

Energy Management in Smart Power Systems

Miner Huang

*Yichang Longpanhu School, Yichang, China
Js_em@outlook.com*

Abstract. The sharp increase in residential and industrial electricity demand has overwhelmed legacy grids, leading to frequent energy waste or supply shortfalls. Acting as a “digital brain,” the smart grid continuously monitors demand and generation, then reallocates power in real time through deep data analytics. This review highlights AI-driven forecasting technology that not only anticipates the impact of weather variability on renewable energy generation but also precisely identifies next-day demand peaks, thereby enabling optimized dispatch. When coupled with a dynamic tariff scheme, this technology incentivizes consumers to shift their usage away from peak periods. Additionally, it proactively notifies consumers of low-price windows, helping them reduce energy costs. However, future work must address several key challenges, including high equipment costs, limited rural coverage, and the need to cultivate user awareness. Continuous refinement of grid operations is also essential to ensure power quality. Despite these hurdles, the smart grid remains a pivotal route to a green-energy transition.

Keywords: Smart Grid, Dynamic Pricing, Distributed Energy Storage, Demand Response, Energy Management

1. Introduction

One of the cornerstone technologies in power-system automation is the smart grid, also known as an intelligent or modernized grid. This advanced system transforms the traditional power infrastructure into a more intelligent, efficient, and reliable network by integrating information and communication technologies, advanced sensing and control mechanisms, and sophisticated computing capabilities. Its essence lies in establishing high-performance communication networks and data-transmission systems that enable real-time information sharing and monitoring among all grid components, thereby supporting real-time supervision and remote control [1]. With renewables—especially solar and wind—expanding globally, power-system volatility and uncertainty have escalated. Consequently, energy storage, functioning as a critical buffer and regulator, has become increasingly prominent. Furthermore, in the face of contingencies and natural disasters, storage systems provide vital emergency power supplies [2].

This study focuses on how smart grid technologies mitigate the core challenges of renewable energy volatility and real-time power supply-demand imbalance. This research provides essential technical references for constructing new power systems that integrate high-penetration renewable

energy sources. This is crucial for modernizing the grid to accommodate the increasing share of renewables.

2. Storable energy resources

2.1. Solar-photovoltaic systems

The fundamental mechanism of solar generation is the absorption of photons by semiconductor materials, such as silicon cells. The photon energy excites electrons, which then migrate under the built-in electric field of the PN junction to form a direct current. Consequently, the output power is dependent on irradiance, temperature, and cell efficiency [3]. Given the significant fluctuations induced by weather, the operation of photovoltaic (PV) systems relies heavily on intelligent forecasting, coordinated storage solutions (such as batteries or pumped hydro), and distributed control for volatility management. For rooftop PV and other distributed generators, effective operation is inseparable from smart metering and communication systems that maintain real-time power balance [4].

The computational formula is as follows [5]:

$$P_{PV} = A \times \eta \times G \times (1 - 0.005 (T_{amb} + 0.025G - 25)) \quad (1)$$

Where P_{PV} represents the output power in watts (W); A denotes the area of the photovoltaic panel in square meters (m^2); η is the photoelectric conversion efficiency, typically ranging from 15% to 22%; G signifies the solar irradiance in watts per square meter (W/m^2); T_{amb} is the ambient temperature in degrees Celsius ($^{\circ}C$).

This formula takes into account the impact of ambient temperature on the output power of photovoltaic panels, with the temperature coefficient used to adjust for the effects of temperature variations on the photoelectric conversion efficiency. By employing this formula, we can more accurately predict and calculate the actual output power of photovoltaic systems under different environmental conditions.

2.2. Wind-power systems

Wind-power generation involves the conversion of aerodynamic energy into electrical energy. The process begins with wind driving the blades of a turbine, which transforms the kinetic energy into mechanical energy through the forces of lift and drag. This mechanical energy is then increased in rotational speed by a gearbox to drive an alternating current (AC) generator [6]. The expansion of wind energy has been rapid, with China's renewable energy installed capacity surpassing thermal power for the first time in 2023, accounting for more than half of global additions. Specifically, China added 75.9 GW of new wind capacity from January to December 2023, marking a year-on-year increase of 102 %.

The computational formula is as follows [7]:

$$P_{wind} = \frac{1}{2} \rho A v^3 C_P \quad (2)$$

Where P_{wind} is the output power in watts (W); ρ is the air density in kilograms per cubic meter (kg/m^3), approximately 1.225 under standard conditions. A is the rotor swept area in square meters

(m^2), calculated as ($A = \pi r^2$); v is the speed of the wind in meters per second (m/s); C_p is the power coefficient, with a theoretical limit of 0.59 and a practical range of 0.35 to 0.45.

This formula allows for the calculation of the potential output power of a wind turbine given the air density, the area swept by the rotor, the wind speed, and the power coefficient, which is a measure of the turbine's efficiency in converting wind energy into mechanical energy.

3. Smart-grid mechanisms for power monitoring and allocation

Smart grids achieve efficient energy management through a “sense-analyze-decide” closed loop.

3.1. Real-time monitoring

Smart meters equipped with communication chips are installed in every household or factory, autonomously uploading consumption data that record which appliances were used, when, and how much energy they drew. The data collection frequency of smart meters varies significantly depending on application scenarios and monitoring requirements. In accordance with national standards, State Grid smart meters utilize a fixed 15-minute data collection cycle, amounting to 96 readings per day, to meet the specifications outlined in the DL/T 645 communication protocol. For energy monitoring systems in public buildings, a 5-minute interval is recommended, striking a balance between data precision and system load, with this interval resulting in 288 readings daily. Key energy-consuming units' online monitoring systems implement the 15-minute real-time data collection standard. In industrial settings, factory energy management requires high-frequency 15-second collection to meet process monitoring needs, while specialized industrial control systems may demand millisecond-level (e.g., 100ms) real-time data capture. Contemporary smart meter systems typically offer the flexibility to configure data collection cycles, allowing adjustments from as short as 10 minutes to as long as 1 hour, to accommodate various monitoring needs and optimize system performance. This tiered collection frequency design ensures both standardized data exchange for grid-level applications (e.g., State Grid's 96-points/day) and meets precision energy management needs in industrial/commercial scenarios, demonstrating the technical advantages of smart metering devices in protocol compatibility and application adaptability [8]. Smart meters provide users with integrated electricity management solutions through four core capabilities. Real-time power monitoring enables immediate detection of abnormal consumption to prevent electrical hazards like short circuits or overloads. The remote operation feature eliminates manual meter reading through wireless data transmission, reducing operational costs. Energy optimization algorithms analyze historical usage patterns to automatically suggest efficiency improvements, achieving consumption reduction. Interactive dashboards visually present consumption trends through dynamic charts and comparative analytics, enhancing consumer energy awareness. These interconnected functions establish a secure, efficient and user-friendly smart electricity ecosystem that transforms traditional power management.

3.2. Dynamic allocation

Adhering to the principle of prioritizing self-consumption, particularly for locally generated renewable energy sources like rooftop photovoltaic (PV) systems, any excess energy produced is stored in batteries. This stored energy can subsequently be traded on the power market. This approach helps to balance supply and demand, enhancing the overall efficiency and reliability of the energy grid. When storage is full and generation exceeds demand, the system automatically sells the

excess to the grid—preferably during high-price windows. AI-powered energy management systems leverage historical and real-time data to build high-precision predictive models that transform traditional energy operations into intelligent, proactive processes. By accurately forecasting energy demand across hourly, daily, and weekly timeframes, these systems enable optimized procurement and scheduling while continuously monitoring consumption patterns to instantly detect anomalies that may indicate equipment malfunctions or operational inefficiencies. The integration of renewable energy forecasts allows for dynamic balancing between conventional and clean power sources, maximizing the utilization of sustainable energy. Beyond predictive analytics, these AI systems autonomously execute optimization strategies by intelligently adjusting high-energy equipment parameters, strategically scheduling energy-intensive operations during off-peak pricing periods, and implementing predictive maintenance protocols based on continuous equipment performance analysis. This comprehensive approach creates a closed-loop intelligent management ecosystem that fundamentally shifts energy management from reactive troubleshooting to proactive optimization, delivering substantial improvements in operational efficiency, cost reduction, and sustainability performance across industrial and commercial energy systems [9]. A pilot in Shanxi, after one year of data accumulation, increased independent-storage revenue by 10 %. Static simulations of this station yielded an average daily profit of 60 k CNY, peaking at 400 k CNY. Yet achieving the 400 k CNY figure requires high-price windows that appear more frequently in July–August. The challenge is that these lucrative trading windows often last only 15–30 minutes. Leveraging AI to capture market signals, sense system states, and rapidly control equipment to exploit these fleeting opportunities is a complex systems-engineering task [10].

3.3. Intelligent decision-making

Cloud-based control centers use big-data forecasting models (historical load + weather forecasts) to pre-schedule regional energy. For instance, if tomorrow is predicted to be overcast (low PV output), the system will charge storage overnight with low-price electricity to reduce daytime expensive purchases. The application principles can be summarized as shown in Figure 1.

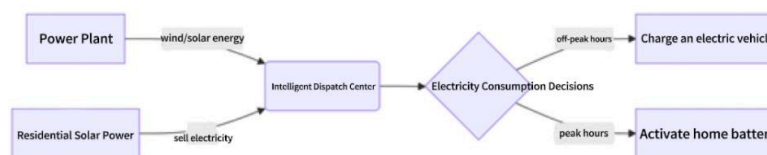


Figure 1. Application principles

4. Discussion

In power-system automation, energy-storage and dispatch technologies are pivotal. Storage refers to preserving energy in a physical medium for later release to balance supply and demand, whereas dispatch involves arranging generation and consumption economically, safely, and efficiently. Technologies range from batteries and pumped hydro to compressed-air energy storage. When

demand exceeds generation, stored energy is discharged; conversely, excess generation is stored. This flexibility mitigates renewable variability: wind and solar are climate-dependent, but storage allows these otherwise curtailed resources to be banked and dispatched as needed. Dispatch also encompasses intelligent scheduling and optimization of grid devices [1].

Nonetheless, smart-grid storage faces numerous challenges. The foremost is reconciling renewable volatility with system-stability requirements, manifesting as ramping shortfalls: sudden drops in renewable output demand rapid grid adjustments. For instance, in 2024, the Northeast China grid faced a demand for an 8.01 GW ramp within a 40-minute timeframe. However, thermal plant ramp rates of only 0.65% per minute were recorded, which was significantly below the required standards and led to frequency instability. Such fluctuations degrade power quality and can trigger blackouts, exemplified by Spain's nationwide outage in April 2025 attributed to voltage-control failure—underscoring grid vulnerability at high renewable penetration. Storage systems must discharge during peaks and charge during troughs, imposing stringent requirements on efficiency, capacity, and response speed. Moreover, monitoring storage health is difficult: batteries' real capacity, state-of-health, and round-trip efficiency vary with age and usage. Rural and remote western regions still lack robust grid infrastructure, and their smart upgrades demand time and capital. Beyond technology, ensuring appropriate conductor and meter materials during high-load periods is essential to prevent short-circuits and maintain regional grid stability.

5. Conclusion

This paper analyzes key technologies, applications, and challenges of smart grids and energy management. Results indicate that digitalization, automation, and distributed-resource integration markedly enhance system efficiency, reliability, and sustainability. Technical bottlenecks—data security, storage costs—still require interdisciplinary collaboration. Smart-grid deployment is not merely technological innovation but an infrastructural reconfiguration of the energy system: real-time pricing and demand-side management engage consumers in conservation, foster emerging markets (storage, EVs, microgrids), and advance “dual-carbon” goals by curbing fossil-fuel dependence.

Future research should focus on three key directions to advance smart energy systems: First, it should deepen the integration of AI and blockchain technologies in power dispatch operations to enhance the security of massive datasets and strengthen privacy protection. Second, efforts must concentrate on refining smart-grid interoperability standards while establishing incentive mechanisms for regional demonstration projects to accelerate practical implementation. Third, researchers should explore innovative business models such as shared energy storage systems and virtual power plant architectures, which could significantly reduce the financial barriers to grid modernization and retrofitting costs. Together, these strategic research priorities would drive both technological innovation and market transformation in the energy sector.

The convergence of smart grids and energy management signals a paradigm shift from “passive supply” to “interactive energy.” Despite hurdles, its potential to enhance energy resilience and green development is irreplaceable. Sustained technological innovation, supportive policies, and international collaboration are essential to build a cleaner, more efficient, and inclusive modern energy system.

However, several limitations should be acknowledged. First, the study primarily relies on recent case studies and pilot projects, which may not fully capture long-term operational challenges or scalability issues in diverse geographical and infrastructural contexts. Second, the discussion on AI and blockchain integration remains theoretical in parts, as large-scale implementations are still in

early stages, limiting empirical validation. Future studies could incorporate longitudinal data and cross-regional comparisons to strengthen generalizability. Two notable limitations warrant consideration: First, the empirical literature exhibits geographical gaps, particularly regarding developing regions such as Africa and South Asia, potentially constraining the generalizability of technical findings across diverse infrastructural contexts. Second, the rapid evolution of smart grid technologies means certain referenced technical parameters (2023-vintage) have since undergone iterations, necessitating ongoing verification with the latest industry benchmarks to maintain analytical relevance.

References

- [1] Wu, J. Y. (2024). Application of automated power system technology in energy transition. *Engineering Construction New Technology*, 12. <https://doi.org/10.37155/2811-0609-0312-60>
- [2] Mei, Q., & Zhou, X. L. (2024). Innovations in energy storage and management under the construction of new power systems. *China Science and Technology Journal Database, Industrial A*, 11, 92-94.
- [3] Green, M. A. (2020). *Solar cells: Operating principles, technology and system applications* (pp. 32–35). UNSW.
- [4] U.S. Department of Energy. (2022). DOE Report Integrating Renewable Energy into the Smart Grid, DOE/EE-2041. https://www.energy.gov/sites/default/files/2022-05/2020%20Smart%20Grid%20System%20Report_0.pdf
- [5] Stein, J., & Maugeri, G. (2024). Performance analysis of photovoltaic power generation systems. <https://iea-pvps.org/wp-content/uploads/2024/07/Chinese-Task-13-Bifacial-Factsheet.pdf>
- [6] Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2022). *Wind energy explained* (pp. 87–92). Wiley.
- [7] Burton, T., Sharpe, D., Jenkins, N., & Bossanyi, E. (2001). *Wind energy handbook*. John Wiley & Sons, Ltd. https://library.uniteddiversity.coop/Energy/Wind/Wind_Energy_Handbook.pdf
- [8] Ji Xiang Technology. (2024). How often does the smart meter collector collect data? <https://www.techphant.cn/blog/95894.html#:~:text=%E6%99%BA%E8%83%BD%E7%94%B5%E8%A1%A8%E9%87%87%E9%9B%86%E5%99%A8%E7%9A%84%E9%87%87%E9%9B%86%E9%A2%91%E7%8E%87%E5%9B%A0%E5%BA%94%E7%94%A8%E5%9C%BA%E6%99%AF%E5%92%8C%E5%85%B7%E4%BD%93%E9%9C%80%E6%B1%82%E8%80%8C%E6%9C%89%E6%89%80%E4%B8%8D%E5%90%8C,%E6%AF%8F%E5%A4%A9%E5%85%B1%96%E6%AC%A1%E3%80%82>
- [9] Tencent Cloud. (2025). Energy efficiency optimization: Application practices of AI large models in energy consumption management.. <https://cloud.tencent.com/developer/news/2589689#:~:text=AI%E5%A4%A7%E6%A8%A1%E5%9E%8B%E8%B5%8B%E8%83%BD%E8%83%BD%E8%80%97%E7%AE%A1%E7%90%86%E7%9A%84%E5%8E%9F%E7%90%86, AI%E5%A4%A7%E6%A8%A1%E5%9E%8B%E8%83%BD%E5%A4%9F%E6%95%B4%E5%90%88%E6%9D%A5%E8%87%AA%E4%BC%81%E4%B8%9A%E5%86%85%E5%A4%96%E9%83%A8%E7%9A%84%E5%A4%9A%E6%BA%90%E5%BC%82%E6%9E%84%E8%83%BD%E8%80%97%E7%9B%B8%E5%85%B3%E6%95%B0%E6%8D%AE%E3%80%82>
- [10] China Energy Transformation Program. (2024). China Energy Policy Newsletter. <https://www.cet.energy/2024/11/15/china-energy-policy-newsletter-november-2024/>