

Modernization of Relay Protection and Automation Systems at Generation Facilities and Networks: Impact on Reliability and Economics (SAIDI/SAIFI, EENS, fines/market)

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Abstract— The article is devoted to a systematic investigation of how modernization of relay protection and automation complexes (RPA) is reflected in the reliability and economic performance of contemporary power systems in the context of the technological transformation of 2024–2025. As the target objective, the study considers a quantitative assessment of the techno-economic effect achieved when transitioning from conventional solutions to digital intelligent electronic devices (IED), as well as when deploying wide-area monitoring systems (WAMS), which provide more accurate and faster recording of dynamic processes in the grid. The methodological basis of the research is formed as a combination of comparative processing of operational indicators, a systematized analysis of industry reporting and materials from regulators (ACER, ENTSO-E), and an examination of applied cases. Such cases include processes associated with the integration of the power system of Ukraine into the European network, which makes it possible to compare the effects of digitalization under different institutional and technological conditions. The results obtained indicate a pronounced improvement in the responsiveness of emergency control when implementing digital RPA based on the IEC 61850 standard and applying WAMS technologies: the interval for detecting and identifying emergency events is reduced from the scale of minutes to fractions of a second. This effect translates into a measurable increase in the reliability of electricity supply, expressed as a reduction in the SAIFI/SAIDI indices at the level of 15–20%, as well as into a decrease in the expected energy not supplied (EENS) due to more precise selectivity, faster fault localization, and a reduction in the duration of forced outages. The conclusions formulated at the end confirm that, as markets move to 15-minute settlement intervals, capital investments in automation and digital RPA loops take on the character of a strategic risk-management instrument: increasing the speed and credibility of protection-and-automation functions reduces the probability of deviations from schedules and operating constraints, thereby decreasing the likelihood of penalty sanctions and limiting the cost of lost load (VOLL). The provisions presented have applied significance for engineering and technical divisions of power companies, specialists in the field of pricing, and management teams of infrastructure projects.

Keywords— RPA, grid automation, power system reliability, SAIDI, SAIFI, EENS, VOLL, WAMS, hydropower engineering, digital substation.

I. INTRODUCTION

The technological restructuring of the global energy complex in 2024–2025 is accompanied by a sharp increase in the complexity of power-system operating control and by heightened requirements for the speed of emergency decision-making. According to analytical reporting, aggregate global investments in grid infrastructure by the beginning of 2025 exceeded 470 billion dollars, a development attributable both to the need to expand network transfer capacity and to adaptation to rising loads from data centers and the accelerated electrification of the industrial sector [1]. In the first half of 2025, within the United States, demand for capacity for artificial-intelligence computations increased fivefold relative to the 2024 level, while long-term estimates indicate attainment on the order of 176 gigawatts by 2035 [1]. This trend evolves in parallel with decarbonization: in 2024, the share of renewable energy sources in the European energy balance reached 48%, which is naturally associated with a reduction in system inertia and with a more complex task of frequency maintenance under an increasing share of generation with an inverter-based interface [2, 3].

Against this background, the modernization of relay

protection and automation (RPA) assumes the character of a critically necessary measure, because electromechanical solutions and early generations of microprocessor devices do not provide the required dynamic characteristics under high generation volatility and under the specific features of emergency control in networks dominated by inverter-interconnected renewable energy sources [4, 5]. An additional tightening of requirements is formed by market architecture: in September 2025, the wholesale electricity markets of the European Union switched to 15-minute settlement intervals, which makes delays in automatic regulation and disturbance localization a direct factor in imbalances, the financial consequences of which in individual incidents can reach millions of euros [6, 8]. The financial burden associated with ensuring reliability is confirmed by 2024 statistics: in the European Union, approximately 11 billion euros were directed to security-of-supply measures, and the indicator of the cost of lost load (VOLL) in a number of jurisdictions, including Poland and Ireland, was revised upward to 32,000–35,000 euros per megawatt-hour [7].

A substantial scientific gap in the subject area is conditioned by the fact that existing studies have not sufficiently and consistently linked the technical reliability parameters of digital

RPA devices with market mechanisms for the quantitative assessment of damage from energy not supplied under near-real-time operating conditions.

In this regard, the purpose of the study is reduced to establishing quantitative and qualitative relationships between the level of automation of power facilities and their economic characteristics through interpretation of the SAIDI/SAIFI indices and the EENS indicator.

The author’s hypothesis proceeds from the proposition that the transition to a digital substation architecture and the implementation of synchronized phasor measurement systems (WAMS) ensure not only increased power-system resilience, but also the economic justification of projects through the reduction of penalty payments and the optimization of operating expenditures (OPEX).

Scientific novelty is formulated as the substantiation of a direct relationship between the implementation of WAMS and the reduction of market risks when transitioning to high-granularity 15-minute settlement intervals under conditions of power-system inertia deficit.

II. MATERIALS AND METHODS

To achieve the stated objective, a comprehensive analytical toolkit was applied, oriented toward comparing technological solutions and their economic consequences under conditions of power-system digitalization. Within the framework of comparative techno-economic analysis, operational parameters of electromechanical devices, standard microprocessor-based complexes, and intelligent relay protection and automation (RPA) systems implemented on the principles of digital interaction under the IEC 61850 standard were compared, with emphasis on differences in operating speed, functional completeness, and total cost of ownership.

The systematic review of scholarly literature and the regulatory framework was constructed on an analysis of recent-year publications indexed in high-ranking scientific sources (IEEE, Scopus, MDPI) and on the study of normative documents of the European Commission, as well as the regulations of transmission system operators and the relevant requirements of ENTSO-E. Use of this methodological block ensured alignment of technical modernization criteria with the operative rules of operational reliability and market regulation.

Situational analysis was carried out through case studies, including an in-depth examination of the effects of implementing WAMS in the power system of Ukraine as an element of enhancing stability during integration into ENTSO-E (January 2024). This approach made it possible to trace how the introduction of synchronized measurements and digital control loops transforms emergency-control practice and affects reliability indicators in systems with different generation structures and grid topology.

III. RESULTS AND DISCUSSION

Modernization of relay protection and automation systems in 2024–2025 has taken the form of a technological reconceptualization of the architecture of secondary systems and of the principles of their operation, rather than being reduced to a mechanical replacement of physically worn

devices. New-generation intelligent electronic devices (IED) integrate advanced self-monitoring loops and functional diagnostics; according to Schweitzer Engineering Laboratories, this enables the detection of up to 75% of internal faults in real time and thereby reduces the probability of false operations or failures of protection functions [14]. A substantial difference from electromechanical relays is also manifested in maintenance regulations: whereas conventional solutions require regular scheduled inspections, digital complexes permit prolonged operation without calibration procedures for up to 12 years, which results in a noticeable reduction in operating expenditures (OPEX) through decreasing the volume of periodic work and the associated organizational overheads [14, 15].

A separate development vector is associated with transferring protection, automation, and control (PAC) functions into a software-defined environment. Virtualization of the functions under consideration creates prerequisites for a transition from hardware-bound implementations to software-configurable platforms on which virtual IEDs (vIED) are deployed. The results of studies published in 2024 indicate that the use of vIED can provide a reduction in capital expenditures (CAPEX) of approximately 20%, while the costs of subsequent upgrades decrease by 60% in comparison with conventional digital solutions, primarily due to the unification of computing resources, simplified scaling, and acceleration of the modernization life cycle [11]. A comparison of the economic and technical effects of different generations of automation systems, including the advantages indicated above, is presented in Table 1.

TABLE 1. Comparative analysis of the efficiency of relay protection and automation technologies (compiled by the author based on [11]).

Comparison criterion	Electromechanical systems	Digital IEDs (standard)	Virtualized IEDs (IEC 61850)
Probability of failure-free operation	0.90–0.95	> 0.998	> 0.999
Maintenance interval (years)	1–2	6–8	10–12
Reduction in cabling costs	0%	30–40%	Up to 70% (process bus)
Fault detection time	50–100 ms	20–40 ms	< 10 ms
Adaptability to network changes	Extremely low	Moderate	High (software-defined)

The application of the IEC 61850-9-2 profile, oriented toward the transmission of sampled values of current and voltage, creates prerequisites for a substantial reduction in the volume of copper secondary circuits at substations by shifting information exchange into the digital environment. The replacement of copper connections with fiber-optic lines in 2024 gained significance not only as a measure for optimizing material intensity, but also as an instrument for improving the operational robustness of secondary systems: the optical transmission medium virtually eliminates the influence of electromagnetic interference, which, with the growth of unit capacities of power equipment and the increasing complexity

of switching modes, becomes a critical source of signal distortions and, consequently, a factor of false operations of protection functions [16, 20].

Assessment of modernization effectiveness traditionally relies on internationally recognized reliability indicators SAIDI (average outage duration per customer) and SAIFI (average outage frequency per customer), which make it possible to compare the effects of technological solutions across different jurisdictions. Data for 2024 demonstrate a pronounced correlation between the level of distribution-grid automation and the dynamics of these indicators, which is interpreted as a consequence of faster fault localization, improved outage selectivity, and the implementation of automatic service restoration algorithms. A representative example is Germany, where active development of digital sectionalizing and the self-healing grid concept was accompanied by a reduction in the average time without electricity supply per customer to 11.7 minutes in 2024, which corresponds to one of the best global levels for this criterion [9].

The dynamics of reliability change and an illustration of the effect of large-scale investments in automation are presented in Figure 1, where the divergence of SAIDI/SAIFI trajectories is visually recorded as a function of the degree of implementation of intelligent control functions and digital technologies of secondary systems.

opposite pole is the situation in the United States, where pronounced volatility of reliability indicators persists (exceeding 100 minutes), which correlates to a substantial degree with the physical and technological obsolescence of distribution infrastructure: approximately 60% of distribution-grid lines have exceeded the designed service life of 50 years [18].

An illustrative example of the transformation of tools for operating-security assurance is the modernization of relay protection and monitoring systems in Ukraine, within which the technological platform WAMS (Wide Area Monitoring Systems) demonstrated the potential to sustain infrastructure operability under extreme impacts. Although WAMS does not belong to solutions formed exclusively by the logic of a commercial product, its implementation delivered significant operational effects and established the technical basis for synchronization with the European power system ENTSO-E in January 2024. The key outcome was the establishment of real-time operating-state monitoring: construction of a detailed operating-state profile of the grid ensured observability of dynamic oscillatory processes that previously were not captured by SCADA tools at comparable temporal resolution [22, 23]. A substantial change also affected the speed of deviation detection: the application of synchronized PMU (Phasor Measurement Units) measurements reduced the time required to detect emergency processes from a minutes-scale interval to fractions of a second, thereby increasing the capacity of automation to prevent cascading outages during abrupt generation losses or during violations of network connectivity due to line breaks [19, 21]. The deployment scale encompassed more than 40 key substations, providing spatially distributed coverage of the principal electricity-transmission nodes. The integration effect manifested in the fact that WAMS functioned as one of the technical conditions for synchronous operation with the European market: by March 2024, the volume of electricity imports from the European Union increased by 94%, which made it possible to partially compensate for a capacity deficit caused by the loss of approximately 9–10 gigawatts of generating capacity as a result of hostilities [19, 20]. In strategic terms, the significance of the system was expressed in maintaining stability under recurrent external impacts: accelerated restoration after disturbances became achievable due to improved accuracy of computational models calibrated on WAMS data, which enhanced the adequacy of dynamic-stability assessments and the correctness of emergency-control actions.

The economic dimension of reliability in 2024–2025 is increasingly reduced to the task of monetizing the consequences of electricity-supply interruptions, in which the VOLL (Value of Lost Load) indicator occupies a central place as an estimate of the cost of unserved load. In the legal-enforcement and project practice of the European Union, the calculation of VOLL is effectively secured as a mandatory element in the development of capacity-adequacy mechanisms, which institutionalizes the linkage between technical characteristics of stability, EENS indicators, and the financial consequences of consumption constraints (see Table 2).

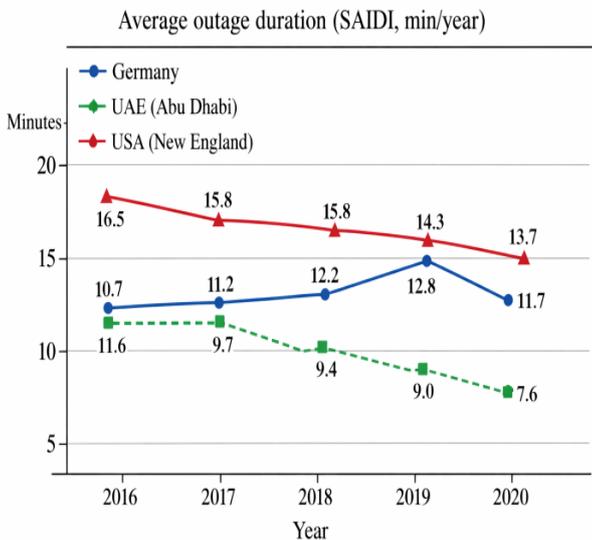


Fig. 1. Dynamics of the SAIDI index in leading power systems (compiled by the author based on [9]).

Of particular interest is the practice of the United Arab Emirates (Abu Dhabi), where, as a result of comprehensive digitalization of the substation complex and the implementation of intelligent load-management control loops, a SAIDI level of approximately 7.6 minutes was achieved by 2024 [17]. In industrial clusters, including ICAD (Abu Dhabi), the average annual duration of electricity-supply interruptions was reduced to less than 4 minutes, which is of fundamental importance for the siting of energy-intensive manufacturing in the semiconductor industry and for large data centers that are critically sensitive to power-quality parameters [10, 12]. At the

TABLE 2. Comparative cost of lost load (VOLL) by country in 2024 (compiled by the author based on [7]).

Country / Region	VOLL (EUR/MW*h)	Calculation method	Market impact
Ireland	€35,000	Consumer survey	High risk of shortage
Poland	€32,000	Macroeconomic	Modernization of coal-fired thermal power plants
Czech Republic	€28,000	Mixed	Fourfold increase since 2023
Texas (ERCOT)	\$35,685	Market volatility	Lessons from winter storms
United Kingdom	£16,940	Stated preferences	Basis for TSO investments

In economic interpretation, the indicator of expected energy not supplied (Expected Energy Not Supplied, EENS) in effect represents a direct projection of technological failures onto financial losses. With the wholesale electricity price level in the European Union at approximately 114 euros per megawatt-hour at the beginning of 2025 and with VOLL reaching 35,000 euros per megawatt-hour, preventing the disconnection of a 100-megawatt load for 1 hour corresponds to preserving more than 3.5 million euros in terms of social welfare and associated penalty costs, because the dominant factor becomes not the value of the unserved energy as a commodity, but the price of losing the electricity-supply service as an economic factor [6].

For generating facilities, modernization of relay protection and automation (RPA) forms an additional monetization channel by expanding access to ancillary-services markets. High operating speed of protection functions and increased precision of operating-state control when using WAMS create prerequisites for power plants to provide fast reserve services and frequency regulation, which, in the market configuration of 2025, as a rule is accompanied by higher tariffs in comparison with the baseline sale of electricity.

The digital transformation of hydropower plants is supplemented by the implementation of predictive analytics oriented toward a transition from scheduled maintenance to risk- and condition-based asset management. In scenario assessments by NREL (2024), it is shown that the application of smart automation and remote monitoring makes it possible to plan repairs more rationally and to reduce fixed operation and maintenance costs (FOM), with a target reduction of up to 40% by 2035. [13] The author’s model of the influence of RPA modernization on the life cycle of a hydroelectric generating unit is presented in Figure 2.

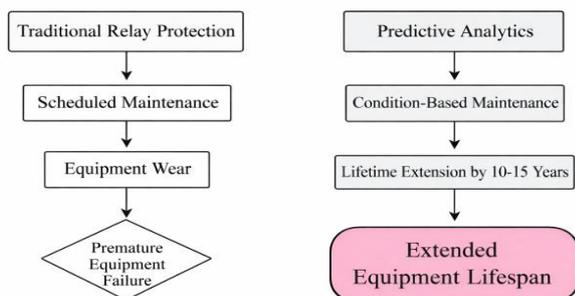


Fig. 2. Diagram of the influence of automation on the life cycle of hydropower plant assets (compiled by the author based on [13]).

When developing cost-estimate and investment assessments, it is fundamentally important to account for the fact that capital investments in digital relay protection and automation (RPA) complexes typically exceed the cost of analog solutions by 20–30%; however, this increase in price is not a linear equivalent of an increase in total project costs. The transition to fiber-optic infrastructure for secondary circuits reduces installation labor intensity and the material intensity of the cable system, while simultaneously shortening the duration of commissioning activities due to interface standardization, automation of testing, and higher reproducibility of configurations. As a result, the CAPEX difference characteristic of the equipment supply level is, as a rule, already offset at the construction stage through lower work costs and a reduced calendar duration for commissioning, which increases the predictability of implementation schedules and reduces the risk of project cost escalation due to delays.

At the same time, modernization is accompanied by a set of risks that, in 2025, have acquired particular acuity and require inclusion in the loops of technical and economic management. The most sensitive direction is cybersecurity: transferring secondary circuits and data-exchange functions into an Ethernet environment expands the attack surface of substations and creates prerequisites for impact through DDoS loads, as well as scenarios of false-data injection that can lead to erroneous interpretation of operating parameters and unauthorized impacts on equipment. It has been reported that in 2024, attempts of remote influence on relay devices were recorded with the aim of disconnecting distribution lines, which underscores the necessity of network segmentation, the application of strict authentication, and continuous monitoring of information-security events [24, 25].

A significant constraint is the workforce deficit conditioned by the increasing complexity of contemporary system architectures. Operation and support of digital RPA and communication infrastructure require competencies at the intersection of electric power engineering and information technology, including an understanding of network protocols and the specific features of IEC 61850 implementation. The shortage of engineers possessing these skills is regarded as one of the key factors slowing the development of smart grids in the United States and in Asian countries, because even when equipment and financing are available, a competency deficit leads to growth in configuration errors and an increase in operational risks [22, 26].

An additional layer is formed by the technological dependence of supply chains. Under trade restrictions, sanctions regimes, and tariff barriers current for the 2024–2025 period, the availability of critically important equipment—digital relays, measurement sensors, and specialized communication components—may decline, which translates into longer delivery times, revision of project specifications, and the risk of disruption of the calendar plans of infrastructure programs. This risk increases the significance of import-substitution strategies, qualification of alternative suppliers, and advance reservation of the component base at the planning stage [27].

IV. CONCLUSION

The analysis conducted confirms that renewal of relay protection and automation systems and the expansion of automated control functions, both at generation facilities and within the grid complex, constitute foundational prerequisites for the technical and economic sustainability of the electric power sector in 2025. The transition to a digital implementation of protection-and-automation functions transforms the role of relay protection and automation (RPA): from a predominantly reactive safety-assurance loop, it evolves into a controllable technological mechanism that affects market outcomes by reducing the frequency and duration of electricity-supply disturbances, decreasing expected energy not supplied, and limiting exposure to penalty risk.

It has been established that the implementation of WAMS and intelligent electronic devices (IED) operating within the IEC 61850 logic provides an improvement in reliability indicators, expressed as a reduction of SAIDI/SAIFI in the range of 15–67% depending on the initial grid architecture, the degree of sectionalizing automation, and the maturity of operational dispatch-control loops. The case of Ukraine demonstrates that the availability of synchronized measurements and high-frequency operating-state monitoring is a critical element of ensuring power-system resilience under physical damage to infrastructure, because it makes it possible to identify developing emergency processes more rapidly and to increase the effectiveness of emergency automation.

The economic component of modernization is revealed through the monetary valuation of the consequences of electricity-supply interruptions via the VOLL indicator, reaching 35,000 euros per megawatt-hour, which renders investments in automation financially justified even when preventing a single large-scale systemic event. In addition, it is shown that virtualization of RPA functions creates the potential to reduce the total life-cycle cost of assets by up to 60% through unification of the computing environment, acceleration of upgrades, and a reduction in support costs.

For hydropower, modernization with an emphasis on digital equipment models, predictive maintenance instruments, and extended monitoring loops makes it possible simultaneously to increase the effective utilization of installed capacity and to form a long-term effect in reducing operating expenses, reaching 40% by 2035 through optimization of repairs and increased unit availability.

The practical value of the results obtained consists in the formation of a substantiated model of technological choice for cost-estimate and investment calculations and for design, accounting for the interrelationship between technical reliability indicators and the financial consequences of unserved energy within market mechanisms. The further evolution of automation is logically associated with the implementation of artificial-intelligence algorithms for adaptive real-time modification of protection settings, which is regarded as the next stage in the development of intelligent power systems.

REFERENCES

1. 2026 Power and Utilities Industry Outlook | Deloitte Insights. Retrieved

from: <https://www.deloitte.com/us/en/insights/industry/power-and-utilities/power-and-utilities-industry-outlook.html>(date accessed: November 3, 2025).

2. Global Grid Investment Could Top \$470 Billion for the First Time in 2025: BloombergNEF | BloombergNEF. Retrieved from: <https://about.bnef.com/insights/clean-energy/global-grid-investment-could-top-470-billion-for-the-first-time-in-2025-bloombergnef/> (date accessed: December 2, 2025).

3. Electricity in 2024: emissions hit historic low, average prices declined but demand did not pick up | Eurelectric. Retrieved from: <https://www.eurelectric.org/news/electricity-in-2024-emissions-hit-historic-low-average-prices-declined-but-demand-did-not-pick-up/> (date accessed: October 8, 2025).

4. European Electricity Review 2025 | Ember. Retrieved from: https://ember-energy.org/app/uploads/2025/01/EER_2025_22012025.pdf (date accessed: October 12, 2025).

5. Relay protection for power-electronics-dominated power grids: Technical challenges and future roadmap | IEC. Retrieved from: https://www.iec.ch/system/files/2025-08/iec_sttr_relay_protection_en_lr.pdf (date accessed: October 18, 2025).

6. Electricity market design | Energy - European Commission. Retrieved from: https://energy.ec.europa.eu/topics/markets-and-consumers/electricity-market-design_en (date accessed: October 20, 2025).

7. ERAA – European Resource Adequacy Assessment | ENTSO-E. Retrieved from: <https://www.entsoe.eu/eraa/>(date accessed: December 22, 2025).

8. ACER: €11 Billion Spent EU-Wide On Fragmented Electricity Security-Of-Supply Support In 2024 | Mondo Visione. Retrieved from: <https://mondovisione.com/media-and-resources/news/acer-11-billion-spent-eu-wide-on-fragmented-electricity-security-of-supply-sup-20251120/> (date accessed: November 24, 2025).

9. Electricity supply interruptions in 2024 shorter than in the previous year – Germany's electricity grid one of the most reliable in a European comparison | Bundesnetzagentur. Retrieved from: https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/EN/2025/20251009_SAIDI_Strom.html(date accessed: October 15, 2025).

10. Abu Dhabi report highlights performance of power distribution to industrial sector in the Emirate | Department of Energy – Abu Dhabi. Retrieved from: <https://www.doe.gov.ae/en/Media-Centre/News/Department-of-Energy-Abu-Dhabi-report-highlights-performance-of-power-distribution> (date accessed: October 22, 2025).

11. Leiva Vilaplana, J. A., Kabbara, N., Coste, T., Morais, H., Zeriffi, H., & Gibescu, M. (2024). Virtualized protection, automation, and control in electrical substations: An open-source dynamic cost-benefit assessment model. *IEEE Access*, 12, 107488–107504. <https://doi.org/10.1109/ACCESS.2024.3435972>. Retrieved from: https://research-portal.luu.nl/ws/portalfiles/portal/235629375/Virtualized_Protection_Automation_and_Control_in_Electrical_Substations_An_Open-Source_Dynamic_Cost-Benefit_Assessment_Model.pdf (date accessed: November 5, 2025).

12. Leiva Vilaplana, J. A. (2025). Dynamic cost-benefit analysis of digitalization in the energy sector: Concept, modeling, and applications (Doctoral dissertation). <https://doi.org/10.11581/d77b0318-5cbf-442b-92b6-43b94790f145>. Retrieved from: https://www.researchgate.net/publication/392859421_Dynamic_cost-benefit_analysis_of_digitalization_in_the_energy_sector_Concept_modeling_and_applications (date accessed: November 6, 2025).

13. Hydropower | Electricity | 2024 | ATB | NREL. Retrieved from: <https://atb.nrel.gov/electricity/2024/hydropower>(date accessed: October 30, 2025).

14. Digital Protective Relays Demonstrate Superior Reliability and Improve System Performance | Schweitzer Engineering Laboratories (SEL). Retrieved from: <https://selinc.com/api/download/140975/> (date accessed: November 12, 2025).

15. Digital Substation Market Size 2026–2035, Global Trends Report | Global Market Insights. Retrieved from: <https://www.gminsights.com/industry-analysis/digital-substation-market> (date accessed: December 24, 2025).

16. Zhou, H., Yu, H., Zou, Z., Su, Z., Xu, Z., Yang, W., & He, C. (2025). Relay protection device reliability assessment through radiation, fault injection and fault tree analysis. *Micromachines*, 16(1), 69.

- <https://doi.org/10.3390/mil6010069>. Retrieved from: <https://www.mdpi.com/2072-666X/16/1/69> (date accessed: November 9, 2025).
17. Electricity & Water Statistics for Reliability and Quality of Supply | KAHRAMAA. Retrieved from: [https://www.km.qa/MediaCenter/Publications/Electricity%20and%20Water%20Statistics%20\(Reliability%20and%20Quality%20of%20Supply\)%202020-2024.pdf](https://www.km.qa/MediaCenter/Publications/Electricity%20and%20Water%20Statistics%20(Reliability%20and%20Quality%20of%20Supply)%202020-2024.pdf) (date accessed: November 18, 2025).
 18. Report Modernizing the Electric Grid: State Role and Policy Options | National Conference of State Legislatures (NCSL). Retrieved from: <https://www.ncsl.org/energy/modernizing-the-electric-grid> (date accessed: November 25, 2025).
 19. 2 years since Ukraine and Moldova synchronised electricity grids with EU | Energy - European Commission. Retrieved from: https://energy.ec.europa.eu/news/2-years-ukraine-and-moldova-synchronised-electricity-grids-eu-2024-03-15_en (date accessed: October 5, 2025).
 20. ACER. (2025). ACER 2025: Security of EU electricity supply (Monitoring report). Retrieved from: <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-2025-Security-of-EU-electricity-supply.pdf> (date accessed: November 23, 2025).
 21. Value of Lost Load Study for the ERCOT Region | The Brattle Group. Retrieved from: <https://www.brattle.com/wp-content/uploads/2024/09/Value-of-Lost-Load-Study-for-the-ERCOT-Region.pdf> (date accessed: October 28, 2025).
 22. Value of Lost Load: Preliminary Survey of Values for Alberta | AESO Engage. Retrieved from: <https://aesoengage.aeso.ca/42905/widgets/179261/documents/136884> (date accessed: November 2, 2025).
 23. High electricity prices and more price fluctuations | FAU Erlangen-Nürnberg. Retrieved from: <https://www.fau.eu/2025/01/news/research/the-scenario-high-electricity-prices-and-more-price-fluctuations-until-2030/> (date accessed: November 15, 2025).
 24. Hydropower: the forgotten giant of low-carbon electricity | International Energy Agency (IEA). Retrieved from: <https://www.iea.org/commentaries/hydropower-the-forgotten-giant-of-low-carbon-electricity> (date accessed: October 25, 2025).
 25. At the Intersection of Hydropower and Cybersecurity | NREL. Retrieved from: <https://www.nrel.gov/news/detail/program/2024/at-the-intersection-of-hydropower-and-cybersecurity> (date accessed: October 10, 2025).
 26. Grid Modernization Market: Industry Analysis & Future Trends | BCC Research. Retrieved from: <https://www.bccresearch.com/custom-market-research/grid-modernization-market-industry-analysis.html> (date accessed: December 18, 2025).
 27. Grid Modernization Market Growth And Forecast Report 2025–2034 | The Business Research Company. Retrieved from: <https://www.thebusinessresearchcompany.com/report/grid-modernization-global-market-report> (date accessed: December 15, 2025).