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INTERNATIONAL TRENDS IN IMPROVING THE OPERATIONAL EFFICIENCY OF RENEWABLE ENERGY ASSETS: TECHNICAL AND ECONOMIC APPROACHES

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Abstract

The article examines trends in improving the operational efficiency of renewable energy assets, taking into account the interrelation between technical and economic approaches to their operation. It is shown that current management practice for solar and wind facilities is increasingly based on digital monitoring, predictive maintenance, generation forecasting, energy storage integration, and operating cost optimization. The approaches applied in the United States, Kazakhstan, and a number of countries with a developed renewable energy sector are analyzed. It is established that the most promising model is integrated asset management, in which technical reliability, system flexibility, and economic performance are treated as interrelated elements of a unified operational strategy.

Keywords: *renewable energy, operational efficiency, asset management, predictive maintenance, digital monitoring, operating costs*

Introduction

Renewable energy development is increasingly shaped not only by the expansion of solar and wind capacity, but also by growing attention to the operational efficiency of assets already in service. At this stage, the competitiveness of renewable energy facilities depends not only on electricity output, but also on stable generation, high technical availability, controlled operating costs, and predictable financial results. The relevance of this study lies in the fact that improving operational efficiency is becoming a key factor in the resilience of energy companies under growing infrastructure complexity and long-term asset value management requirements.

The purpose of this study is to analyze international trends in improving the operational efficiency of renewable energy assets through a comparison of technical and economic approaches used in current management practice. Particular attention is paid to the relationship between technical operating parameters and the economic outcomes of asset management.

Methods

The methodological framework of the study was based on the analysis, synthesis, comparison, and generalization of academic literature, industry analytical materials, and international operational practices related to solar and wind power facilities. To identify stable approaches to improving efficiency, the study used a comparative analysis of engineering solutions in monitoring, maintenance, diagnostics, and digital asset management, as well as economic instruments associated with operating cost optimization, improved equipment availability, and higher financial returns. In addition, a systems approach was applied, allowing operational efficiency to be examined as the result of the interaction between technical reliability parameters, organizational management mechanisms, and economic criteria for evaluating operational performance.

Operational efficiency of renewable energy facilities: content and key indicators

Under current conditions, the operational efficiency of renewable energy facilities should be regarded as an independent asset management category rather than merely a derivative of installed capacity or electricity output. This perspective is justified by the scale of growth in the sector itself: according to IRENA, global renewable energy capacity additions reached 692 GW in 2025, bringing total installed renewable capacity to 5,149 GW, while renewables accounted for 85.6% of total power capacity additions worldwide (International Renewable Energy Agency, 2026).

From a theoretical perspective, the operational efficiency of a renewable energy asset is an integral characteristic reflecting its ability to provide the maximum possible and stable useful output at an acceptable level of operating costs, technical losses, and downtime. To present the content of operational efficiency more clearly, it is advisable to systematize the main indicators used for its assessment (table 1).

Table 1. *Main indicators for assessing the operational efficiency of renewable energy facilities*

Indicator	Description	Significance for assessing operational efficiency
Technical availability of equipment	Reflects the share of time during which the equipment remains in working condition and is able to perform its functions.	Demonstrates operational reliability and the ability of the facility to ensure continuous electricity generation.
Capacity factor	Shows the extent to which the installed capacity of the facility is utilized over a given period.	Makes it possible to assess actual operating performance and compare potential and real electricity output.
Duration and frequency of downtime	Shows the length and recurrence of equipment shutdowns caused by failures, maintenance, or external constraints.	Allows assessment of operating stability and the effect of disruptions on total electricity generation.
Technical losses	Includes electricity losses associated with conversion, transmission, equipment limitations, and deviations from normal operating conditions.	Characterizes the extent to which actual results differ from the technically achievable level.
Compliance with operating standards	Reflects the degree to which technical requirements, design conditions, and operating regulations are observed.	Allows assessment of operational correctness and the risk of reduced reliability and equipment lifetime.
Operating costs	Includes expenses related to maintenance, repair, diagnostics, monitoring, and associated operational processes.	Shows the economic efficiency of operation and the cost level required to maintain asset performance.

Indicator	Description	Significance for assessing operational efficiency
Recovery time	Characterizes the time required to eliminate a failure and return the equipment to normal operation.	Reflects the quality of operational management and affects the volume of lost electricity generation.

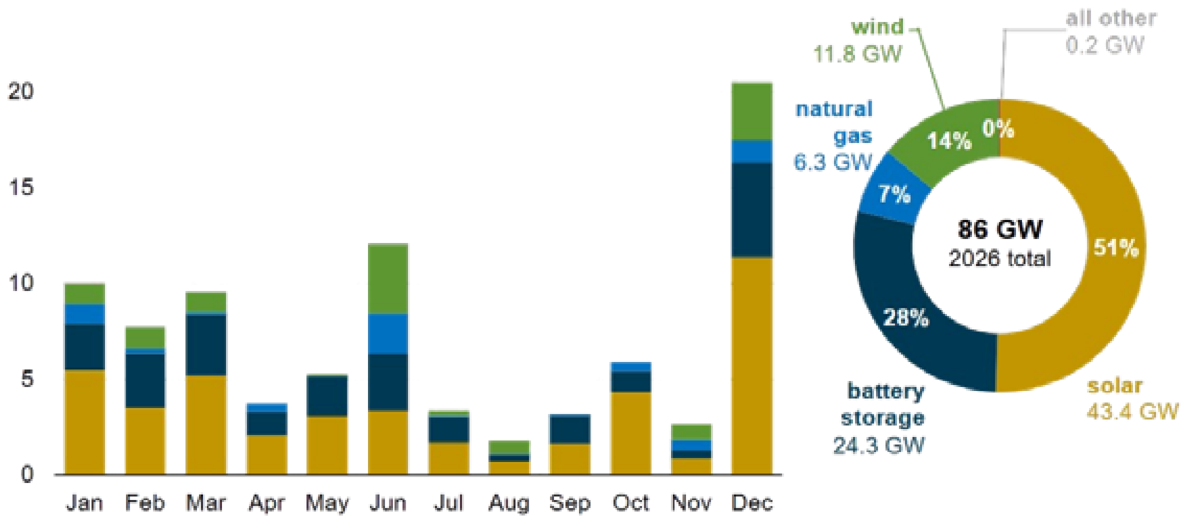
The quantitative relevance of these indicators is evident from the wide variation in operating results even among technologically mature renewable energy facilities. According to NREL, the expected capacity factor for utility-scale solar PV ranges from 21.4% to 34.0%, while U. S. Energy Information Administration (EIA) data for the United States in 2024 show actual monthly values of 13.4–31.6% for utility-scale solar and 25.2–43.7% for wind power. At the same time, Fraunhofer ISE reports that the typical performance ratio of modern photovoltaic systems in 2025 is about 80–90%, while NREL uses an availability benchmark of about 95% for wind assets. These data indicate that operational efficiency should be understood as a multidimensional characteristic shaped by resource conditions, technical reliability, maintenance quality, and operating management rather than by installed capacity alone.

International application of technical solutions to improve the operational efficiency of renewable energy assets

Efforts to improve the operational efficiency of renewable energy facilities are becoming less reliant on routine maintenance and more dependent on continuous operational data. This shift is reflected in models combining SCADA monitoring, forecasting, predictive analytics, digital twins, storage, and flexible dispatch control. The International Energy Agency (IEA) links this process to successive phases of VRE integration, while the World Bank/ESMAP emphasizes forecasting for lower balancing costs and curtailment, and IEA PVPS highlights digital twins for photovoltaic performance analysis, predictive maintenance, and lifecycle decision support.

At present, the most advanced technical model can be observed in the **United States**, where improvements in operational efficiency are increasingly based on the combination of data-driven O&M and the accelerated integration of energy storage systems. Based on the data from the EIA, it is clear that solar energy production combined with storage and utility-scale storage were anticipated to account for 81% of all new capacity additions in 2025. The latter was estimated to increase by 18.2 GW. In 2026, the operators of U.S. power plants have planned to expand their capacity by 86 GW (fig. 1).

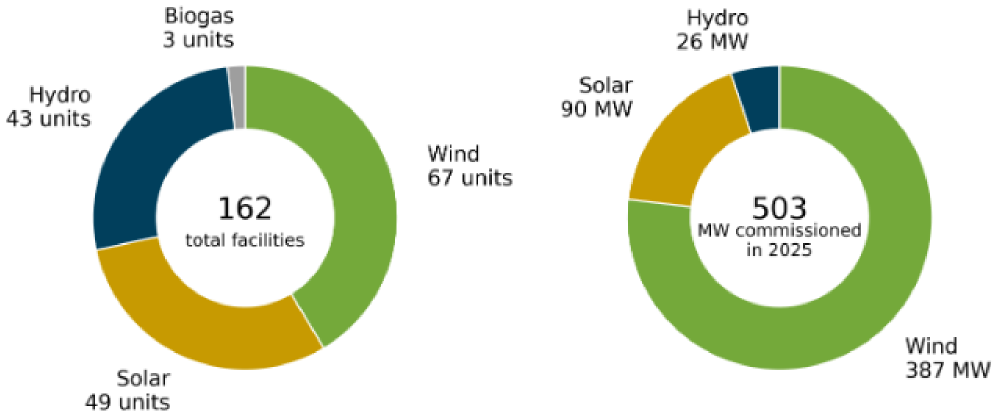
Figure 1. *Structure of planned new utility-scale generating capacity additions in the United States in 2026, GW (EIA, 2026)*



For operational practice, this means a shift from managing an individual power plant to managing a hybrid energy asset, where efficiency is determined not only by electricity output, but also by the ability to smooth the generation profile and support grid stability. U.S. practice is also characterized by a high level of maturity in the analysis of operational data: reliability studies of utility-scale solar use the PVROM database, which contains operations, maintenance, and production records for more than 50,000 O&M tickets from 837 sites across the United States.

In **Kazakhstan**, the adoption of modern technical solutions in renewable energy is developing under conditions of rapid transformation of the entire power system. According to expert estimates, whereas 10–12 years ago the total installed capacity of renewable energy facilities in the country was about 200–250 MW, by early 2026 it had approached 3.5 GW. At the same time, the share of renewables in annual electricity generation reached 7% by 2025 and continues to grow (fig. 2).

Figure 2. *Structure of operating renewable energy facilities in Kazakhstan and structure of newly commissioned renewable energy capacities in 2025 (Ministry of Energy of the Republic of Kazakhstan, 2025)*



Under these conditions, the technical priority is shifting from simply expanding installed capacity to improving the flexibility, stability, and controllability of the power system. Greater importance is now attached to flexible generation, energy storage, digital monitoring, and accurate forecasting, since system reliability depends not only on the scale of new capacity additions, but also on the quality of grid integration. Overall, Kazakhstan is moving toward a more advanced model of renewable asset operation, in which operational efficiency depends on grid integration, generation predictability, balancing resources, and the maturity of energy infrastructure management. This direction is consistent with the national target of carbon neutrality by 2060 and was further supported in 2025 by memorandums signed with the European Investment Bank and the EBRD to finance renewable energy, grid modernization, and large hydropower projects.

European practice shows that as the share of renewables rises, technical solutions become increasingly specialized and focused on system flexibility. **Denmark** remains one of the clearest examples: according to the latest fully reported annual data, wind and solar generation reached 24,329 GWh in 2024 and covered 63% of national electricity demand, confirming the country's position as a leader in variable renewable energy integration. In **Germany**, however, we see a distinct approach, where, in 2025, renewables supplied 55.9% of gross public power production, wind still led as the source of power production, while photovoltaic production grew by 21%, surpassing lignite power production for the first time. All of these examples demonstrate that, when renewable energy production is mature enough, efficiency does not rely exclusively on growth in power production capacity.

An example of Asian practice is **China**, which demonstrates a large-scale model of digitally and market-managed renewable energy operation with a pronounced dominance of solar generation. According to official data, by the end of 2025 the country's installed solar capacity had reached 1.2 billion kW, while installed wind capacity amounted to 640 million kW. This indicates that the specific feature of the Chinese model lies primarily in the large-scale expansion of photovoltaic systems, whose integration requires grid adaptation, digital control, and market-based coordination of operating modes.

From a comparative perspective, Denmark can be seen as a benchmark of system flexibility, Germany as a benchmark of technological modernization of the existing fleet, and China as a benchmark of scalable digital operation and a high level of installed capacity utilization.

International organizations and cooperative platforms play an important role in shaping these approaches by transforming fragmented national practices into reproducible technical solutions. The IEA provides a framework for assessing renewable integration maturity, the World Bank/ESMAP develops guidance on forecasting and grid integration, IEA PVPS systematizes reliability and digital twin solutions for photovoltaics, and IEA Wind Task 43 advances data standards and digital O&M models for wind energy. As a result, the international trend is shifting from operating renewable facilities in isolation to managing them as part of a digitally coordinated energy ecosystem spanning equipment, plants, the grid, and the overall asset portfolio.

Economic mechanisms of operational efficiency in renewable energy assets

In international practice, the operational efficiency of renewable energy assets is increasingly assessed from the perspective of economic performance. At a mature stage of sector development, competitiveness depends not only on new capacity additions, but also on stable output, controlled operating costs, acceptable electricity cost, and predictable financial results. Under these conditions, renewable asset management includes not only project capital parameters, but also O&M optimization, contractual mechanisms, energy storage, and portfolio management (table 2).

Table 2. *Main economic instruments for improving the operational efficiency of renewable energy assets (Emblemsvåg, 2025; Abreu et al., 2025)*

Instrument	Economic content	Significance for improving operational efficiency
LCOE-based management	Assessment of the cost of electricity over the asset life cycle, taking into account both capital and operating expenditures.	Makes it possible to relate technical decisions to the long-term economic efficiency of the project.
O&M cost management	Control and optimization of expenditures on maintenance, repair, diagnostics, and monitoring.	Contributes to reducing specific operating costs while maintaining equipment reliability.
Performance-based contracts	Contractual arrangements in which the operator's compensation depends on achieved operational results.	Increases the operator's responsibility for availability, output, response time, and loss reduction.
Integration of energy storage	Use of storage systems to smooth the generation profile and increase the economic value of delivered electricity.	Reduces losses associated with curtailment and improves revenue stability.
Portfolio asset management	Operational decision-making based on the combined profitability and risk profile of a group of assets.	Makes it possible to coordinate maintenance, modernization, and resource allocation at the portfolio level.

The economic significance of these instruments is reflected not only in the cost of electricity, but also in the structure of operating expenditures and in the ability to maintain asset performance over time. In this context, the efficiency of renewable energy asset operation depends on how effectively technical reliability is translated into controllable costs, stable output, and lower revenue losses. Therefore, economic assessment at the operational stage is primarily associated with O&M cost management, the design of contractual incentives, the use of energy storage, and coordination at the portfolio level.

For example, in the United States, the U. S. Department of Energy estimates utility-scale PV O&M at about $19/kW DC per year for a 100 MW DC plant, while NREL reports a possible range of $0–$40/kW DC depending on project configuration and market conditions. For fixed-bottom offshore wind, total OpEx is estimated at $135/kW per year. At the same time, according to IRENA, the total installed cost of utility-scale BESS declined by 93% between 2010 and 2024, from $2,571 to $192/kWh. This indicates that economically efficient renewable energy operation depends not on simple cost reduction, but on cost optimization combined with reliability, flexibility, and effective asset management.

Thus, the economic performance of renewable energy assets should be assessed not only through electricity cost, but also through operating expenditure structure, contractual flexibility, and revenue resilience under changing system conditions (Lin & Zhu, 2025). Economically efficient operation therefore depends on the coordinated use of cost management, storage integration, and portfolio-level decision-making, forming a more integrated asset management model in which technical and economic parameters are treated as interdependent elements of operational efficiency.

Current trends in the integration of technical and economic mechanisms in renewable energy asset management

The current stage of renewable energy development is characterized by a transition from the separate use of engineering and financial instruments to their integration into a unified asset management system. Whereas technical operation was previously viewed mainly as a task of maintaining equipment functionality and economic efficiency as the result of investment and tariff parameters, these dimensions are now increasingly functioning as an interconnected management model (Eleiwi & Habeeb, 2025).

In practice, this means that improving the operational efficiency of renewable energy assets is increasingly based on a **data-driven management** architecture in which technical data are used directly for economic optimization. Digital twins, advanced SCADA monitoring, predictive analytics, IoT components, and decision-support tools are applied not only for equipment diagnostics, but also for selecting the most rational maintenance scenario, planning repairs, and reducing the risk of underproduction.

Artificial intelligence occupies a special place in this model because it already produces measurable effects in forecasting and maintenance of renewable energy assets. A 2025 systematic review in Energy Strategy Review showed that generative adversarial network models can reduce RMSE in solar forecasting by about 15–20% (Khouili, 2025). In photovoltaic maintenance, a 2025 review reported that CatBoost and Random Forest models achieved accuracy above 99% in multiclass fault diagnosis and PV performance prediction tasks (Vichare & Gaikwad, 2025). Together with digital twins, these results reflect a shift from simple digitalization to intelligent management aimed at better maintenance decisions and lower revenue losses.

One of the clearest international trends is the integration of **flexibility into operational efficiency management.** As the share of renewables grows, output and availability alone are no longer sufficient, since curtailment, grid integration quality, temporal shifting of generation, and participation in balancing processes become increasingly important. The IEA notes rising curtailment in major markets, and reports that curtailed renewable generation in the European Union exceeded 10 TWh in 2024. This reflects a shift from measuring how much energy an asset produces to assessing how controllable, economically valuable, and system-integrated that generation is.

Another important trend is the **increasing scale of renewable energy facilities and the growing complexity of renewable asset portfolios**, under which operation can no longer be viewed as a set of isolated technical tasks and instead becomes a full-fledged management function. As projects move toward capacities measured in hundreds of megawatts and operators manage multiple heterogeneous assets simultaneously, the role of operational analytics, failure forecasting, coordinated maintenance decisions, and systematic workforce management becomes more significant (Joaqui-Barandica et al., 2025). Under these conditions, companies that invest early in a mature operating model achieve more stable output, greater predictability of financial performance, and a higher level of resilience to technical and organizational risks.

The economic integration of technical solutions is especially visible in the link between digitalization and storage economics. Falling storage costs and the growing role of batteries make storage not only a reliability tool, but also a means of improving generation revenues. According to IRENA, the total installed cost of utility-scale battery storage fell to $192/kWh in 2024, while the IEA reports continued battery price declines and about 63 GW of new utility-scale storage added in the power sector. At the same time, IRENA notes that 91% of new utility-scale renewable projects commissioned in 2024 generated electricity more cheaply than the cheapest new fossil-fuel alternative. As a result, asset management increasingly evaluates forecasting, diagnostics, storage integration, and dispatch through their impact on LCOE, O&M, curtailment losses, and cash-flow stability.

Thus, current international trends point to a new renewable energy asset management model in which operational efficiency results from the integration of digital maturity, technical reliability, system flexibility, and economic controllability. This approach combines forecasting, equipment assessment, contract design, storage investment, and portfolio management within a single decision-making logic and appears to be the most promising for ensuring stable and profitable operation across the asset life cycle.

Conclusion

In current international practice, improving the operational efficiency of renewable energy facilities goes beyond the local refinement of individual operating procedures and increasingly takes the form of a complex management task. The efficiency of renewable energy assets is determined not only by the technical condition of equipment and the volume of generation, but also by the quality of integration of technical, digital, and economic mechanisms into a unified decision-making system. This approach makes it possible to view operation as a strategic function in which reliability, flexibility, controllability, and economic performance are shaped in interaction rather than in isolation.

On this basis, it can be assumed that the further development of renewable energy asset management models will be associated with the deepening of data-driven approaches and the wider use of intelligent analytics, digital twins, energy storage, and portfolio-based coordination methods. A particularly promising model is one in which technical decisions are assessed not only from the standpoint of engineering feasibility, but also in terms of their impact on financial resilience, power system adaptability, and the long-term value of the asset. It is precisely this management logic that creates the foundation for more mature, resilient, and economically grounded operation of renewable energy facilities throughout their entire life cycle.

References

Abreu, S., Rodrigues, F., & Pereira, J. (2025). Clustering of renewable energy assets to optimize resource allocation and operational strategies. Journal of Intelligent Information Systems, – 63 (3). –P. 831–853.

EIA. (2026) New U. S. electric generating capacity expected to reach a record high in 2026. U.S. [cited: 03.04.2026]. Available from: https://www.eia.gov/todayinenergy/detail.php?id=67205

Eleiwi, M. A., & Habeeb, L. J. (2025). Strategic engineering management for renewable energy projects: Trends, challenges, and future outlook. African Journal of Economics and Business Research, – 1 (2).

Emblemsvåg, J. (2025). Rethinking the "Levelized Cost of Energy": A critical review and evaluation of the concept. Energy Research & Social Science, – 119. – 103897 p. URL: https://doi.org/10.1016/j.erss.2024.103897

International Renewable Energy Agency. (2026) Renewable Capacity Statistics 2026. [cited: 03.04.2026]. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2026/Mar/IRENA_DAT_RE_capacity_statistics_2026.pdf

Joaqui-Barandica, O., Manotas-Duque, D. F., & Uribe, J. M. (2025). Pathways to specialized renewable energy generation: insights from integer portfolio optimization in a globalized electricity market. Energy, Sustainability and Society, – 15 (1). – 11. URL: https://doi.org/10.1186/s13705–024–00508–6

Khouili, O. (2025). Evaluating the impact of deep learning approaches on solar and photovoltaic power forecasting: A systematic review. Energy Strategy Reviews, – 59. – 101735 p. URL: https://doi.org/10.1016/j.esr.2025.101735

Lin, B., & Zhu, Y. (2025). Supply chain configuration and total factor productivity of renewable energy. Renewable and Sustainable Energy Reviews, – 209. – 115140 p. URL: https://doi.org/10.1016/j.rser.2024.115140

Ministry of Energy of the Republic of Kazakhstan. (2025) Half a gigawatt of green energy: 9 renewable energy projects were launched in Kazakhstan in 2025. [cited: 03.04.2026]. Available from: https://www.gov.kz/memleket/entities/energo/press/news/details/1137212

Vichare, R. V., & Gaikwad, S. R. (2025) AI-based predictive maintenance of solar photovoltaics systems: A comprehensive review. Energy Informatics, – 8 (1). – 128 p.

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