RESEARCH ARTICLE

Check for updates

A Model for Assessing the Degree of Digitalization in Electric Power Networks

Plamen Stanchev[1], **Nikolay Hinov**[2,*] and **Zoran Zlatev**[3]

[1] Department of Information Technology in Industry, Faculty of Computer Systems and Technologies, Technical University of Sofia, Sofia 1000, Bulgaria
[2] Department of Computer Systems, Faculty of Computer Systems and Technologies, Technical University of Sofia, Sofia 1000, Bulgaria
[3] Faculty of Computer Science, Goce Delčev University of Štip, Štip 2000, Republic of North Macedonia

Abstract

The increasing integration of digital technologies into electric power networks has transformed traditional grids into complex cyber-physical systems. Yet, the level of digital maturity across operators remains uneven, lacking a unified assessment framework. This paper proposes a structured model for evaluating the degree of digitalization in power grids, integrating technological, organizational, and analytical dimensions. The model introduces six core domains, technological infrastructure, data and analytics, operational processes, cybersecurity, organizational culture, and distributed energy integration, each evaluated across four maturity levels. A weighted scoring system is used to compute a Digitalization Score Index (DSI), allowing quantitative comparison and benchmarking. The proposed model is tested through a case study involving a regional grid operator, demonstrating its capability to identify gaps and guide digital transformation strategies. Results show that such an approach enhances transparency, supports investment prioritization, and aligns network modernization with the principles of smart grid development.

Keywords: digitalization, power grid, maturity model, smart grid, assessment framework.

1 Introduction

The digital transformation of electric power systems has emerged as a central driver of the sustainability, flexibility, and resilience objectives of modern energy infrastructure. Through the convergence of Information and Communication Technologies (ICT) with Operational Technologies (OT), traditional power networks are evolving into complex cyber-physical energy systems capable of real-time monitoring, predictive analytics, and autonomous control. These transformations enable advanced functionalities such as demand response, predictive maintenance, distributed energy resource (DER) management, and enhanced system reliability [1–3].

Despite these advances, the degree of digitalization across electricity network operators remains highly heterogeneous. Some utilities have achieved a high level of integration, leveraging AI-based

Submitted: 17 November 2025
Accepted: 19 December 2025
Published: 30 December 2025

Vol. 1, **No.** 2, 2025.
10.62762/TEPNS.2025.524616

***Corresponding author:**
Nikolay Hinov
hinov@tu-sofia.bg

Citation
Stanchev, P., Hinov, N., & Zlatev, Z. (2025). A Model for Assessing the Degree of Digitalization in Electric Power Networks. *ICCK Transactions on Electric Power Networks and Systems*, 1(2), 93–108.

analytics, digital twins, and cloud-based Supervisory Control and Data Acquisition (SCADA)/ Energy Management System (EMS) platforms, while others still rely on legacy systems and manual processes. This disparity results in an unequal pace of modernization, complicating regulatory harmonization, interoperability, and coordinated planning across the energy value chain [25]. Furthermore, many utilities lack a systematic method for assessing their current digital maturity and identifying strategic pathways toward full smart grid implementation.

Existing frameworks and maturity models, such as those developed by the [4], the IEA Digitalization reports, and [5] asset management standards, provide valuable guidelines but often remain generic or sector-neutral, with limited applicability to the specific operational, regulatory, and organizational characteristics of power distribution and transmission systems. Moreover, they tend to emphasize technology readiness, overlooking crucial aspects such as organizational culture, cybersecurity resilience, and integration of distributed and flexible resources [6, 7].

In this context, there is a clear need for a comprehensive yet practical model that captures the multidimensional nature of digitalization in electric power networks. Such a model should bridge the gap between qualitative assessments and quantitative indicators, allowing for transparent benchmarking, strategic planning, and monitoring of progress over time [8].

Therefore, the main objective of this study is to develop and validate a Digitalization Assessment Model (DAM) that quantifies the degree of digital maturity in electric power networks. The proposed model integrates technological, analytical, operational, and organizational dimensions into a unified evaluation framework, resulting in a DSI. This index enables quantitative comparison between operators, supports investment prioritization, and aligns network transformation strategies with the overarching principles of smart grids and Industry 4.0.

2 Literature Review

The digitalization of power systems has become a key prerequisite for the development of smart, resilient and highly efficient grids. According to a number of international studies and strategic documents, including the reports of the International Energy Agency (IEA), Conseil International des Grands Réseaux Électriques (CIGRE) and the European Smart Grid Task Force, digital transformation is the focus of the development of electricity distribution system operators (DSOs) and their transfer to architectures based on real-time observability, predictive maintenance and automated management. Nevertheless, a comparative analysis of the scientific literature shows significant differences in the degree of implementation of digital technologies between individual operators, which necessitates the need for uniform methodologies for assessing digital maturity.

2.1 Digital maturity models and their application in the energy sector

Different digital maturity frameworks are used in different industries, but few of them are adapted to the specifics of the electricity sector. Classic methodologies such as Capability Maturity Model Integration (CMMI) and the structures of the Industry 4.0 paradigm provide a conceptual approach for the phased development of processes, automation and information flows. However, these models are mainly oriented towards IT and manufacturing environments and do not fully reflect the specificities of electricity networks, where critical infrastructure, regulatory constraints and operational security require a much more specific approach [9].

In the context of electricity, the European frameworks created by the [4], as well as international standards, including [5] (asset management) and [10, 11] (Common Information Model –CIMNP standards), introduce principles for data, asset and reliability management. However, they do not define specific maturity levels or a mechanism for quantitative comparison between operators. Their main focus is on operational and regulatory requirements, rather than on the degree of digital transformation.

2.2 Key technology trends in the literature

A review of recent scientific publications highlights several technological trends that are shaping the digital evolution of distribution networks [12–14].

Artificial Intelligence and Machine Learning. AI-based methods are increasingly being used for load and production forecasting, anomaly detection, equipment diagnostics, and network optimization. Numerous authors emphasize that the digital maturity of operators is determined not only by the availability of data, but also by their ability to implement predictive and autonomous algorithms in routine operations [15, 16].

Digital Twins for Power Systems. A rapidly growing body of work focuses on the use of digital twins as high-fidelity, cyber-physical replicas of power system assets and networks. Recent reviews show that digital twins are being developed for generation, transmission and distribution systems, enabling real-time simulation, what-if scenario analysis, predictive maintenance and optimization of the entire system [27–30]. In particular, they identify distribution management, fault diagnosis and asset health assessment as key application areas where digital twins provide added value through improved observability and advanced analytics [31, 32]. More recent studies propose large-scale digital twins of the European electricity grid and discuss the regulatory, operational and cybersecurity challenges associated with their implementation. In the context of digital maturity, the integration of digital twins is widely recognized as a hallmark of higher-level capabilities, as it implies consistent data models, standardized interfaces and a close connection between OT and IT layers.

Internet of Things (IoT)-based metering and monitoring systems. In parallel with digital twin research, a significant literature has emerged on Internet of Things (IoT)-based monitoring architectures for smart grids. IoT devices, such as smart meters, phasor meters, and environmental sensors, provide dense, time-synchronized measurements that significantly increase system observability. Recent reviews and case studies report on IoT-based platforms for real-time monitoring of power distribution systems, renewable energy systems, and consumer installations, often combined with cloud-based or edge-based analytics for fault prediction and demand response [32, 33]. These systems demonstrate that the depth of IoT integration, network coverage, protocol interoperability, and data quality are strong predictors of the overall degree of digitalization. At the same time, they emphasize the importance of standardized communication protocols and secure data management strategies.

Cybersecurity in OT Environments. With the advent of two-way communication architectures and the increasing penetration of DER (Data Enrichment Through Digital Technologies), cybersecurity has become a critical research topic. Numerous studies identify OT security as one of the least developed areas in many utilities and point to typical vulnerabilities in SCADA, substation automation, and IoT-based field devices [17–19, 26]. The literature suggests that advanced intrusion detection, security monitoring centers, and systematic risk management procedures are necessary prerequisites for a secure digital transformation.

Overall, the current state of the art clearly demonstrates that digital twins and IoT-based monitoring systems are not isolated technologies, but an integral part of advanced digitalization strategies. Their successful implementation requires mature data and analytics capabilities, robust communication infrastructures, and strong cybersecurity practices, precisely the dimensions covered by the six domains of the proposed DAM.

2.3 Limitations in existing approaches

Despite progress in international initiatives, many existing maturity models remain limited in scope and applicability to the electricity sector. Several frameworks are overly generic and insufficiently adapted to the real operational processes of distribution utilities, which makes their practical use challenging. Furthermore, their predominantly qualitative nature hinders meaningful comparison between different operators and reduces the ability to track progress over time. Another important limitation frequently noted in the literature concerns the omission of organizational aspects, such as digital skills, innovation culture, and change management, which have been shown to be critical determinants of successful digital transformation. Finally, many existing models remain technologically oriented and do not incorporate analytical, strategic, or interoperability considerations, which reduces their usefulness for operators seeking a comprehensive assessment framework [20–22].

2.4 Need for an integrated assessment model

The synthesis of the literature reveals a clear need for a structured, sector-specific and quantitative methodology capable of capturing the multidimensional nature of digital maturity in electricity operators. Such a model must integrate technological, organizational and analytical components, define measurable maturity levels, and support transparent and comparable assessments across different operators. It should also provide practical guidance for prioritizing investments and planning development trajectories, while remaining flexible enough to accommodate different system sizes, regulatory conditions and technological baselines. Within this context, the proposed DAM addresses the identified gaps by combining six domains, four maturity levels and a weighted scoring mechanism into a unified framework suitable for real-world operational assessments and strategic planning.

In this context, the proposed DAM fills the existing gap in the literature by providing a method for a comprehensive and quantitative assessment of digitalization in electricity transmission and distribution companies. The model combines six domains, four maturity levels and a weighted scale, making it suitable for real operational assessments and strategic planning.

Furthermore, recent developments in digital twins and IoT-based measurement and monitoring systems further reinforce the need for a comprehensive assessment framework. Although the literature highlights the growing role of high-quality digital replicas, sensor networks, and real-time IoT platforms in improving grid observability and predictive capabilities, these technologies remain under-reflected in existing maturity models. Most frameworks focus primarily on technology readiness or asset management and fail to capture the organizational, analytical, and interoperability requirements necessary for the successful implementation of digital twins and large-scale IoT infrastructures. Therefore, an integrated assessment model, such as the DAM proposed in this study, is essential to bridge this gap by systematically assessing the technological, analytical, cybersecurity, and organizational dimensions that enable the effective deployment of advanced digital technologies in modern energy grids.

2.5 Comparison with existing maturity models

Several frameworks for assessing digital maturity exist in the literature, including CMMI, the EU Smart Grid Task Force (SGTF) set of indicators, and ISO/IEC management standards. However, these models differ significantly from the needs of electricity grid operators. CMMI, for example, provides a general, process-oriented structure, but does not include elements fundamental to modern energy systems, such as OT/IT convergence, DER integration, IoT-based monitoring, or cybersecurity of industrial control systems. The SGTF framework offers policy-level guidance for smart grid development, but lacks quantitative assessment and does not provide domain-specific indicators for operational technologies or advanced analytics. The standards address individual management domains, but they do not constitute an integrated model for assessing digitalization and do not assess the functional maturity of digital technologies in the grid.

In contrast, the proposed DAM model integrates six domains that reflect the operational, technological, and organizational realities of power grids. It provides a quantitative assessment system, supports internal benchmarking, and explicitly incorporates modern digital tools such as digital twins, IoT-based monitoring, direct source integration (DER), and cybersecurity maturity. This makes the DAM more comprehensive and better aligned with the practical needs of distribution system operators than existing frameworks.

To ensure clarity and consistency, the terminology used in this study follows standardized definitions derived from international organizations such as IEC, ISO, CIGRE, and the EU Smart Grids Working

Table 1. Standardized terminology used in the DAM framework.

Term	Standardized Definition	Source
Digitization	Conversion of analog information into digital formats.	IEC, ISO 8000
Digitalization	Transformation of processes enabled by digital technologies and data-driven decision-making.	CIGRE, EU SGTF
Integration	Functional embedding of new digital components or systems into existing grid operations.	ENTSO-E
Interoperability	Ability of systems to exchange, interpret, and use information consistently across OT/IT layers.	IEC 61970 / 61968 (CIM)
Maturity Levels	Four hierarchical stages describing the evolution of digital capability: Initial $\rightarrow$ Developing $\rightarrow$ Integrated $\rightarrow$ Intelligent.	Proposed DAM model

Group presented in Table 1. In the context of the DAM framework, digitalization refers to the transformation of operational and organizational processes enabled by digital technologies, while digitization means the conversion of analog data into digital form. The term "integration" is used to describe the functional embedding of new digital systems, while interoperability refers to their ability to exchange and interpret information reliably between OT and IT layers. Maturity levels (initial, evolving, integrated, intelligent) are applied consistently throughout the manuscript to describe the development of digital capabilities in a structured and hierarchical manner. All terms are harmonized across the different sections to avoid ambiguity and ensure conceptual consistency.

3 Methodology

The proposed methodology follows a multi-criteria assessment approach that integrates both qualitative and quantitative indicators to evaluate the digital maturity of electric power networks. The model builds upon the principles of systems thinking and digital maturity modeling, combining technical, organizational, and analytical dimensions into a unified evaluation structure. The goal is to provide a holistic view of the digital transformation process and its measurable progress within utility organizations.

3.1 Conceptual Framework

The conceptual foundation of the model is structured around six interrelated domains that together capture the essential dimensions of digital transformation in power networks. The Technological Infrastructure domain focuses on the deployment and interoperability of core digital assets, including SCADA/EMS/DMS platforms, IoT sensors and modern communication protocols [23]. Data and Analytics evaluates the organization's capacity to acquire, manage and exploit data through big data platforms, machine learning techniques and predictive analytics. Operational Processes examines the maturity of automation in asset management, outage detection, condition monitoring and decision support systems. Cybersecurity assesses resilience mechanisms, incident response capabilities and adherence to international standards such as IEC and NIST frameworks [24]. The Organizational Culture and Skills domain reflects the human and institutional readiness for digital transformation, including digital literacy, innovation culture and managerial engagement. Finally, Integration with DER and IoT measures the grid's readiness to incorporate distributed resources, electric vehicles, storage technologies and prosumers through interoperable control systems [22]. Each domain consists of key performance indicators grouped into measurable subcategories designed to capture both technological capability and operational effectiveness, ensuring comparability across operators with different maturity levels and system sizes.

3.2 Maturity Levels

The model adopts a four-level hierarchical maturity scale designed to represent the progressive stages of digital evolution:

- Level 0 – Initial: Digital systems are isolated or non-existent. Processes are predominantly manual, and decision-making relies on operator experience.
- Level 1 – Developing: Partial implementation of digital tools with limited interoperability. Data is collected but not systematically analyzed.
- Level 2 – Integrated: Interconnected digital systems enable real-time monitoring, data-driven decision-making, and partial automation of grid operations.
- Level 3 – Intelligent: Fully integrated cyber-physical environment with AI-enabled automation, digital twins, and predictive control mechanisms.

This progression captures the transition from digitization (basic digital tools) to digital transformation (autonomous and adaptive systems). The maturity scale supports benchmarking, temporal tracking, and gap analysis within or across utilities.

3.3 Scoring and Aggregation Method

The evaluation process uses a weighted scoring approach to quantify the overall DSI. For each domain i, a score $S_n \in [0, 3]$ is assigned based on audits, expert evaluations, or survey data. The score reflects the organization's current position on the maturity scale. Each domain is weighted by a coefficient ω_n to account for its relative importance in the overall digital transformation strategy.

Based on the domain scores and their respective weights, the overall Digitalization Score Index (DSI) is calculated using the weighted aggregation shown in Eq. 1:

$$DSI = \frac{\sum_{i=1}^{n} \omega_i \cdot S_i}{\sum_{i=1}^{n} \omega_i} \tag{1}$$

where S_i represents the normalized maturity score for domain i and ω_i denotes its weighting factor. The sum of all weights equals one $\sum \omega_i = 1$ to preserve proportionality.

The weighting scheme can be determined through Analytic Hierarchy Process (AHP) or expert elicitation, ensuring consistency and reproducibility. The results are visualized through radar charts or heatmaps, allowing intuitive interpretation of strengths, weaknesses, and priority areas for digital investment.

Finally, the methodology supports periodic reassessment, enabling utilities to monitor progress and update strategies as technologies and organizational practices evolve. This dynamic feature ensures that the model remains relevant within rapidly changing technological and regulatory environments.

Figure 1 illustrates the conceptual structure of the proposed DAM. The model consists of six interrelated domains, such Technological Infrastructure, Data and Analytics, Operational Processes, Cybersecurity, Organizational Culture and Skills, and Integration with DER/IoT. These collectively define the multidimensional nature of grid digitalization.

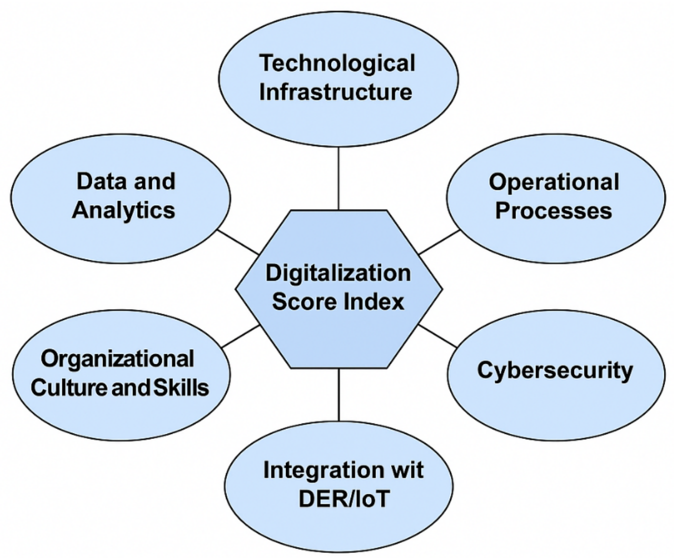


Figure 1. Structure of the Digitalization Assessment Model (DAM).

Each domain includes specific indicators that reflect both technical and organizational aspects of digital transformation. These domains feed into the computation of the DSI through a weighted aggregation mechanism. The DSI provides a single normalized value representing the overall digital maturity of a power network operator.

The framework supports two main analytical functions, such Diagnostic Assessment, identifying the current digitalization level and gaps; and Strategic Benchmarking, allowing comparisons across time, regions, or organizations.

Graphically, the model can be visualized as a radial structure, where the six domains form interconnected axes converging at the DSI core. Higher maturity in each domain extends the radius outward, creating a larger polygon area in the radar chart-symbolizing higher overall digital capability.

4 Case Study

To validate the proposed DAM, a pilot evaluation was conducted on a regional DSO responsible for medium-voltage network management and distributed generation integration. The assessment process combined structured expert interviews, document analysis, and operational data review from the DSO's SCADA and enterprise information systems. The goal was to identify the current digital maturity profile and to verify the model's applicability under real operational conditions.

Each of the six domains defined in Section 2 was evaluated on a 0–3 scale, where higher scores indicate greater digital maturity. Domain weights (ω_i) were determined through expert elicitation, considering both literature references and the DSO's strategic priorities. The overall DSI was then computed using the weighted aggregation method described in Eq. 1.

4.1 Assessment Results

Table 2 summarizes the evaluation outcomes for the six domains. The DSO achieved a DSI of 2.08, corresponding to a transition phase between the Developing and Integrated maturity levels. This result indicates that the operator has established a solid technological base and moderate digital capabilities, but still lacks advanced integration and analytics functions characteristic of fully intelligent grids.

4.2 Analysis and Interpretation

Figure 2 presents the operator's digital maturity profile across the six domains defined in the assessment model. The numerical values shown on the radar chart (1, 2, and 3) correspond directly to the maturity scale introduced in Section 2, where Level 1 = Developing, Level 2 = Integrated, and Level 3 = Intelligent. These concentric levels provide a visual reference that allows

Table 2. Results of digitalization maturity assessment for the pilot DSO.

Dimension	Weight (ω)	Score (S_i)	Weighted Value ($\omega_i S_i$)	Description
Technological Infrastructure	0.20	2	0.40	Partial deployment of digital substations and optical communication.
Data & Analytics	0.15	2	0.30	Real-time data acquisition with limited predictive analytics.
Operational Processes	0.20	2	0.40	SCADA-based automation of fault detection and switching operations.
Cybersecurity	0.15	1	0.15	Basic protection measures; absence of centralized security monitoring.
Organizational Culture & Skills	0.15	2	0.30	Staff training programs in place; limited innovation initiatives.
Integration with DER/IoT	0.15	2	0.30	Initial PV and EV charging integration; IoT pilot projects ongoing.
Total / DSI	1.00	-	2.08	-

the reader to quickly interpret the relative progress achieved in each domain.

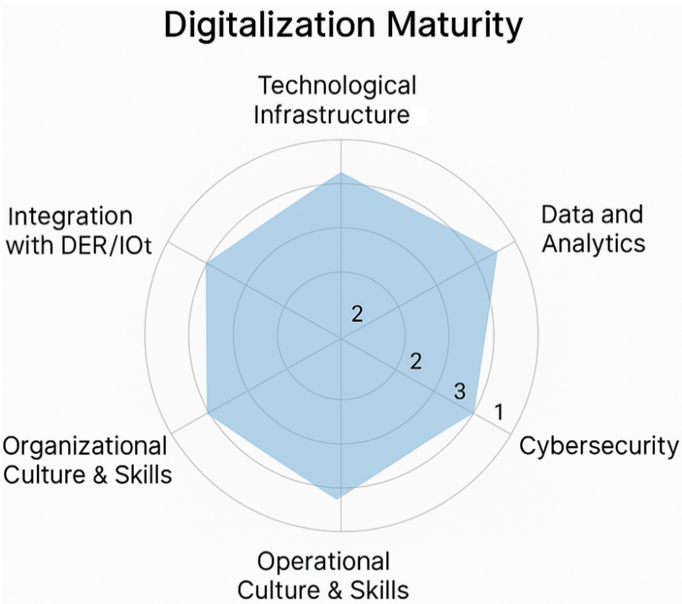


Figure 2. Radar chart of Digitalization Maturity across six domains.

The operator demonstrates the strongest performance in the Technological Infrastructure, Operational Processes, and Data and Analytics domains, where Level 2 maturity is achieved. This indicates that basic SCADA functionalities, digital communication infrastructures, and partially integrated real-time analytical capabilities are already in place.

In contrast, the Cybersecurity domain remains at Level 1, reflecting limited security monitoring and the absence of advanced protection mechanisms, an issue commonly reported among distribution system operators internationally. The Integration with DER/IoT domain also shows an early-stage development profile, highlighting the challenges associated with coordinating distributed resources, smart devices, and flexible loads.

Overall, Figure 2 illustrates that while the operator has established a solid foundation in infrastructure and core operational processes, significant progress is still required in cybersecurity, IoT integration, and advanced analytics. These results confirm that the DAM effectively identifies both strengths and critical weaknesses, providing a valuable basis for continuous performance monitoring and strategic planning.

The pilot operator's assessment and the resulting domain and DSI values serve as a basis for conducting a more in-depth analysis in the next section. Section 5. Results presents additional visualizations, quantitative comparisons, and interpretations that aid in understanding the operator's digital profile and outline potential areas for improvement.

5 Results

This section presents a detailed analysis of the results obtained from the pilot implementation of the proposed DAM on the regional electricity distribution operator. After calculating the domain values and the overall DSI performed within the case study, a series of visual and quantitative indicators were developed, aiming to reveal the structure, dynamics and profile of digital maturity. The presented graphs and charts allow for a deeper comparison between the individual domains, identify key strengths and critical digital deficits, as well as reveal the degree of deviation between the current state and the target levels of development. These results serve as a basis for formulating guidelines for improvement and prioritization of future investments, while also facilitating the strategic planning of digital transformation by operators and regulators.

Figure 3 presents the weighted contribution of each of the six domains to the overall DSI. The bar chart visualizes the $\omega_i S_i$ values, which combine the weight and maturity level of each domain. The highest contributions are made by Technological Infrastructure and Operational Processes, with 0.40 respectively, which indicates that the operator has a relatively strong technical base and basic automation of key processes. They are followed by Data & Analytics (0.30) and Integration with DER/IoT (0.30), reflecting the presence of fundamental data collection mechanisms and initial efforts to integrate distributed resources.

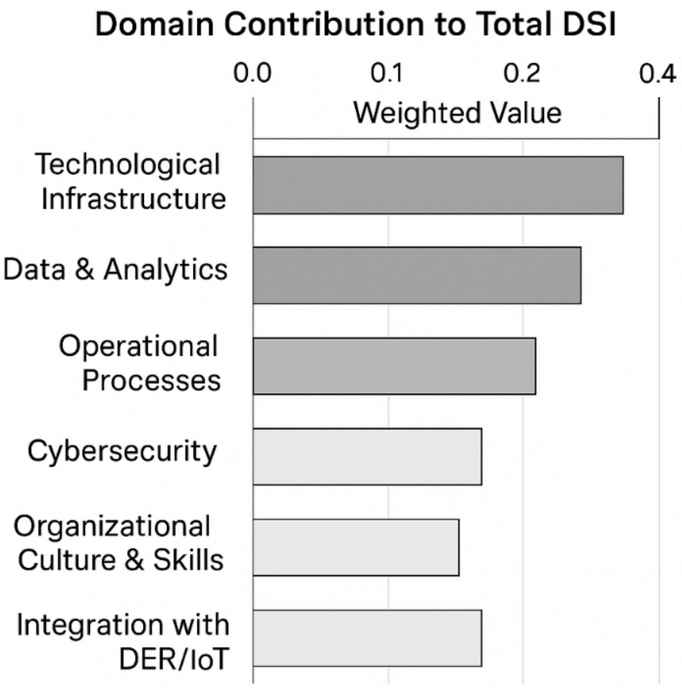


Figure 3. Domain contribution to total DSI.

On the other hand, the domains Organizational Culture & Skills (0.30) and especially Cybersecurity (0.15) show a lower contribution to the DSI. The latter reflects a distinct deficit in the area of cyber protection, which limits the operator's ability to move to higher levels of digital maturity. This disparity shows that despite technical advances, the lack of adequate security policies and tools represents a critical barrier to the development of a smart and resilient network infrastructure.

Figure 4 presents a comparative view of the operator's current digital maturity levels against the strategic targets set for each area. The chart displays two bars per area, Current (blue) and Target (grey), allowing for a clear visual assessment of the distance separating the current state from the desired future maturity.

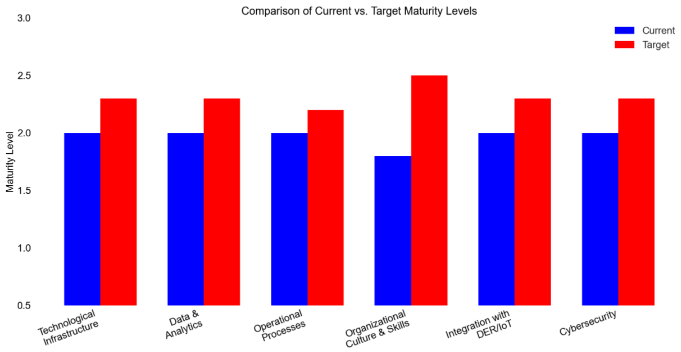


Figure 4. Current vs. Target digital maturity levels.

Analysis of the chart shows that all areas show a measurable difference between the current and target values, confirming an opportunity for structured improvement. The most significant discrepancies are observed in cybersecurity and DER/IoT integration, where maturity levels remain at the lower end of the scale compared to the desired level 3. These findings highlight the need for priority investments in cybersecurity frameworks, DER coordination, IoT device integration and improved monitoring capabilities.

The remaining areas, Technology Infrastructure, Data and Analytics, Operational Processes and Organizational Culture and Skills show smaller but still significant deviations between the current and target levels. This suggests that the operator is positioned at an intermediate stage of digitalization, fundamental technical capabilities are in place, but more advanced analytical, integrative and organizational competencies are needed to progress towards integrated and intelligent maturity. Overall, the figure provides a strategic perspective on development priorities and serves as a valuable tool to support decision-making for planning the next phases of the operators' digital transformation.

Figure 5 presents a heat map that illustrates the distribution of digital maturity indicator values across all six assessment areas. The graduated color scale, from lighter to darker tones, represents increasing levels of maturity, while the numerical

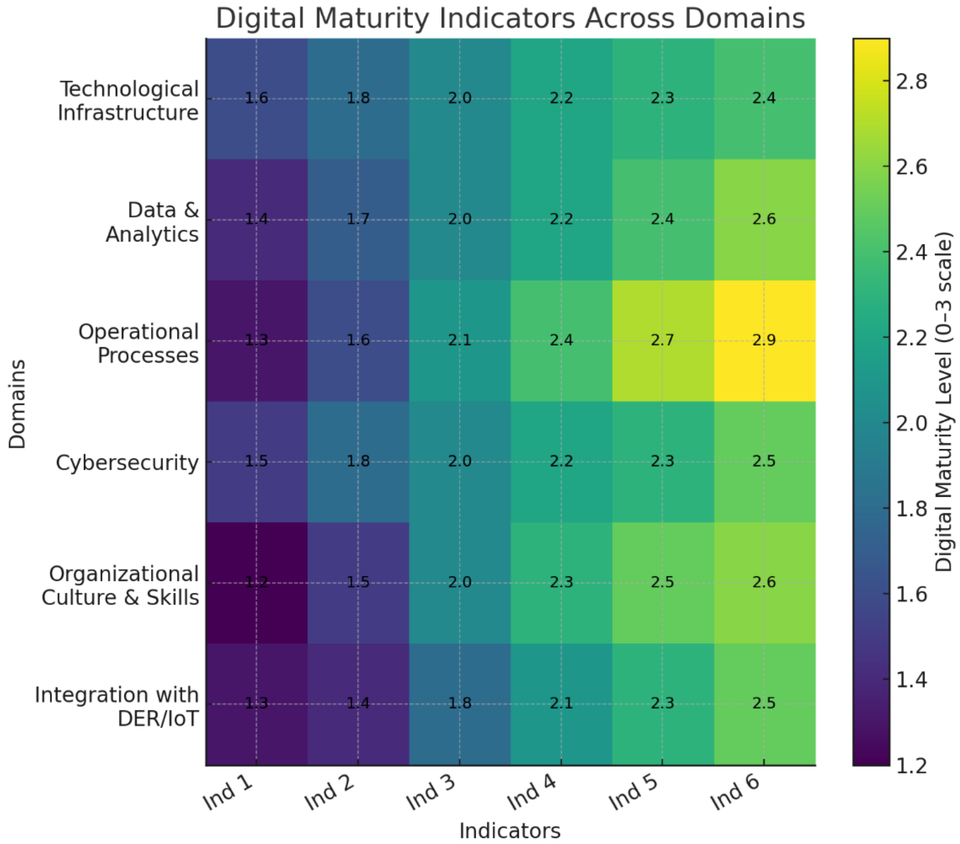


Figure 5. Heatmap of digital maturity indicators across six domains. Darker cells indicate higher maturity scores on a 0–3 scale. Numerical labels within each cell show the exact value of the corresponding indicator.

labels in each cell provide precise values for more precise interpretation. This visualization allows for simultaneous comparison of multiple sub-indicators and highlights the internal variability within each area.

A clear heterogeneity is observed in several areas. In the Operational Processes area, the consistently darker cells towards the right side of the matrix reflect higher levels of maturity in areas such as process automation, advanced control functions, and real-time operational response. The Data and Analytics area demonstrates a similar upward progression across all of its indicators, suggesting improving analytical capabilities and the gradual integration of more sophisticated data-driven tools.

In contrast, the Cybersecurity domain shows mixed maturity patterns, with some indicators showing moderate development, while others remain relatively weak, confirming previously identified vulnerabilities in security monitoring, incident response and protection of OT environments. The Organizational Culture and Skills and DER/IoT Integration domains also show lower values in several indicators, highlighting gaps in digital competencies, innovation practices and implementation of IoT-based monitoring and control systems. Overall, the heat map provides a comprehensive and multidimensional view of the internal structure of digital maturity. By highlighting both strong and weak sub-domains, it supports the identification of priority areas, such as cybersecurity, advanced analytics and IoT integration, that require targeted interventions to accelerate the operator's digital transformation.

Figure 6 illustrates the projected dynamics of the DSI in the period 2020–2028, presented through two separate scenarios: Current trajectory and Optimized scenario. The blue line reflects the realistic pace of development while maintaining the current organizational, technical and investment policies. It is visible that in this scenario the digital maturity of the operator increases gradually, from approximately DSI $\approx$1.1 in 2020 to around 1.7 in 2028 without reaching the maturity levels characteristic of integrated or smart networks.

On the other hand, the gray dotted line represents the Optimized scenario, based on targeted investments in critical areas such as cybersecurity, analytical platforms, IoT infrastructure and digital competencies. In this development, the DSI reaches approximately

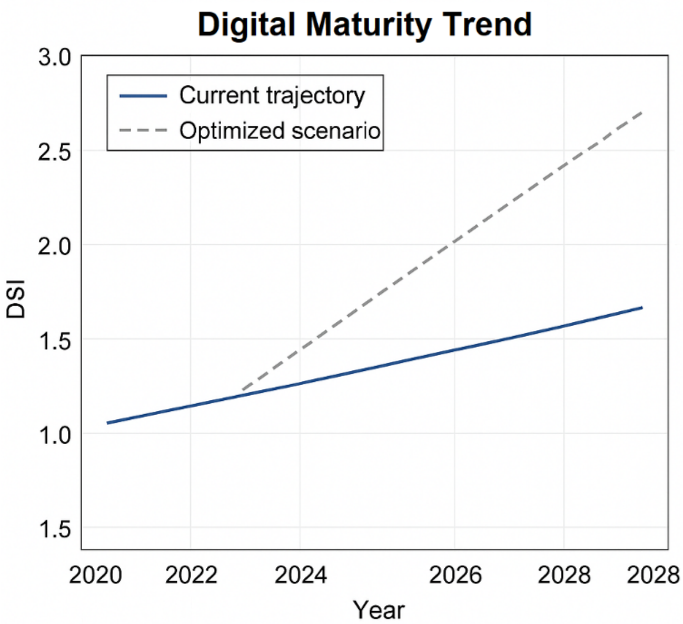


Figure 6. Digital maturity trend under current and optimized scenarios.

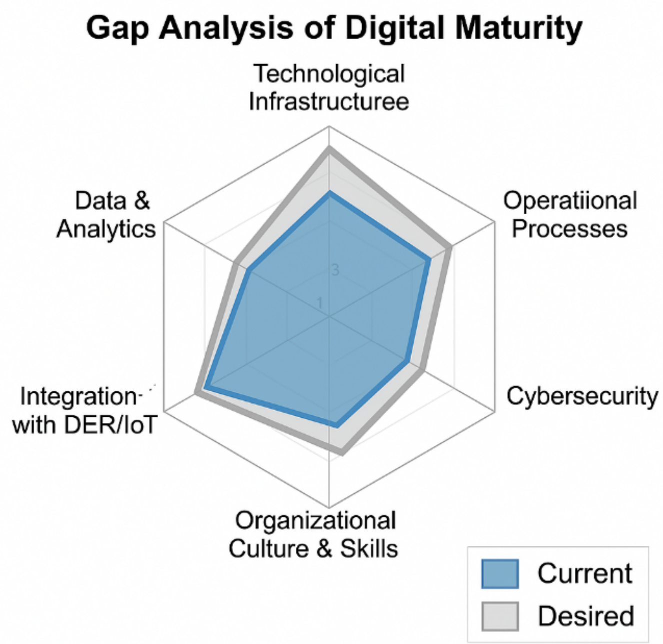


Figure 7. Gap analysis of digital maturity across domains.

2.7 by the end of the period, which is almost twice as high compared to the current trajectory. This difference highlights the importance of systematic and comprehensive digital transformation to accelerate mature growth.

The figure clearly demonstrates that without strategic intervention, the operator would remain in an intermediate stage of development. In contrast, the optimized scenario confirms the potential of DAM to support decision-making through quantifiable goals and predictive trajectories, guiding effective planning of future investments.

Figure 7 presents a comparative analysis of the current and desired levels of digital maturity through a two-layer radar diagram (spider plot). The blue polygon visualizes the actual state of the operator in the six assessed domains, while the gray contour represents the target values, defined as a guideline for achieving higher maturity levels.

The diagram clearly shows that the domains Technological Infrastructure, Operational Processes and Data & Analytics are closest to the desired levels, which confirms the presence of a relatively good technological base and integration of basic digital tools. However, significant differences between the current and desired digital profile are observed in Cybersecurity, Organizational Culture & Skills and Integration with DER/IoT. These domains form the widest "gaps" between the actual and target state, which identifies them as critical areas for intervention.

Cybersecurity stands out as the least developed element, with a clearly lower current level compared to the target. This is consistent with general trends in the energy sector, where OT security often lags behind the rest of the digital transformation. Similarly, the domains Organizational Culture & Skills and Integration with DER/IoT show insufficient readiness, both in terms of competencies and innovation culture, and in terms of management of distributed resources and IoT.

Figure 7 provides a clear visual basis for setting priorities in strategic planning: the biggest improvements should be directed towards cybersecurity, human capital development and expanding integration with DER/IoT. In this way, the gap analysis supports the process of building targeted roadmaps and optimizing investments.

6 Discussion

The results obtained from the application of the DAM on the regional electricity distribution operator reveal a complex and multi-layered profile of digital maturity, typical for a large part of the operators in Europe and the South-Eastern region. The calculated DSI of 2.08 shows that the operator has passed the basic stage of digitalization and has entered the intermediate zone between Developing and Integrated maturity levels, a result that is in line with the published assessments in the international literature for similar-sized DSO structures.

6.1 Interpretation of the maturity domains

The interpretation of the individual maturity domains reveals clear differences between technological and organizational dimensions of digital development. Technological Infrastructure and Operational Processes exhibit the strongest performance, confirming sustained investment in SCADA systems, digital communication channels and automation of core operational activities. These findings align with trends reported by IEA and CIGRE, which indicate that many operators prioritize establishing a solid technological foundation before advancing toward analytics and strategic integration. Data & Analytics demonstrates moderate progress, reflecting the availability of data and basic analytical tools but limited deployment of advanced algorithms. Cybersecurity remains the least developed domain, revealing a common challenge in the energy sector, where OT security often lags behind broader digital transformation efforts. Integration with DER/IoT and Organizational Culture & Skills also indicate incomplete development, especially in areas related to flexible resources, IoT deployment and human capital readiness.

6.2 Implications for strategic planning

The results of the digital maturity assessment reveal several implications for the operator's strategic development, highlighting areas in which targeted interventions may accelerate progress toward higher maturity levels. The relatively advanced state of the Technological Infrastructure and Operational Processes domains indicates that the operator has established a sufficiently robust foundation to support further transformation. However, the moderate performance in Data & Analytics shows that the organization has not yet fully capitalized on the potential of data-driven decision-making. Strengthening analytical capabilities, adopting advanced forecasting tools and expanding the use of machine learning could significantly enhance operational efficiency and asset management.

The low maturity of the Cybersecurity domain presents a considerable concern, as digitalization inherently increases the dependence on interconnected systems and exposes critical infrastructures to new risks. Strengthening cybersecurity governance, deploying real-time monitoring frameworks and aligning internal practices with international standards are essential steps that should accompany any further digital expansion. In addition, the underdeveloped Organizational Culture & Skills and Integration with DER/IoT domains suggest that technological improvements must be accompanied by organizational and cultural change. Building digital competencies, nurturing innovation and restructuring internal workflows will be necessary to enable a sustained transition toward intelligent grid operations. Together, these implications underline the importance of viewing digital transformation not as a collection of isolated upgrades but as a coordinated, cross-organizational process requiring technological, analytical and human-centric development.

6.3 Comparative Insights with Existing Models and International Studies

A structured comparison between the DAM results and existing digital maturity models reveals both convergences and notable distinctions. The SGTF maturity indicators highlight cybersecurity, interoperability, and real-time observability as recurring weaknesses across many European DSOs. This aligns with the findings of the present case study, in which the Cybersecurity and Integration with DER/IoT domains show the lowest maturity levels. According to SGTF reports, more than 60% of surveyed operators demonstrate only partial cybersecurity implementation, which closely corresponds to the Level 1 outcome identified in our assessment.

Similarly, IEA digitalization studies emphasize insufficient use of advanced analytics and limited integration of IoT-based monitoring systems as common barriers to achieving higher digital maturity. The Level 2 score of the Data & Analytics domain in our model reflects this same pattern, indicating that the operator possesses basic real-time data acquisition capabilities but lacks widespread deployment of predictive or machine learning–based tools. This parallels IEA findings that many utilities remain in a transitional stage where foundational digital infrastructure exists, yet analytical and automation capabilities are still emerging.

In contrast to generic maturity frameworks such as CMMI or Industry 4.0 models, which conceptualize maturity primarily through process standardization and automation levels, the DAM explicitly integrates sector-specific operational attributes, including DER coordination, IoT sensor deployment, OT/IT interoperability, and grid resilience. Existing models rarely incorporate these dimensions quantitatively. For example, CMMI provides valuable process structure but does not define maturity criteria for distributed resource integration or real-time grid control. This methodological divergence underscores the relevance of the DAM's domain-based, grid-focused approach, where maturity is evaluated not only as an organizational capability but as a functional characteristic of network operations. Furthermore, recent studies on digital twins and IoT-enabled monitoring systems report that advanced operators typically achieve high maturity in infrastructure and process automation while lagging in organizational readiness and cybersecurity, an asymmetry also observed in our case study. The Level 2 scores in Technological Infrastructure and Operational Processes, combined with lower results in cultural and security domains, align closely with these documented patterns.

Overall, this comparative analysis demonstrates that the DAM results are consistent with trends reported in international research: operators tend to advance technologically before achieving parallel progress in analytics, DER integration, and cybersecurity. At the same time, the DAM provides a more granular, operationally grounded assessment than general-purpose maturity models, making it suitable for practical benchmarking and strategic planning within the electricity sector.

6.4 Limitations and Generalizability

Although the proposed Digitalization Assessment Model (DAM) provides a structured and quantitative framework for evaluating digital maturity in electric power networks, several limitations should be acknowledged in order to ensure balanced interpretation of the results and methodological transparency.

First, the empirical validation of the model is based on a single regional distribution system operator. While the selected case study demonstrates the practical applicability of the DAM and reflects challenges commonly reported in the literature, the specificity of the operator's organizational structure, regulatory environment, and technological baseline limits the generalizability of the results. Consequently, the obtained Digitalization Score Index (DSI) values should be interpreted as illustrative rather than representative for the wider population of electricity network operators. Broader application of the model across multiple DSOs, transmission operators, and different regulatory contexts would be required to establish statistically meaningful benchmarks and sector-wide maturity patterns.

Second, the weighting scheme used to aggregate domain scores into the overall DSI is derived from expert judgment and guidance from the literature. Although this approach is widely adopted in multi-criteria assessment models, the current implementation does not include a formal sensitivity analysis. As a result, the robustness of the DAM with respect to variations in domain weights has not been explicitly quantified. Changes in weighting assumptions may influence the overall maturity score and the relative importance of individual domains, particularly in cases where domain scores exhibit significant variability. Future work should therefore incorporate structured sensitivity analyses, such as scenario-based weighting, Monte Carlo perturbation, or robustness testing, to evaluate the stability of the model under alternative assumptions.

Third, the assessment relies partly on qualitative inputs obtained through expert evaluations, interviews, and document analysis. While these sources are essential for capturing organizational and process-related aspects of digital maturity, they may introduce subjectivity and potential bias. The model currently does not incorporate uncertainty quantification or confidence intervals for individual indicator scores. Extending the DAM to include statistical validation methods, uncertainty modeling, or triangulation with automated data sources would further enhance the reliability and reproducibility of the results.

Finally, the present version of the model focuses on a fixed set of domains and indicators reflecting the current state of digitalization in electricity networks. As digital technologies, regulatory frameworks, and operational practices continue to evolve, certain indicators may require refinement or extension. In particular, future research could expand the DAM by incorporating additional indicators related to artificial intelligence governance, grid resilience, and large-scale digital twin deployment, as well as by integrating the model into digital platforms that enable continuous monitoring and automated reassessment.

Despite these limitations, the DAM provides a transparent and operationally grounded starting point for assessing digital maturity in electric power networks. The identified constraints also define clear directions for future research, including multi-operator benchmarking, sensitivity analysis, and methodological refinement, which are expected to further strengthen the model's applicability and scientific rigor.

7 Conclusion

This study presented a structured and quantitative Digitalization Assessment Model for evaluating the degree of digital maturity of electricity network operators. The proposed framework integrates six interrelated domains—Technological Infrastructure, Data and Analytics, Operational Processes, Cybersecurity, Organizational Culture and Skills, and Integration with DER/IoT—evaluated across four hierarchical maturity levels. By combining these dimensions into a weighted Digitalization Score Index (DSI), the model enables a transparent, measurable, and comparable assessment of digital transformation progress, addressing key limitations of existing qualitative or sector-neutral maturity frameworks.

The application of the DAM to a regional distribution system operator demonstrated the practical relevance and diagnostic capabilities of the proposed approach. The obtained DSI value of 2.08 indicates that the assessed operator is positioned in an intermediate stage between the Developing and Integrated maturity levels. The results reveal a relatively strong technological foundation, particularly in Technological Infrastructure and core Operational Processes, supported by SCADA-based automation and digital communication systems. At the same time, the assessment highlights distinct deficiencies in Cybersecurity, Organizational Culture and Skills, and Integration with DER/IoT, which currently limit the transition toward higher levels of digital maturity.

The use of complementary visual representations—including radar charts, domain contribution analysis, heatmaps, gap analysis, and development scenarios—further enhanced the interpretability of the results. These visual tools enabled a multidimensional understanding of the operator's digital maturity profile, revealing both internal heterogeneity across domains and the gap between current and target states. In this sense, the DAM not only provides a static snapshot of digital maturity but also supports strategic planning by identifying priority areas for targeted investments and organizational interventions.

The findings confirm that digital transformation in electricity networks is not solely a technological challenge, but a systemic process requiring coordinated development across infrastructure, analytics, cybersecurity, organizational capabilities, and resource integration. The observed imbalance between technological advancement and organizational or security-related readiness is consistent with trends reported in international studies and maturity assessments of distribution system operators. By explicitly incorporating these dimensions, the DAM offers a more comprehensive and operationally grounded alternative to existing maturity models.

From a practical perspective, the proposed model can support electricity network operators in benchmarking their digital maturity, monitoring progress over time, and aligning investment strategies with long-term smart grid objectives. At the same time, the framework can serve regulators and policymakers as a decision-support tool for evaluating the readiness of operators to implement advanced digital technologies and comply with evolving regulatory and cybersecurity requirements.

Future research should focus on extending the empirical validation of the DAM through application to multiple operators across different regulatory and technological contexts, enabling comparative benchmarking and statistical analysis of maturity patterns. Additional work is also needed to enhance methodological robustness by incorporating sensitivity analysis of domain weights, uncertainty quantification in indicator assessment, and automated data-driven evaluation mechanisms. Furthermore, the indicator set can be expanded to reflect emerging developments in artificial intelligence governance, large-scale digital twins, grid resilience, and autonomous control systems.

Overall, the proposed Digitalization Assessment Model provides a flexible, transparent, and practically applicable framework for assessing digital maturity in electric power networks. By bridging qualitative insights with quantitative evaluation, the DAM contributes to a clearer understanding of digital transformation pathways and supports informed decision-making in the ongoing modernization of electricity systems.

Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
CIM	Common Information Model
DAM	Digitalization Assessment Model
DER	Distributed Energy Resource
DMS	Distribution Management System
DSI	Digitalization Score Index
DSM	Digital Asset Management
DSO	Distribution System Operators
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
ICT	Information and Communication Technologies
IEA	International Energy Agency
IoT	Internet of Things
KPI	Key Performance Indicators
MQTT	Message Queuing Telemetry Transport
NIST	National Institute of Standards and Technology
OT	Operational Technology
SCADA	Supervisory Control and Data Acquisition
CIGRE	Conseil International des Grands Réseaux Électriques

Data Availability Statement

Data will be made available on request.

Funding

This work was supported by the Bulgarian National Scientific Fund under the project "Optimization of Energy Consumption in Small and Medium Enterprises Based on Micro and Nano Grids" (Project No. KTI-06-M87/2/06.12.2024).

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Aghahadi, M., Bosisio, A., Merlo, M., Berizzi, A., Pegoiani, A., & Forciniti, S. (2024). Digitalization processes in distribution grids: a comprehensive review of strategies and challenges. *Applied Sciences, 14*(11), 4528. [Crossref]

[2] Monaco, R., Bergaentzlé, C., Vilaplana, J. A. L., Ackom, E., & Nielsen, P. S. (2024). Digitalization of power distribution grids: Barrier analysis, ranking and policy recommendations. *Energy Policy, 188*, 114083. [Crossref]

[3] Kiasari, M., Ghaffari, M., & Aly, H. H. (2024). A comprehensive review of the current status of smart grid technologies for renewable energies integration and future trends: The role of machine learning and energy storage systems. *Energies, 17*(16), 4128. [Crossref]

[4] *Smart grids task force – EG3*. (n.d.). Usef Energy – Universal Smart Energy Framework. Retrieved from https://www.usef.energy/implementations/smart-grids-task-force-eg3/ (accessed on 29 December 2025).

[5] Schirn, A. (2025, May 21). *ISO 55000:2024— asset management vocabulary & principles - ANSI blog*. The ANSI Blog. Retrieved from https://blog.ansi.org/ansi/iso-55000-2024-asset-management-vocab-principles/ (accessed on 29 December 2025).

[6] Olson, E. (2024). Digital Transformation and AI in Energy Systems: Applications, Challenges, and the Path Forward. In *Digital Sustainability: Leveraging Digital Technology to Combat Climate Change* (pp. 63-79). Cham: Springer Nature Switzerland. [Crossref]

[7] Force Digitalisation of the Energy System. (2024, June). *Smart grid indicators – The case for observability* (Technical Discussion Paper) [Draft]. DSO Entity. Retrieved from https://odoo.eudsoentity.eu/publications/download/113 (accessed on 29 December 2025).

[8] DSO, E. (2022). The value of the digital transformation-Opportunities for distribution system operators (DSOs). Retrieved from https://www.edsoforsmartgrids.eu/edso-publications/the-value-of-the-digital-transformation-opportunities-for-dsos/ (accessed on 29 December 2025).

[9] Digitalization in the power grid: Driving innovation and transformation. (2024, June 24). Energy Central. Retrieved from https://www.energycentral.com/energy-management/post/digitalization-power-grid-driving-innovation-and-transformation-lAtxAfSNgSoS1bu (accessed on 29 December 2025).

[10] International Electrotechnical Commission. (n.d.). *IEC 61970:2025 ser.: Energy management system application program interface (EMS-API)* [Standard series]. Retrieved from https://webstore.iec.ch/en/publication/61167 (accessed on 29 December 2025).

[11] International Electrotechnical Commission. (2004). Application integration at electric utilities: System interfaces for distribution management. Geneva: International Electrotechnical Commission. Retrieved from https://cdn.standards.iteh.ai/samples/23638/b3d6c39cd2bb4701aedf29431861e4b5/IEC-61968-1-2020.pdf (accessed on 29 December 2025).

[12] Meletiou, A., Vasiljevska, J., Prettico, G., & Vitiello, S. (2023). Distribution system operator observatory 2022. *Joint Res. Centre, Publications Office Eur. Union, Luxembourg, Tech. Rep. EUR, 31481*. [Crossref]

[13] Heymann, F., Milojevic, T., Covatariu, A., & Verma, P. (2023). Digitalization in decarbonizing electricity systems–Phenomena, regional aspects, stakeholders, use cases, challenges and policy options. *Energy, 262*, 125521. [Crossref]

[14] Vilaplana, J. A. L., Yang, G., Monaco, R., Bergaentzlé, C., Ackom, E., & Morais, H. (2025). Digital versus grid investments in electricity distribution grids: Informed decision-making through system dynamics. *Applied Energy, 386*, 125536. [Crossref]

[15] Mahmood, M., Chowdhury, P., Yeassin, R., Hasan, M., Ahmad, T., & Chowdhury, N. U. R. (2024). Impacts of digitalization on smart grids, renewable energy, and demand response: An updated review of current applications. *Energy Conversion and Management: X, 24*, 100790. [Crossref]

[16] Chen, J., Yan, J., Kemmeugne, A., Kassouf, M., & Debbabi, M. (2025). Cybersecurity of distributed energy resource systems in the smart grid: A survey. *Applied Energy, 383*, 125364. [Crossref]

[17] Paul, B., Sarker, A., Abhi, S. H., Das, S. K., Ali, M. F., Islam, M. M., ... & Saqib, N. (2024). Potential smart grid vulnerabilities to cyber attacks: Current threats and existing mitigation strategies. *Heliyon, 10*(19). [Crossref]

[18] Pinto, S. J., Siano, P., & Parente, M. (2023). Review of cybersecurity analysis in smart distribution systems and future directions for using unsupervised learning methods for cyber detection. *Energies, 16*(4), 1651. [Crossref]

[19] Fatemi, A., Tischbein, F., Wirtz, F., Schmoger, C., Dorendorf, S., Schurtz, A., ... & Ulbig, A. (2023). On the impact of smartification strategies for the state estimation of low voltage grids. *arXiv preprint arXiv:2303.07964*.

[20] Cavus, M. (2024). Integration Smart Grids, Distributed Generation, and Cybersecurity: Strategies for Securing and Optimizing Future Energy Systems. [Crossref]

[21] Okafor, W. O., Edeagu, S. O., Chijindu, V. C., Iloanusi, O. N., & Eze, V. H. U. (2023). A Comprehensive Review on Smart Grid Ecosystem. *IDOSR Journal of Applied Science, 8*(1), 25-63.

[22] Wargers, A., Kula, J., Ortiz, F., & Rubio, D. (2018). European Distribution System Operators for Smart Grids. *Smart Charging: Integrating a Large Widespread of Electric Cars in Electricity Distribution Grids*. Available online: https://www.edsoforsmartgrids.eu/wp-content/uploads/EDSO-paper-on-electro-mobility-2.pdf (accessed on 29 December 2025).

[23] International Electrotechnical Commission. (2025). IEC 61850:2025 ser.: Communication networks and systems for power utility automation [Standard series]. Retrieved from https://webstore.iec.ch/en/publication/6028 (accessed on 29 December 2025).

[24] International Organization for Standardization. (2022). *ISO/IEC 27001:2022 Information technology — Security techniques — Information security management systems — Requirements* (3rd ed.) [International standard]. Retrieved from https://www.iso.org/standard/27001 (accessed on 29 December 2025).

[25] Brown, M. A., & Zhou, S. (2019). Smart-grid policies: an international review. *Advances in Energy Systems: The Large-scale renewable energy integration challenge*, 127-147. [Crossref]

[26] Zhang, Z., Liu, M., Sun, M., Deng, R., Cheng, P., Niyato, D., ... & Chen, J. (2024). Vulnerability of machine learning approaches applied in iot-based smart grid: A review. *IEEE Internet of Things Journal, 11*(11), 18951-18975. [Crossref]

[27] Shahbazi, A., Aghaei, J., Pirouzi, S., Niknam, T., Shafie-khah, M., & Catalão, J. P. (2021). Effects of resilience-oriented design on distribution networks operation planning. *Electric Power Systems Research, 191*, 106902. [Crossref]

[28] Siano, P. (2014). Demand response and smart grids—A survey. *Renewable and sustainable energy reviews, 30*, 461-478. [Crossref]

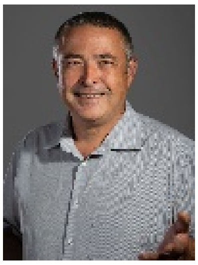
[29] Zhi, H., Mao, R., Hao, L., Chang, X., Guo, X., & Ji, L. (2024). Digital Twin for Modern Distribution Networks by Improved State Estimation with Consideration of Bad Date Identification. *Electronics, 13*(18), 3613. [Crossref]

[30] Haggi, H., Song, M., & Sun, W. (2019). A review of smart grid restoration to enhance cyber-physical system resilience. *2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, 4008-4013. [Crossref]

[31] Jørgensen, B. N., & Ma, Z. G. (2025). Digital Twin of the European Electricity Grid: A Review of Regulatory Barriers, Technological Challenges, and Economic Opportunities. *Applied Sciences, 15*(12), 6475. [Crossref]

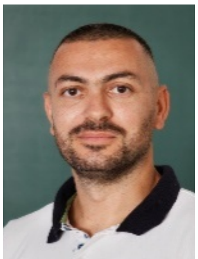
[32] Kirmani, S., Mazid, A., Khan, I. A., & Abid, M. (2022). A survey on IoT-enabled smart grids: technologies, architectures, applications, and challenges. *Sustainability, 15*(1), 717. [Crossref]

[33] Nuruzzaman, M., & Rana, S. (2025). IoT-Enabled Condition Monitoring in Power Distribution Systems: A Review of Scada-Based Automation, Real-Time Data Analytics, and Cyber-Physical Security Challenges. *Journal of Sustainable Development and Policy, 1*(01), 25-43. [Crossref]



Plamen Stanchev received his PhD in Energy Systems from the Technical University of Varna, Bulgaria, in 2023. He has published articles in various journals; his research focuses on modern optimization, simulation, and artificial intelligence methods in power grids. His interests include reliability of photovoltaic inverters, energy efficiency in small and medium-sized enterprises, reinforcement learning-based controllers for distributed generation, and feasibility assessments of storage systems such as lithium-ion, lead-acid, and hydrogen technologies. (Email: p.stanchev@tu-sofia.bg)

Nikolay Hinov – Associated Professor in Department of Computer Systems, Technical University of Sofia, Bulgaria. He received his PhD in 1998 and Dsc in 2024 at Technical University of Sofia. Current research interests: artificial intelligence systems, development and design of power electronic converters with application in industrial technologies, electric vehicles, decentralized generation of electricity and energy storage. (Email: hinov@tu-sofia.bg)



Zoran Zlatev received his PhD in 2020 at Technical University of Sofia. He has published various number of articles that include processing signals and analyzing data, artificial intelligence and power converters. His interests are in researching Power Electronics, DC-DC Converters, Machine Learning in Engineering, Digital Logic Design, Geospatial Analytics, Cloud Computing, Engineering Education, E-Commerce Technologies. (Email: zoran.zlatev@ugd.edu.mk)