Optimal Integration of Battery Energy Storage Systems for Enhancing Operational Efficiency in Distribution Networks

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***Abstract* — The growing penetration of photovoltaic (PV) generation and AI-driven loads is creating challenges in distribution networks, such as voltage rise, peak imbalance, and the duck curve effect. This paper proposes the optimal integration of Battery Energy Storage Systems (BESS) to address these issues.**

A typical distribution feeder is modeled in DIgSILENT PowerFactory to evaluate BESS performance. Results show that BESS effectively smooths load profiles, reduces peak demand, mitigates overvoltage, and lowers network losses. Additionally, BESS enhances system flexibility in handling variable PV generation and dynamic AI loads. Economic analysis also indicates its financial viability, confirming BESS as a practical solution for future distribution networks.

Keywords — BESS, PV, distribution network, AI loads, voltage regulation, peak shaving, economic analysis.

I. .INTRODUCTION:

The rapid growth of artificial intelligence (AI) technologies is expected to significantly increase electricity demand, particularly due to the expansion of AI-driven data centers with high power density and fast-varying load characteristics. At the same time, the increasing penetration of distributed generation (DG), especially photovoltaic (PV) systems, introduces operational challenges in distribution networks, including voltage fluctuations, reverse power flow, and the duck curve phenomenon [1]– [5]. The emergence of highly dynamic AI-related loads is expected to further intensify these issues.

Battery Energy Storage Systems (BESS) have emerged as a promising solution due to their fast response capability and operational flexibility. BESS can smooth load variations, reduce peak demand, mitigate PV intermittency, and improve network stability [6].

Although many previous studies have investigated the technical benefits of BESS, the economic feasibility of BESS deployment has not been sufficiently addressed, particularly through reliable financial indicators. To address this gap, this paper proposes an optimization-based framework for BESS integration in distribution networks with increasing DG penetration and future AI-driven loads. The proposed strategy focuses on evening peak shaving and daily load profile flattening through optimal BESS operation. Since the main objective is peak shaving and load leveling, only active power is considered in the analysis. In addition to technical evaluation, this work also assesses the economic viability of BESS deployment, demonstrating that BESS is not only an effective technical solution but also a feasible investment option for future distribution networks.

II. METHODOLOGY :

A. Feeder 484HKH2 :

The 484HKH2 distribution feeder, supplied from the Hoa Khanh 2 substation located in Lien Chieu District, Da Nang City, is selected as the case study for this research.

The selected feeder is characterized by a heterogeneous load composition, including both residential, commercial and industrial loads. This mixed load profile enables a more realistic representation of load variability and demand patterns over time.

TABLE I. CHARACTERISTICS OF FEEDER 484HK2

Description	Detail
Buses	143
Transformer units	89
Peak load demand	11.6 MW
Total installed PV capacity	3.31 MWp

$$PV\ penetration\ (\%) = \left(\frac{Total\ Installed\ PV\ Peak\ Power}{Peak\ Load\ Demand}\right) \times 100\%$$

The current penetration level of distributed photovoltaic (PV) generation in the feeder is relatively high (28.5%), indicating that renewable energy resources are already significantly integrated and play an important role in the system, while still offering potential for further optimization and expansion.

From a structural perspective, the 484HKH2 feeder consists of multiple buses interconnected through medium-voltage distribution lines, supplying a large number of load points. The system also includes several distribution transformers with various rated capacities, serving different consumers. The spatial distribution of loads and transformers is non-uniform, which is typical of urban distribution networks.

The network model is developed and analyzed by using DIgSILENT PowerFactory, a widely used professional software tool for power system analysis. The software provides comprehensive capabilities for steady-state analysis, including power flow calculation, voltage profile assessment, and loss evaluation.

The net load profile as shown in Figure 1, under high distributed generation (DG) penetration exhibits a typical daily variation, ranging from 6.8 MW to 11.6 MW. Demand is lowest during off-peak hours (02:00–05:00) and rises rapidly in the morning (06:00–10:00). At midday, net load decreases noticeably due to strong PV generation, while in the evening (18:00–22:00), it increases sharply as demand grows and PV output drops to nearly zero.

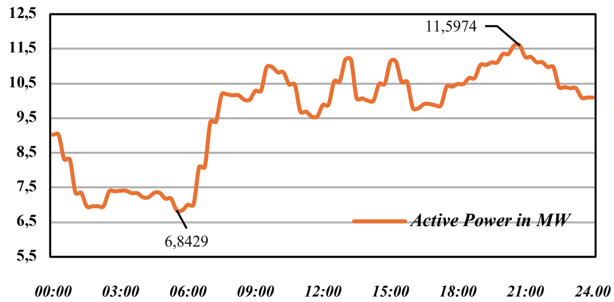

Figure 1. Net load profile

This creates a characteristic "duck curve," with a deep midday valley and a steep evening peak, posing challenges in managing rapid load changes and peak demand. Battery Energy Storage Systems (BESS) provide an effective solution through energy shifting storing excess energy during low-demand periods and supplying it during peak hours thereby smoothing the load profile and improving system performance.

This trend is further supported by recent policy adjustments in Vietnam, where peak hours have been redefined to 17:30–22:30 (Monday to Saturday) [7], closely matching the observed evening peak. This alignment highlights the increasing role of BESS in peak shaving and load shifting, contributing to reduced system stress, improved energy efficiency, and cost savings for users.

B. BESS modeling:

The Battery Energy Storage System (BESS) is modeled in DIgSILENT PowerFactory 15.1 for detailed analysis of distribution network operation. The model includes key components such as the inverter, battery, and controller, defined by parameters including rated power, energy capacity, efficiency, state of charge (SoC) limits, and operational constraints. BESS is integrated at selected buses to assess its impact on voltage profiles, power losses, and power quality through load flow and quasi-dynamic simulations. In addition, optimal placement and size of BESS are considered to maximize its effectiveness in the network.

In this study, the BESS is operated under a light-duty regime, with approximately 300–400 cycles per year and a state-of-charge (SOC) range of 10% to 90%.

The round-trip efficiency of the BESS is assumed to be 90%. In addition, the simulation is performed using a half-hour time step based on a typical daily load profile.

1) BESS placement :

a) Voltage Sensitivity Consideration

BESS can mitigate short-term voltage deviations caused by active power fluctuations. In this study, only active power variations are considered. The voltage sensitivity at bus *i* is defined as:

$$I_i = \sum_{j=1}^{n} R_{ij}$$

Where R_{ij} represents the sensitivity of voltage at bus *i* to power variations at bus *j*. The voltage deviation risk is given by:

$$S_i = \frac{I_i}{\Delta V_{ai}}$$

Buses with lower S_i are more vulnerable and are selected for BESS placement to improve voltage regulation[7].

b) Load Characteristics Consideration

Load magnitude and variation significantly affect BESS performance. Buses with high and fluctuating demand are ideal, as BESS can charge during low demand and discharge during peak periods. This reduces peak load, lowers losses, and improves voltage quality.

c) Installation Cost Consideration

BESS placement must balance technical benefits and economic feasibility. The objective is to minimize total costs, including energy losses and investment costs. Locations far from existing infrastructure may increase installation and maintenance costs, reducing overall benefits.

d) Transformer Availability Consideration

The availability of suitable transformers is a key factor. Installing BESS at buses with existing transformer capacity avoids additional investment and takes full advantage of infrastructure utilization, thereby enhancing economic efficiency.

2) BESS size :

The optimal capacity of the Battery Energy Storage System (BESS) is determined by considering three main objectives: minimizing investment costs, reducing peak demand, and smoothing the daily load profile.

To simplify the calculations, all BESS units are assumed to be aggregated and operated as a single large-scale BESS. This BESS system operates under a fixed charging and discharging schedule, specifically charging during off-peak hours and discharging during peak hours with constant charging and discharging power levels.

To achieve the optimal BESS size, the objective function simultaneously considers the investment cost, peak shaving capability, and load smoothing performance:

$$Min\ F = \omega_1 \frac{Cost}{Cost_{max}} + \omega_2 \frac{P_{peak\ new}}{P_{peak\ old}} + \omega_3 \frac{\Delta P_{new}}{\Delta P_{old}} \quad [8]$$

Where:

- $Cost = c_{BESS} \times Cost_{per\ kWh}$
- $P_{peak\ new} = P_{maxload} - P_{d.ch}$
- $\Delta P_{new} = (P_{maxload} - P_{d.ch}) - (P_{minload} + P_{ch})$

- $\omega_1, \omega_2, \omega_3$: Weighting factors used to represent the relative importance of the objectives.

$$\omega_1 + \omega_2 + \omega_3 = 1$$

The charging and discharging powers are assumed to be constant during operation and are calculated as:

- $P_{ch} = \frac{1}{\eta_{ch}} \times \frac{c_{BESS} \times \%_{SOCusable}}{T_{ch}}$
- $P_{d.ch} = \eta_{d.ch} \times \frac{c_{BESS} \times \%_{SOCusable}}{T_{d.ch}}$

Subject to: $0 \leq Cost \leq Cost_{max}$;

- $0 < P_{peak\ new} \leq P_{peak\ old}$; $0 < \Delta P_{new} \leq \Delta P_{old}$
- $SoC_{min} \leq SoC(t) \leq SoC_{max}$; SOC(T)=SOC(0)
- $P_{ch}, P_{d.ch} \leq P_{rated}$; $V_i^{min} \leq V_i \leq V_i^{max}$

The decision variable of the optimization problem is the BESS energy capacity: $x = c_{BESS}$.

This optimization framework enables the selection of an appropriate BESS size that balances economic efficiency and technical performance for distribution network operation.

C. *Simulation scenarios:*

The simulation scenarios are designed to evaluate the operational impacts of BESS and increased PV penetration on the distribution network under different operating strategies.

Scenario 1: The existing distribution network is integrated with a BESS system whose optimal capacity is determined based on the optimization framework proposed in the previous section. The BESS charges during off-peak hours (00:30–06:30) when electricity demand and prices are low, and discharges during peak hours (18:00–22:00) to reduce peak load demand and improve load profile [9], [10].

Scenario 2: The network is expected to be integrated with an AI data center and a PV system in the future, which will lead to a typical duck curve characterized by midday net-load reduction and steep evening ramping. A BESS will be deployed to absorb excess PV generation during low net-load periods and discharge during evening peak demand, thereby mitigating ramping, reducing transformer loading, and smoothing the net-load profile.

III. RESULT:

A. *Scenario 1:*

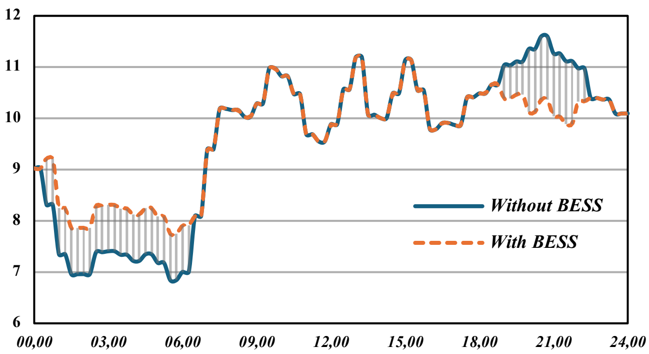

Figure 2. Active Power Profile with and without BESS Showing Load Leveling and Peak Shaving Effects

Figure 2 shows that integrating BESS 6 MWh significantly improves load operation. Without BESS, power varies from 6.84 to 11.6 MW, with a fluctuation of 4.76 MW. With BESS, the range is reduced to 7.74–11.2 MW, corresponding to a smaller amplitude of 3.46 MW (reduce 27.31% power fluctuation).

During the peak period (18:00–22:00), the maximum power decreases from 11.6 MW to 10.34 MW, achieving 1.26 MW (10.86%) peak shaving, indicating BESS discharges to support demand. In contrast, during off-peak hours (00:30–06:30), the minimum power increases from 6.84 MW to 7.74 MW, showing that BESS charges under low demand conditions.

TABLE II. TRANSFORMER LOADING LEVEL AT 20:30

Transformer Location	Loading Level (%)	
	Without BESS	*With BESS*
CDX T2	0,3	32
TTHL	0,6	54
TTD T3	1	24,6

Table II shows that these distribution transformers were almost unloaded during the evening peak period (20:30). After the BESS was installed, their loading levels increased because part of the power previously supplied by the intermediate substation transformer was redistributed through these transformers. This helps reduce the loading burden on the intermediate substation transformer.

If these distribution transformers were already supplying local loads, the BESS would directly support those loads, thereby reducing the loading levels of both the distribution transformers and the upstream intermediate substation transformer.

These results confirm that BESS effectively performs load leveling, peak shaving and reducing power fluctuation [11]. Technically, reducing peak demand by over 8.1% alleviates stress on lines and transformers, improving system reliability. Economically, energy shifting between off-peak and peak periods enhances operational efficiency and cost optimization.

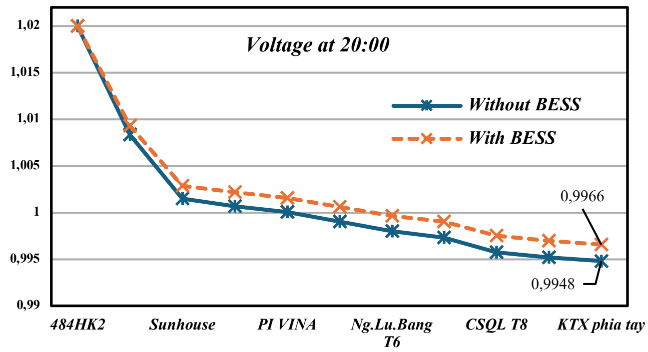

Figure 3. Voltage Profile at typical Buses

Figure 3 shows that integrating a Battery Energy Storage System (BESS) improves voltage conditions in the distribution network. In both cases, voltage decreases from the source to the end of the feeder; however, with BESS, voltages are slightly higher and more stable across all buses. At the source bus, the voltage remains around 1.020 pu with negligible change. At intermediate buses, the voltage increases by approximately 0.0014–0.0016 pu (about 0.14–0.16%). At remote buses, the improvement is maintained, with an increase of about 0.17%. These results indicate that BESS reduces voltage drop along the feeder, improves voltage levels at remote buses, and maintains voltages within acceptable limits, thereby enhancing power quality, and improving system reliability.

Furthermore, Battery Energy Storage Systems (BESS) offer superior operational flexibility compared to traditional generation sources, primarily due to their power electronic interface and the absence of mechanical inertia. This enables near-instantaneous response and precise bidirectional control of power without startup delays or fuel constraints. In contrast, traditional generators are limited by slower dynamic response and operational inflexibility [12].

B. *Scenario 2:*

The rapid growth of AI-driven data centers and photovoltaic (PV) generation has intensified the duck curve phenomenon in distribution networks. Data centers introduce continuous, high baseload demand, while PV generation creates midday overgeneration and steep evening ramping due to its intermittent nature and lack of nighttime output. This mismatch increases transformer loading and can lead to significant voltage drops during evening hours. As electricity demand continues to rise, these issues may exceed existing network limits, requiring costly grid upgrades, even though both AI loads and PV integration are essential developments.

Battery Energy Storage Systems (BESS) offer an effective solution to address these challenges. By storing excess PV energy during the day and discharging it during peak or nighttime periods, BESS reduces renewable curtailment, alleviates transformer loading, smooths net load, and mitigates voltage deviations. It also enhances system flexibility and supports stable operation under high PV penetration and dynamic AI loads.

Assuming the integration of a 2 MW AI data center together with a 1.5 MWp PV system supplying this load as shown in Figure 4, causes the existing grid to exhibit a typical duck curve profile, characterized by midday net-load depression and steep evening ramping requirements. In such a scenario, a 10 MWh Battery Energy Storage Systems (BESS) can serve as an effective mitigation measure by performing energy shifting, peak shaving, and fast-response balancing.

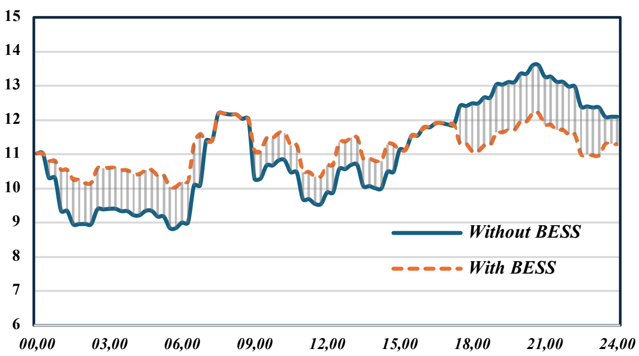

Figure 4. Net Load Smoothing and Duck Curve Reduction by BESS under AI Data Center and PV Integration

By rapidly compensating for fluctuations in both generation and demand, BESS enhances system stability and enables more efficient integration of these evolving energy resources. As a result, BESS not only alleviates duck curve impacts but also reduces the need for costly grid reconfiguration or infrastructure reinforcement to accommodate growing societal and technological demand.

IV. ECONOMIC ANALYSIS:

To evaluate the economic feasibility of the Battery Energy Storage System (BESS) in practical applications, this study employs several key financial indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), Weighted Average Cost of Capital (WACC), and Payback Period. These indicators provide a comprehensive assessment of investment efficiency, profitability, and financial risk over the project lifetime [13].

A. *Financial indicators:*

The Net Present Value (NPV) is used to evaluate the project by comparing discounted cash inflows and outflows over time:

$$NPV = \sum_{t} \frac{CF_t}{(1+r)^t}$$

Where CF_t is cash flow in year t, and r is the discount rate. A project is considered feasible if $NPV > 0$.

In this study, the discount rate is determined based on the Weighted Average Cost of Capital (WACC), which reflects the minimum required return by investors:

$$WACC = \frac{E}{V} \times K_e + \frac{D}{V} \times K_d \times (1 - T_c)$$

Where $\frac{E}{V}, \frac{D}{V}$ represent proportions of equity and debt, k_e is cost of equity, k_d is cost of debt, T_c is tax rate.

The Modified Internal Rate of Return (MIRR) is a measure of the profitability of a project or other investment. It assumes that positive cash flows are reinvested at the firm's cost of capital and that the initial outlays are financed at the firm's financing cost.

In addition, the Payback Period indicates the time required to recover the initial investment, a shorter period implies a more attractive project.

B. *Case study:*

Based on the current characteristics of the 484HKH2 feeder and the defined criteria for optimal BESS placement and size, three installation locations are identified, including Con Duong Xanh substation, Trung Tam hoc lieu substation, and Thuong Thang Dat T3 substation. The total required BESS energy capacity for peak shaving is determined to be 6 MWh.

1) *Investment costs for the project:*

A commercially available BESS unit, the OMNI AL 120-250 liquid-cooled all-in-one cabinet (120 kW / 250 kWh), is selected for this study, with an estimated cost of 1,094,299,052 VND per unit (including VAT)[14]. Based on the required total energy capacity of 6 MWh, the total investment cost of the BESS system is approximately 26.3 billion VND.

Additionally, installation costs are assumed to be 5% of the total investment cost. The operation and maintenance (O&M) cost is determined by 1% of the battery cost. In the first 5 years, the BESS has a warranty for 5 years so the O&M cost in these years is lower than in other years.

2) Revenue from the project:

The economic benefits of the BESS arthan in in ininly derived from energy arbitrage, where the battery is charged during off-peak periods and discharged during peak demand periods. In addition, the deployment of BESS contributes to the reduction of network power losses, thereby providing further economic value to the distribution system.

From the distribution network operator's perspective, maximizing economic returns is a primary objective. Therefore, the commercial customer sector is selected as the main target for demand management due to its relatively high electricity consumption during peak hours and its greater potential for peak shaving. Based on the simulation results, the final proposed strategy achieves a peak demand reduction of 10.89% for commercial customers. Subsequently, a detailed economic assessment is carried out to evaluate the financial viability and investment performance of the proposed BESS-based solution.

In this study, the BESS is assumed to operate under a light-duty regime, with approximately 300–400 charge–discharge cycles per year and a state-of-charge (SOC) operating range of 10%–90%. Under these conditions, the battery capacity is assumed to degrade at an average annual rate of 1%.

The round-trip efficiency of the BESS is assumed to be 90%. Furthermore, the electricity price is assumed to increase at an average annual rate of 5% [17]– [19]. The retail electricity price from commercial customers of the project is shown in table II.

TABLE III. RETAIL ELECTRICITY PRICE FOR COMMERCIAL CUSTOMERS[20]:

Customer classes	Price (VNĐ/Kwh)
Voltage level from 22kV to 110kV	
Normal hours	2.887
Off-peak hours	1.609
Peak hours	5.025

Thus, the income from commercial customers of the project is shown in table III.

TABLE IV. LONG TERM ECONOMIC BALANCE

Time	Revenue (VNĐ)	Investment (VNĐ)	NPV (VNĐ)
1	4.801.936.958	27.615.000.000	-22.813.063.042
2	4.670.297.032	131.500.000	4.538.797.032
3	4.542.265.873	131.500.000	4.410.765.873
4	4.417.744.550	131.500.000	4.286.244.550
5	4.296.636.845	131.500.000	4.165.136.845
6	4.178.849.177	263.000.000	3.915.849.177
7	4.064.290.531	263.000.000	3.801.290.531
8	3.952.872.387	263.000.000	3.689.872.387
9	3.844.508.651	263.000.000	3.581.508.651
10	3.739.115.590	263.000.000	3.476.115.590
11	3.636.611.766	263.000.000	3.373.611.766
12	3.536.917.974	1.578.000.000	1.958.917.974
13	3.439.957.180	263.000.000	3.176.957.180
14	3.345.654.462	263.000.000	3.082.654.462
15	3.253.936.951	263.000.000	2.990.936.951
16	3.164.733.777	263.000.000	2.901.733.777
17	3.077.976.011	263.000.000	2.814.976.011
18	2.993.596.616	263.000.000	2.730.596.616
19	2.911.530.392	263.000.000	2.648.530.392
20	2.831.713.924	263.000.000	2.568.713.924
	Total profit		41.300.146.647

3) Cost- benefit analysis:

a) Cost assumptions:

In general, the operation and maintenance (O&M) costs of BESS are relatively modest, mainly associated with periodic inverter replacement as a key maintenance requirement.

For the financial analysis, it is assumed that 70% of the project capital is financed by debt, with the remaining 30% provided as equity. Considering prevailing market conditions, the following parameters are applied:

- Interest rate: 8% annually
- Expected return on equity: 8% annually
- Loan tenure: 9 years
- The standard corporate income tax rate of 20% applies to most enterprises with a total annual revenue exceeding 50 billion VND.

b) Cost benefit analysis implementation

The expected lifetime of the Battery Energy Storage System (BESS) is assumed to be approximately 15–20 years, depending on operating conditions and degradation characteristics. The cost–benefit analysis is conducted based on the initial investment cost of the BESS, associated installation and operation costs, and the economic benefits obtained from peak shaving and loss reduction, as described in the previous sections[21].

The economic performance of the project is evaluated considering key financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period over a 20-year project horizon. The analysis also accounts for battery degradation, system efficiency, and the annual increase in electricity prices. The resulting financial indicators of the project over the initial 20 years of operation are presented in Table V.

TABLE V. FINANCIAL INDICATORS

Customer	Commercial customers
The investment cost (VNĐ)	27.615.000.000
WACC (%)	6,88
NPV (VNĐ)	41.300.146.647
MIRR (%)	9,717%
The payback period includes discount rate	6 years 5 months

Based on Table IV, the proposed BESS project for commercial customers is economically feasible. The project achieves a positive NPV of approximately 41,3 billion VND, indicating profitable investment potential. In addition, the MIRR of 9,717% is higher than the WACC of 6,88%, confirming that the expected return exceeds the capital cost. Although the discounted payback period is about 6 years and 5 months, the project still shows good long-term economic performance under the studied conditions.

V. CONCLUSION :

In conclusion, this study confirms that the optimal integration of Battery Energy Storage Systems (BESS) can significantly improve the operational performance of distribution networks under high photovoltaic (PV) penetration. By optimally determining both the placement and capacity of BESS, the proposed framework effectively reduces peak demand, smooths the load profile, mitigates the duck curve effect, and improves voltage regulation across the network.

The simulation results also demonstrate that BESS enhances the hosting capacity of the distribution system and helps defer costly reinforcement by alleviating network congestion and voltage constraints. From an economic perspective, the project is financially feasible for commercial customers, as indicated by the positive NPV and MIRR values exceeding the WACC.

Moreover, the continuous decline in BESS prices together with supportive energy policies in Vietnam is expected to accelerate the adoption of energy storage systems in future power networks. Therefore, BESS can be considered a practical, scalable, and promising solution for improving grid flexibility, supporting large-scale renewable energy integration, and accommodating future high-demand loads such as AI-driven data centers.

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