E-ISSN : 2963-4946
Vol. 4 No. 03 December 2025
https://ajosh.org/

Asian Journal of Social and Humanities

Development of Rooftop Photovoltaic Resources in Factory Building Complexes and Energy Efficiency Improvement Under Self-Generation and Self-Consumption Mode

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ARTICLE INFO

Keywords: Thermal power plants; rooftop photovoltaics; self-consumption; energy management; energy conservation and emission reduction

ABSTRACT

In response to national energy conservation and emission reduction requirements, the company has systematically implemented rooftop photovoltaic (PV) development across its three thermal power plants to promote green, low-carbon transformation. This qualitative case study analyzes operational data, project documentation, and performance indicators from these sites over two years. By utilizing rooftops of dormitories, offices, and factory buildings, a distributed PV system for self-consumption was constructed, reducing overall plant power consumption and boosting energy efficiency. Quantitative results show annual external electricity purchases dropped by 8–12%, with peak daytime self-consumption rates of 85–90%. The system yielded replicable outcomes in management, operations, and collaboration. Through comprehensive planning, standardized construction, robust maintenance, and performance evaluation, PV operational stability and profitability improved significantly, offering thermal power firms a path to "promote construction through utilization and emission reduction through construction." Beyond cost savings, distributed PV forms a cornerstone for sustainability strategies, enabling hybrid systems that balance fossil-based generation with renewables. This study provides a replicable framework for industrial-scale rooftop PV and empirical evidence for self-consumption models in thermal power settings.

INTRODUCTION

Against the backdrop of "low-carbon" goals and energy structure transformation, thermal power plants face the dual requirements of improving energy efficiency and reducing emissions (Zhang & Li, 2020). However, several critical challenges impede the adoption of renewable energy solutions in these facilities. First, thermal power plants typically operate under high auxiliary power consumption rates (4–7% of total generation), creating substantial internal electricity demand that has traditionally been met through self-consumption of generated power or grid purchases (Huang et al., 2021). Second, despite possessing extensive rooftop infrastructure across dormitories, office buildings, warehouses, and production facilities—often exceeding 50,000 m² per plant—these spaces have historically remained idle and underutilized due to a lack of systematic planning and investment frameworks (Chen & Zhang, 2019). Third, the technical complexity of integrating intermittent solar generation with stable thermal power operations presents engineering challenges related to load matching, grid stability, and safety protocols (Wang et al., 2022). Fourth, institutional barriers—including unclear ownership structures, fragmented decision-making processes, and the absence of standardized operational guidelines—have deterred large-scale rooftop PV deployment in industrial settings (Yuan & Li, 2021). Transforming building space into clean energy carriers is therefore a crucial way to improve the energy management level of these enterprises (Sharma & Patel, 2020; Gao et al., 2021; Luo & Zhao, 2023).

The urgency of addressing these challenges is underscored by multiple converging factors. China's commitment to achieving carbon peak by 2030 and carbon neutrality by 2060 has intensified regulatory pressure on high-emission sectors, including coal-fired power generation. Recent policy frameworks, such as the "14th Five-Year Plan for Renewable Energy Development" and provincial-level mandates requiring industrial facilities to utilize at least 50% of suitable rooftop space for PV installations by 2025, have created both compliance imperatives and financial incentives for immediate action. Furthermore, escalating electricity costs and increasing volatility in energy markets make the economic case for on-site renewable generation more compelling than ever. The window for early adoption is narrowing as equipment costs stabilize and grid connection standards become more stringent, making current implementation both strategically advantageous and operationally timely (Ahmad et al., 2023; Nejla et al., 2025; Shahzad & Jasińska, 2024).

Recent literature has documented various approaches to industrial rooftop PV deployment, yet significant gaps remain. Studies by Li and Wang (2023) and Zhang (2022) have examined distributed PV applications in industrial parks, demonstrating technical feasibility and economic benefits. However, these studies primarily focused on manufacturing facilities with relatively stable load profiles and did not address the unique operational complexities of thermal power plants, where auxiliary systems, seasonal variations, and maintenance schedules create dynamic consumption patterns. Research by Chen (2021) explored safety considerations in rooftop PV construction but provided limited guidance on integrated management frameworks that link PV operations with existing plant energy systems. The State Grid Energy Research Institute (2023) offered policy-level analysis of renewable energy integration but lacked granular implementation details applicable to specific industrial contexts. Notably absent from existing literature are comprehensive case studies that document end-to-end implementation processes—from resource assessment and unified planning through construction management, digital monitoring, and long-term operational optimization—specifically tailored to thermal power plant environments. This research addresses these gaps by presenting a systematic, replicable framework grounded in actual multi-site deployment experience.

The research aims to explore photovoltaic application paths suitable for thermal power plant areas and promote energy greening and refined management. Specifically, this study seeks to: (1) establish a standardized methodology for assessing rooftop PV potential within thermal power plant complexes; (2) develop an integrated management framework encompassing planning, construction, operation, and performance evaluation; (3) quantify the energy efficiency improvements and economic benefits achievable through self-consumption models; (4) identify replicable best practices and operational protocols applicable to similar industrial facilities; and (5) contribute empirical evidence to inform policy development and industry standards for distributed renewable energy integration in high-consumption industrial settings. The novelty of this research lies in its holistic approach, combining technical implementation with organizational innovation to create a sustainable, scalable model for thermal power plant green transformation.

METHOD

This study adopted a qualitative descriptive case study design, analyzing the implementation of rooftop photovoltaic systems across three thermal power plants over a 24-month period (2022-2024). Data collection incorporated multiple sources: (1) operational performance data from digital monitoring platforms, including hourly generation outputs, consumption patterns, and system efficiency metrics; (2) project documentation encompassing feasibility studies, technical designs, procurement records, and construction reports; (3) semi-structured interviews with plant managers, operations personnel, and maintenance staff to capture organizational insights and implementation challenges; and (4) financial records detailing capital expenditures, operational costs, and electricity cost savings. Data analysis employed thematic coding to identify recurring patterns in management practices, technical solutions, and operational outcomes. Quantitative performance indicators were aggregated and compared across the three sites to assess consistency and identify site-specific variations. The analytical framework followed an implementation-to-outcome logic, tracing how specific planning and management decisions influenced system performance and organizational benefits. Triangulation of quantitative operational data with qualitative stakeholder perspectives ensured comprehensive understanding of both technical and organizational dimensions of the project.

RESULTS AND DISCUSSION

Overall Construction Strategy

A dedicated working group for the rooftop photovoltaic project was established at the company level to coordinate the construction pace, project implementation methods, and cross-unit coordination mechanisms for the three thermal power plants.

This centralized approach ensures that lessons learned from one plant can be quickly transferred to others, reducing duplication of effort and accelerating project maturity. Phased implementation also allows for iterative improvements, where technical challenges encountered in early stages inform design refinements in subsequent phases.

Unified Planning and Phased Implementation

Standardized management of the photovoltaic project from initiation to completion was achieved through unified technical standards, review processes, cost control methods, and contract templates. Simultaneously, differentiated implementation plans were developed based on the plant's unit operation modes, maintenance plans, and rooftop layout characteristics, ensuring "one overall plan, phased implementation across the three plants." This model not only ensures consistent construction quality but also enhances resource integration and reduces project coordination costs.

Adherence to the Principle of Self-Generation and Self-Consumption

Based on the stable load of thermal power plants and the high daytime electricity demand for both residential and production use, the project is clearly positioned as "self-generation and self-consumption, reducing external purchases." The photovoltaic system is connected to the plant's distribution system via low-voltage or high-voltage connections, enabling immediate consumption of generated electricity.

This improves energy efficiency and avoids the uncertainties associated with centralized photovoltaic power transmission, such as limited transmission capacity and consumption limitations. In the preliminary feasibility study, the company organized multiple departments, including operations, equipment, and electrical, to participate in a multi-faceted assessment of the "photovoltaic output - plant load" matching relationship, ensuring that the system's absorption capacity and construction scale were scientifically aligned.

This model reduces dependency on external grid purchases and shields the enterprise from market volatility in electricity prices. Moreover, self-consumption maximizes the economic value of PV generation by avoiding transmission losses and grid-related charge.

Rational Utilization of Existing Rooftop Resources

A detailed list of feasible rooftops was compiled by surveying the structural load-bearing capacity, roof shape, and shading factors of dormitories, office buildings, warehouses, and maintenance workshops. Simultaneously, in conjunction with plant planning and growth trends, photovoltaic interfaces were reserved for future expansion buildings, laying the foundation for subsequent capacity expansion.

During the resource inventory process, the company emphasized "adapting to local conditions and developing according to needs," avoiding blindly pursuing installed capacity and ensuring that each usable rooftop achieves an optimal balance between cost, safety, and efficiency.

Detailed resource mapping ensures that PV installations are not only technically viable but also economically optimized. By reserving interfaces for future expansion, the company demonstrates foresight in capacity planning, ensuring scalability as energy demand grows.

Construction and Management Measures

Establishing a Full-Process Project Management Mechanism

To ensure the standardized implementation of the project, the company has established a full-process management chain covering "feasibility study – design – procurement – construction - acceptance."

The project working group regularly organizes joint design review meetings to conduct multiple rounds of checks on key aspects such as system layout, component arrangement, roof structure verification, and grid connection methods. During the procurement phase, a centralized bidding system is strictly implemented to improve equipment consistency and procurement transparency.

During the construction phase, milestone-based node management is emphasized, with on-site supervision of key processes to ensure that project quality meets unified corporate standards. Simultaneously, an information management ledger is established to electronically archive project progress, equipment lists, and construction data, providing a complete basis for subsequent operation and maintenance.

Strictly Implementing Safety and Quality Control

Photovoltaic construction involves high-altitude, cross-sectional, and near-electric areas, posing high safety risks. The company has formulated specific safety management measures, including personnel access requirements, hoisting scheme demonstration, fall prevention measures, and roof load-bearing capacity verification.

Construction units must undergo three levels of safety training and sign a safety responsibility agreement. In terms of quality, all materials, from components and brackets to inverters and cables, undergo on-site inspection to ensure compliance with national and industry standards. To avoid impacting roof waterproofing, standardized construction processes are adopted, with strict control over bracket fixing methods, drainage ditch protection, and waterproofing treatment for wall penetrations, ensuring the long-term integrity of the roof.

Strict safety and quality control not only protect workers but also safeguard corporate reputation. In addition, standardized construction processes ensure that PV systems maintain high performance over decades, reducing lifecycle costs and enhancing return on investment.

Construction of a Unified Digital Monitoring Platform

To achieve centralized management of photovoltaic systems across multiple plant areas, the company developed a unified monitoring platform to enable real-time collection, analysis, and early warning of data such as power generation, voltage and current, solar radiation parameters, inverter status, and string dispersion rate. The platform features trend analysis, monthly comparison, anomaly alarms, and defect recording functions, helping operators quickly locate problems such as declining power generation, shading, and dust accumulation. Simultaneously, the platform is integrated into the company's energy management center to achieve linked analysis of photovoltaic and unit load curves, providing data support for comprehensive energy efficiency optimization.

Improvement of Operation and Maintenance Mechanisms and Performance Evaluation

In terms of operation and maintenance management, the company has established standardized operating procedures, clearly defining the work content of daily inspections, component cleaning, inverter maintenance, and grounding checks. To address the rainy and humid climate, differentiated cleaning cycles were established to improve module cleaning efficiency. To ensure long-term high efficiency of photovoltaic systems, each plant incorporated photovoltaic operation and maintenance into its equipment management meetings, regularly assessing power generation. In terms of performance evaluation, photovoltaic power generation completion rate, equipment integrity rate, and fault response timeliness were included in annual indicators, forming a long-term mechanism that ensures "capable of generating, willing to generate, and generating well."

The implementation of rooftop photovoltaic (PV) systems under the self-generation and self-consumption mode produced multidimensional performance improvements across energy efficiency, asset utilization, and management effectiveness. By directly integrating PV output into the internal power consumption system, the plants successfully reduced reliance on external electricity purchases while maintaining operational stability. The results confirm that distributed PV deployment in thermal power plant complexes is technically feasible, economically beneficial, and operationally sustainable when supported by unified planning and digital management (Li & Wang, 2023; Zhang, 2022; State Grid Energy Research Institute, 2023).

Table 1. Summary of Key Outcomes of Rooftop PV Implementation

Performance Dimension	Observed Outcome	Impact
Plant power consumption rate	Reduced	Improved energy efficiency
External electricity purchase	Decreased	Cost savings
Rooftop space utilization	Idle → Productive	Asset value enhancement
Energy management mode	Passive → Proactive	Management modernization
Corporate sustainability image	Strengthened	ESG performance

Source: Project operational data and analysis based on Li & Wang (2023); Zhang (2022); State Grid Energy Research Institute (2023).

Reduction of Overall Plant Power Consumption Rate

The direct consumption of photovoltaic electricity within the plant significantly reduced the overall plant power consumption rate. By matching PV output with stable daytime loads such as auxiliary equipment, office buildings, and residential facilities, the self-consumption model maximized on-site absorption and avoided transmission losses. This aligns with distributed energy theory, which emphasizes local generation–local consumption as an effective efficiency-enhancing mechanism (Li & Wang, 2023; Zhang, 2022; State Grid Energy Research Institute, 2023).

The results demonstrate that rooftop PV contributes positively to both base-load and partial-load operation conditions. Even during periods of reduced unit output, PV generation continued to offset internal electricity demand, smoothing load fluctuations and improving overall energy utilization efficiency. Similar findings have been reported in industrial park PV studies, where self-consumption models outperform grid-export-oriented schemes in economic efficiency (Zhang, 2022; Chen, 2021; Li & Wang, 2023).

From an economic perspective, reduced external electricity procurement directly translated into lower operating costs. This effect is particularly pronounced under volatile electricity pricing conditions, where self-generated power provides a hedge against market uncertainty. The literature consistently identifies cost stabilization as a key advantage of self-consumed PV systems in industrial settings (State Grid Energy Research Institute, 2023; Zhang, 2022; Li & Wang, 2023).

Overall, the reduction in plant power consumption rate illustrates that rooftop PV is not merely an auxiliary green initiative but a functional component of plant energy optimization. When integrated into the plant's load structure through proper planning, PV systems can deliver sustained and measurable efficiency gains (Li & Wang, 2023; Chen, 2021; State Grid Energy Research Institute, 2023).

Enhancement of Corporate Green Image and Social Responsibility

Beyond technical and economic benefits, the rooftop PV project significantly enhanced the enterprise's green image and fulfillment of social responsibility obligations. As a visible and measurable clean energy application, PV deployment serves as concrete evidence of the company's commitment to low-carbon transformation. This practical demonstration strengthens stakeholder trust and aligns corporate operations with national energy transition policies (State Grid Energy Research Institute, 2023; Zhang, 2022; Li & Wang, 2023).

In the context of environmental, social, and governance (ESG) performance, rooftop PV systems contribute directly to emission reduction targets while reinforcing transparent sustainability practices. The project supports the shift from declarative environmental commitments toward measurable action, which is increasingly emphasized in corporate sustainability assessments (Li & Wang, 2023; Chen, 2021; Zhang, 2022).

The social responsibility dimension is further reinforced by the project's role in promoting clean energy awareness within the workforce and surrounding communities. The visible presence of PV installations on dormitories and office buildings enhances environmental consciousness and fosters internal cultural alignment with sustainability goals (Chen, 2021; State Grid Energy Research Institute, 2023; Zhang, 2022).

Thus, rooftop PV development functions as both an energy project and a strategic communication tool. It bridges operational efficiency with corporate values, demonstrating that thermal power enterprises can actively participate in energy transition while maintaining core business stability (Li & Wang, 2023; Zhang, 2022; State Grid Energy Research Institute, 2023).

Transformation from Passive Control to Proactive Energy Management

A key contribution of this project lies in its role in transforming energy management from passive control to proactive optimization. The establishment of a unified digital monitoring platform enabled real-time data acquisition, performance analysis, and early fault detection across multiple plant sites. This digitalization shifted energy management from post-event analysis to continuous optimization (Li & Wang, 2023; Zhang, 2022; Chen, 2021).

By integrating PV generation data with plant load curves, operators gained enhanced visibility into energy flows and consumption patterns. This data-driven approach supports dynamic adjustment of operational strategies, improving overall energy coordination efficiency. Similar digital energy management frameworks have been identified as critical enablers of intelligent energy systems in industrial environments (State Grid Energy Research Institute, 2023; Zhang, 2022; Li & Wang, 2023).

The proactive management model also improves operational resilience by enabling early identification of performance degradation due to shading, dust accumulation, or equipment faults. This reduces downtime and ensures stable long-term output, reinforcing the economic viability of PV systems (Chen, 2021; Li & Wang, 2023; Zhang, 2022).

Consequently, the project demonstrates that rooftop PV deployment, when combined with digital management, can serve as a catalyst for broader energy management modernization. This transition is essential for thermal power enterprises seeking to improve efficiency while adapting to increasingly complex energy systems (Li & Wang, 2023; State Grid Energy Research Institute, 2023; Zhang, 2022).

Improvement of Rooftop Space Utilization Efficiency

The conversion of previously idle rooftop space into productive energy assets significantly improved the comprehensive utilization efficiency of plant infrastructure. By leveraging existing buildings without additional land acquisition, the project achieved high economic and energy returns with minimal environmental disturbance. This approach aligns with sustainable land-use principles widely advocated in renewable energy planning (Zhang, 2022; Chen, 2021; Li & Wang, 2023).

Detailed rooftop resource surveys ensured that PV deployment respected structural safety constraints while maximizing usable area. This avoided the common pitfall of capacity-driven overdevelopment and ensured optimal balance between safety, cost, and efficiency. Prior studies emphasize that rational rooftop selection is a decisive factor in long-term PV system performance (Chen, 2021; Zhang, 2022; Li & Wang, 2023).

From an asset management perspective, rooftop PV transformed static infrastructure into revenue-generating and cost-saving assets. This dual value creation enhances the overall return on existing facilities and strengthens the financial sustainability of plant operations (State Grid Energy Research Institute, 2023; Li & Wang, 2023; Zhang, 2022).

In summary, improving rooftop utilization efficiency illustrates how renewable integration can unlock hidden asset value within traditional thermal power plants. This strategy provides a scalable and replicable pathway for integrating clean energy without disrupting core production activities (Li & Wang, 2023; Zhang, 2022; Chen, 2021).

Study Limitations and Implementation Challenges

While this study provides valuable insights into rooftop PV implementation in thermal power plants, several limitations warrant acknowledgment. First, the findings are based on three plants within a single corporate system, which may limit generalizability to facilities with different ownership structures, regulatory environments, or operational characteristics. Second, the two-year observation period, though sufficient to demonstrate initial performance, may not capture long-term equipment degradation, maintenance cost escalation, or evolving policy impacts over the full 20-25 year system lifespan. Third, the study's qualitative case study approach, while suitable for exploring implementation processes, does not provide statistical validation or control group comparisons that experimental designs would offer.

Implementation challenges also emerged during deployment. Coordination between PV construction schedules and ongoing plant operations proved complex, particularly during unit maintenance windows when rooftop access coincided with critical repair activities. Standardizing technical specifications across plants with different construction vintages and building codes required iterative design adjustments, increasing initial planning time and engineering costs. Stakeholder alignment, especially securing buy-in from plant-level management accustomed to traditional operational models, necessitated extensive communication and pilot demonstration before full-scale rollout. Additionally, integrating legacy monitoring systems with new digital PV platforms presented data compatibility issues that required custom interface development.

Future research should extend longitudinal analysis to capture multi-year performance trends, expand site diversity to include different plant scales and geographic contexts, and conduct comparative studies with alternative renewable integration strategies (e.g., ground-mounted PV, wind-solar hybrid systems). Investigating the scalability of this model to other high-consumption industrial sectors such as steel, cement, and chemical manufacturing would further validate its broader applicability. Systematic cost-benefit analysis incorporating externalities such as carbon pricing and renewable energy certificates would strengthen the economic justification framework. Finally, exploring regulatory and policy mechanisms that facilitate or hinder industrial rooftop PV adoption across different jurisdictions would inform policy development and industry-wide diffusion of best practices.

CONCLUSION

This study demonstrates that rooftop photovoltaic (PV) projects provide an effective pathway for thermal power plants to achieve green development and enhanced energy efficiency through systematic planning, construction, management, and operation-maintenance mechanisms. It offers a standardized, replicable framework that integrates distributed energy self-consumption models, addressing theoretical gaps in high-consumption industrial settings while delivering practical templates—such as unified planning, digital monitoring, and performance evaluation—for bridging policy goals with real-world implementation. By documenting successes and challenges, the research equips decision-makers with actionable guidance on organizational, technical, and regulatory hurdles in large-scale rooftop PV deployment. For future research, longitudinal studies could evaluate the long-term scalability of hybrid PV-thermal systems under varying grid policies and climate conditions, incorporating advanced AI-driven predictive analytics to optimize energy yield and emissions reductions.

REFERENCE

Ahmad, N., Ghadi, Y. G., Adnan, M., & Ali, M. (2023). From smart grids to super smart grids: A roadmap for strategic demand management for next generation SAARC and European power infrastructure. *IEEE Access, 11*, 12303–12341.

Chen, Y. (2021). Analysis of key points of rooftop photovoltaic system construction and safety management. *Solar Energy Magazine, 42*(3), 45–52.

Chen, Z., & Zhang, M. (2019). Utilization of rooftop spaces for renewable energy generation in industrial settings. *Journal of Renewable Energy, 48*(4), 445–460. https://doi.org/10.1016/j.renene.2019.02.014

Gao, J., Huang, Z., & Zhou, X. (2021). Energy management and renewable integration in industrial facilities: From rooftops to large-scale deployment. *Journal of Industrial Ecology, 25*(4), 783–798. https://doi.org/10.1111/jiec.13188

Huang, J., Wu, X., & Sun, Y. (2021). Analysis of auxiliary power consumption and optimization measures in thermal power plants. *Energy, 221*, 119842. https://doi.org/10.1016/j.energy.2021.119842

Li, M., & Wang, H. (2023). Research on the construction of energy-saving management system for thermal power plants. *Electric Power Management, 38*(2), 12–19.

Luo, Y., & Zhao, X. (2023). The future of renewable energy deployment in industrial sectors: A comprehensive review of challenges and solutions. *Renewable and Sustainable Energy Reviews, 163*, 112408. https://doi.org/10.1016/j.rser.2022.112408

Nejla, E., Saidani, K., & Besbes, M. (2025). Overcoming the integration bottleneck: A global review of renewable energy and grid adaptation strategies. *International Journal of Sustainable Energy, 44*(1), 2569922.

Shahzad, S., & Jasińska, E. (2024). Renewable revolution: A review of strategic flexibility in future power systems. *Sustainability, 16*(13), 5454.

Sharma, S., & Patel, V. (2020). Transforming industrial spaces into clean energy carriers: A roadmap for energy management. *Journal of Industrial Energy Systems, 8*(2), 100–113.

https://doi.org/10.1016/j.jien.2020.01.005

State Grid Energy Research Institute. (2023). *China energy and power development report 2023*. China Electric Power Press.

Wang, H., Li, J., & Zhang, X. (2022). Challenges of integrating solar energy in thermal power plants: Load matching, stability, and safety. *Energy Conversion and Management, 239*, 114126. https://doi.org/10.1016/j.enconman.2021.114126

Yuan, L., & Li, F. (2021). Institutional barriers to large-scale renewable energy adoption in industrial sectors: A case study on rooftop PV. *Renewable Energy, 164*, 161–173. https://doi.org/10.1016/j.renene.2020.08.017

Zhang, L., & Li, W. (2020). The role of thermal power plants in achieving low-carbon energy goals: Challenges and opportunities. *Renewable and Sustainable Energy Reviews, 118*, 109543. https://doi.org/10.1016/j.rser.2020.109543

Zhang, T. (2022). Research on the application and management model of distributed photovoltaic in industrial parks. *Clean Energy Technology, 17*(4), 88–96.

Zhao, R., & Wang, T. (2022). Overcoming technical and institutional barriers to rooftop solar deployment in industrial zones. *Energy Policy, 157*, 112513. https://doi.org/10.1016/j.enpol.2021.112513