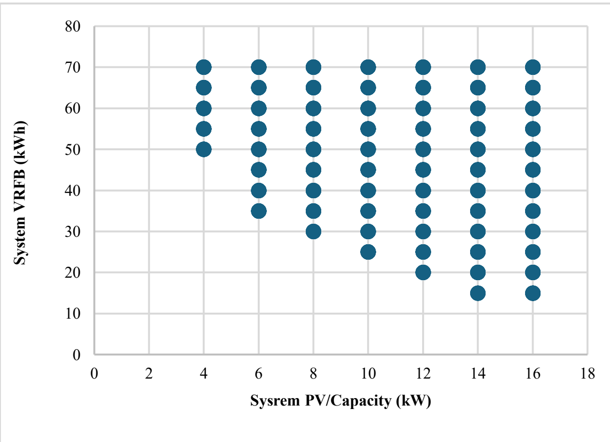

Fig 9 System of PV with VRFB

The results presented in Figure 9 were analyzed to determine the optimal PV and VRFB system configurations for various PV sizes (2, 4, 6, 8, 10, 12, 14, and 16 kW). For instance, a 2 kW PV system paired with VRFBs could not provide sufficient power to the load. On the other hand, a 4 kW PV system paired with VRFBs ranging from 50 to 70 kWh showed that 5 pairs could adequately supply power. Similarly, a 6 kW PV system paired with 35 to 70 kWh VRFBs could be paired with 8 pairs to supply power effectively. As the PV size increased, the corresponding VRFB capacity and number of pairs also adjusted accordingly: an 8 kW PV system with a 30 to 70 kWh VRFB required 9 pairs, while a 10 kW PV system paired with 25 to 70 kWh VRFBs needed 10 pairs. For larger PV systems (12, 14, and 16 kW), the number of VRFB pairs increased to ensure adequate power supply. Based on the experiment's findings, a total of 67 VRFB pairs were determined to be sufficient to meet the load requirements across all configurations. Evaluating the cost efficiency of these systems, it was found that the PV system paired with a 6 kW PV and a 35 kWh VRFB (as shown in Figure 10) offered the lowest energy cost among the seven configurations studied.

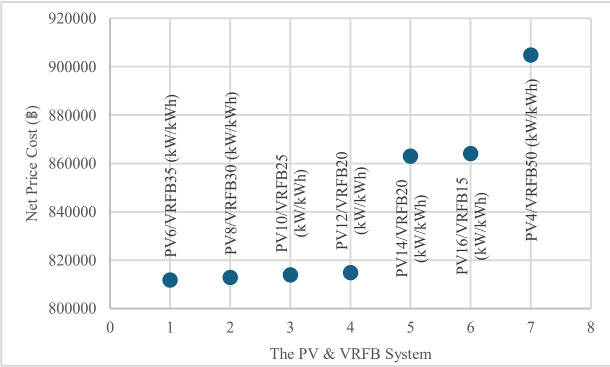

Fig. 10: Optimum of PV & VRFB system

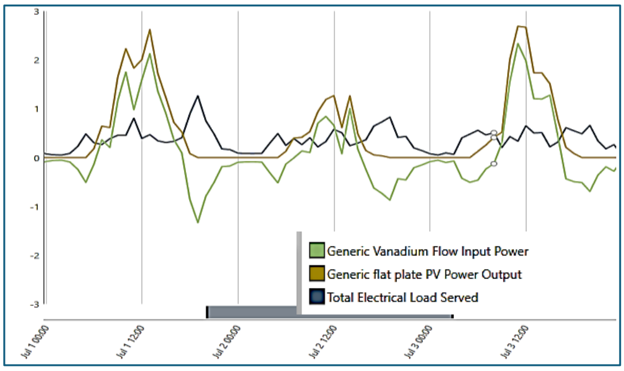

Fig. 11: Overview of Electrical Energy Production, Distribution, and Storage in the System

This figure 11 illustrates the status of electrical energy production, distribution, and storage within the system configuration specified:

- PV capacity: 6 kW
- VRFB capacity: 2.5 kW / 35 kWh

During times when solar energy production is insufficient to meet the load demand, the VRFB releases stored energy to ensure continuous supply. This process supports stable and reliable distribution of electrical energy within the system.

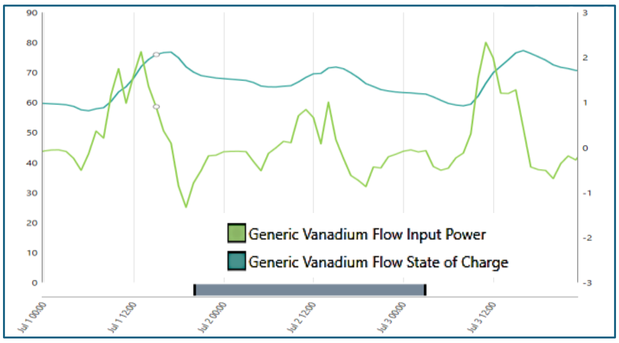

Fig. 12 Charging and Discharging Status of the Vanadium Redox Flow Battery (VRFB)

Charging Status:

- During periods of high solar irradiance and surplus energy production from the PV system (6 kW), the VRFB is charged.
- Excess electrical energy generated by the PV system is used to charge the VRFB, storing it as chemical potential energy.

Discharging Status: The stored energy in the VRFB is released to supplement the PV system's output, ensuring continuous supply of electricity to meet the demand

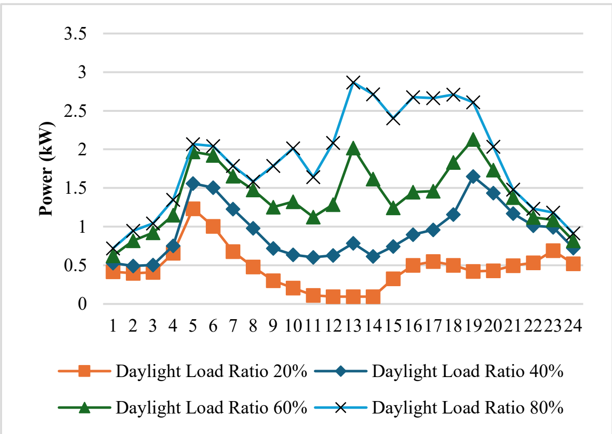

Fig. 13 Daylight load Chang Ratio

The graph depicts the ratio of changes in electrical load throughout daylight hours. It shows how the load varies in relation to solar irradiance and PV system output. Peaks and dips in the graph indicate periods when the electrical load increases or decreases relative to solar energy availability. The higher load ratios indicate significant fluctuations in electrical load during daylight hours, possibly influenced by varying energy demand and solar conditions. Understanding this ratio helps in assessing the dynamic nature of electrical load patterns and optimizing energy storage and distribution strategies. Importance, Monitoring the daylight load change ratio provides insights into optimizing the PV and VRFB systems’ s capacity to meet fluctuating energy demands effectively. It supports decision-making processes for enhancing energy efficiency and system reliability.

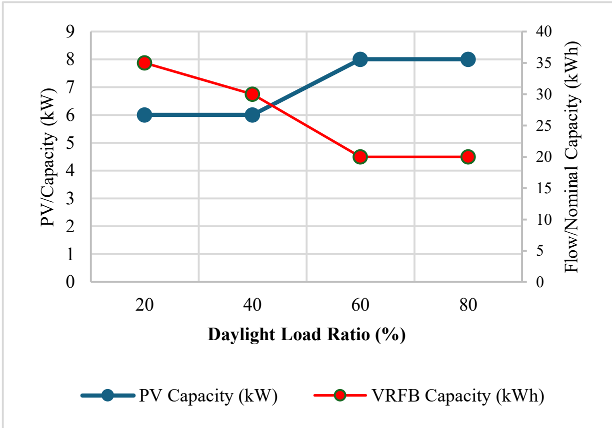

Fig 14. Prediction of System size

The graph forecasts the optimal system size required to efficiently meet energy demands, considering the specified PV and VRFB capacities. It incorporates predictive modeling to anticipate the system's capacity needs over time, accounting for variations in energy production and consumption. The graph helps in determining the appropriate scale of PV and VRFB systems necessary to maintain a reliable energy supply. It considers factors such as peak energy demand, solar irradiance variations, and storage capacity to optimize system performance. Importance, the prediction of system size aids in planning and deploying PV and VRFB systems that are cost-effective and capable of meeting long-term energy requirements. It supports decision-making processes for scaling up or optimizing energy storage solutions based on anticipated future needs.

IV. Conclusions

The study identifies an optimal PV-VRFB configuration that provides a balance between cost and reliability, demonstrating the potential of VRFBs to significantly enhance energy storage solutions in residential settings. Based on the simulation experiment of the PV system with VRFB, where solar energy values and load specifications were defined and the sizes of PV and VRFB were increased to maintain consistent load distribution, it was determined that optimizing the system for a load size of 4,109.12 kWh/year resulted in an optimal configuration of approximately PV = 6 kW and VRFB = 35 kWh. This configuration ensures that the PV size is three times the maximum load demand of 2.06 kW and the VRFB size is three times the daily energy production of 11.26 kWh/day, with sufficient stored energy to reliably power the load at minimal energy cost. In subsequent tests, varying the ratio of daytime load to nighttime load (20%, 40%, 60%, and 80%) necessitated corresponding adjustments in system size. This highlights the importance of appropriately scaling the PV with the

VRFB system to match changing load profiles. Utilizing experimental data when determining system size, the next step should involve considering the ratio of daytime to nighttime load. For instance, if this ratio is calculated to be 60%, it is advisable to increase the PV size by one time the maximum load demand and reduce the VRFB size by one time.

While these simulation results provide fundamental insights for designing PV with VRFB systems, caution should be exercised when applying them. For operations requiring precision, it is recommended to conduct further simulations in subsequent applications to refine and validate system parameters effectively.

While the study provides valuable insights, the modeling assumptions regarding load variability and PV efficiency under different weather conditions may limit the applicability of the results to regions with significantly different climates. Future studies should explore the integration of VRFBs with other renewable sources, such as wind, and consider hybrid systems that combine multiple storage technologies to enhance reliability and efficiency. Further research should also focus on real-world testing of VRFB systems in various geographical and climatic conditions to validate the simulation results.

V. Acknowledgments

We gratefully acknowledge the support and contributions that made this research possible. We extend our sincere appreciation to Assoc Prof. Dr. Boonyang Plangklang and Rajamangala University of Technology Thanyaburi, Pathum Thani, Thailand, for their invaluable assistance and expertise throughout the course of this study. Their guidance and resources have been instrumental in shaping the outcomes and conclusions presented in this work.

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