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Inteligencia artificial generativa en la transición energética: una revisión de alcance

Generative Artificial Intelligence in the Energy Transition: A Scoping Review

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Resumen

La transición energética enfrentó desafíos asociados a la integración de fuentes de energía renovable variable, la gestión de la incertidumbre y la creciente complejidad de los sistemas energéticos, frente a los cuales la inteligencia artificial (IA) generativa emergió como una herramienta aún no sistematizada. El objetivo de este estudio fue analizar y sistematizar, mediante una Revisión de Alcance (Scoping Review) conforme a las directrices PRISMA-ScR, la evidencia científica sobre el uso de la IA generativa en la transición energética, con el fin de identificar sus principales dominios de aplicación, enfoques metodológicos y vacíos de investigación. La búsqueda bibliográfica se realizó el 17 de diciembre de 2025 en IEEE Xplore, Scopus, Web of Science y Springer Nature, con criterios de inclusión y exclusión definidos previamente; se incluyeron estudios revisados por pares publicados entre 2020 y 2026, con lo cual se conformó un corpus final de 12 estudios, analizados mediante un enfoque cualitativo y descriptivo. Los estudios incluidos evidenciaron tres ejes principales de aplicación: la generación de escenarios y datos sintéticos, la optimización de procesos operativos y de mantenimiento, y el apoyo a la toma de decisiones en sistemas energéticos inteligentes. Persistieron limitaciones relacionadas con la escasa validación en entornos reales, la dependencia de los datos, la escalabilidad computacional y la ausencia de marcos regulatorios. Se concluyó que la IA generativa constituyó un enfoque emergente y transversal en la transición energética, cuya consolidación práctica requiere mayor validación empírica. El protocolo fue registrado en el Open Science Framework (OSF) bajo el código 10.17605/OSF.IO/BYM7A.

Palabras clave: Inteligencia artificial, Política energética, Recursos energéticos, Fuente de energía renovable.

Abstract

The energy transition faced challenges associated with the integration of variable renewable energy sources, the management of uncertainty, and the growing complexity of energy systems, and generative artificial intelligence (AI) emerged as a tool that remained largely unsystematized. The objective of this study was to analyze and synthesize, through a Scoping Review conducted under the PRISMA-ScR guidelines, the scientific evidence on the use of generative AI in the energy transition, to identify its main application domains, methodological approaches, and research gaps.

The literature search was carried out on December 17, 2025, in IEEE Xplore, Scopus, Web of Science, and Springer Nature, under previously defined inclusion and exclusion criteria; peer-reviewed studies published between 2020 and 2026 were included, which resulted in a final corpus of 12 studies analyzed through a qualitative and descriptive approach. The included studies evidenced three main application axes: the generation of scenarios and synthetic data, the optimization of operational and maintenance processes, and support for decision-making in intelligent energy systems. Limitations persisted regarding limited validation in real-world settings, data dependency, computational scalability, and the absence of specific regulatory frameworks. It was concluded that generative AI constituted an emerging, cross-cutting approach within the energy transition, whose practical consolidation requires further empirical validation. The protocol was registered in the Open Science Framework (OSF) under code 10.17605/OSF.IO/BYM7A.

Keywords: Artificial intelligence, Energy policy, Energy resources, Renewable energy sources.

Introduction

The energy transformation constitutes one of the main technological and strategic challenges of recent decades, due to the need to reduce polluting emissions, integrate variable renewable energy sources, and ensure the security of electricity supply. This process, commonly referred to as the energy transition, involves structural changes not only in generation technologies but also in the planning, design, operation, and governance of increasingly complex and interconnected energy systems (Adewoyin et al., 2025; Alvarez et al., 2025; Erdiwansyah et al., 2025). In this context, the integration of non-conventional renewable sources and the digitalization of the electricity sector are part of the recent evolution of energy systems (Meza Jimenez y Perez, 2022; Razak et al., 2025).

With the advancement of digitalization, artificial intelligence (AI) has consolidated itself as a relevant tool to support the management of complex and dynamic energy systems(Algburi et al., 2025; Rolnick et al., 2023; Safari et al., 2024). Machine learning and deep learning approaches have been applied to tasks such as demand forecasting, renewable generation prediction, power grid optimization, and fault detection (Benti et al., 2023; Gao et al., 2022; Zhang y Strbac, 2025). However, these approaches remain mostly oriented toward predictive and optimization tasks, which may limit their capacity to represent multiple probable system scenarios and to capture the deep uncertainty and variability inherent in energy systems with high renewable penetration (Dumas et al., 2021; Zhang y Strbac, 2025).

In recent years, generative artificial intelligence emerged as an extension of deep learning aimed at modeling the underlying distribution of data and generating new plausible instances such as scenarios, system configurations, or synthetic time series through models that include generative adversarial networks, variational autoencoders, and large language models (Goodfellow et al., 2020; Kumarage y Saarela, 2026). Unlike conventional AI approaches, generative models are not limited to prediction but enable the exploration of alternative futures and the creation of synthetic data under conditions of limited or uncertain information, which poses a challenge for the energy transition (Alsaigh et al., 2023).Generative AI began to be applied to renewable scenario generation, probabilistic forecasting analysis, synthetic data creation, and support for the design of complex energy systems (Erdiwansyah et al., 2025; Ginzburg-Ganz et al., 2025). Large language models and transformer-based architectures were also explored as assistance tools for technical analysis and decision-making in the electricity sector, and as support for intelligent digital twins in smart grids (Antonesi et al., 2025; Majumder et al., 2024; Ruan et al., 2024). Recent literature documented the incorporation of generative models in systems characterized by high uncertainty and multiple possible evolution pathways, describing applications aimed at scenario analysis and the design of resilient systems (Briceño et al., 2025a; Vamvakas et al., 2025). Additionally, the rapid expansion of generative AI raised concerns regarding its own energy consumption and environmental impact, highlighting the need for a balanced assessment of its benefits and limitations (Balogun Barnabas Friday y Dhakir Abbas Ali, 2024).

Despite the growing interest in generative AI, the available evidence is dispersed across different application domains and methodological approaches, and it had not been systematized from the specific perspective of generative AI as a differentiated paradigm. Previous reviews centered on energy systems and the use of artificial intelligence within predictive and optimization models (Adewoyin et al., 2025) alongside contributions on generative AI in specific application domains (Erdiwansyah et al., 2025; Vamvakas et al., 2025); these works, however, were not fully connected to one another, which kept generative AI from being explicitly conceptualized as a paradigm in its own right. This lack of an integrative approach limited the understanding of generative AI as applied to uncertainty representation, scenario exploration, and data scarcity in complex energy systems.

Therefore, the general objective of this scoping review was to analyze and synthesize the existing scientific evidence on the application of generative artificial intelligence in energy systems related to the energy transition, to identify application domains, methodological approaches, and research gaps.

Material and Methods

Study Design

The present study was conducted as a Scoping Review, in order to map the current state of knowledge and identify emerging trends, application domains, and research gaps related to the use of generative AI in the energy transition. The review was carried out following the methodological guidelines of PRISMA-ScR (Tricco et al., 2016), which enabled a transparent structuring of the identification, selection, and synthesis process of the scientific evidence. The review protocol was registered in the Open Science Framework (OSF) on November 20, 2025, prior to the literature search conducted on December 17, 2025, to ensure methodological transparency and traceability (10.17605/OSF.IO/BYM7A).

Given the exploratory nature of this type of review, the study did not aim to quantitatively assess the performance of the generative models or to conduct statistical comparisons between technical metrics but rather sought to characterize the existing research and conceptually organize the field of study.

Conceptual Framework and Eligibility Criteria

The research question was structured under the Population-Concept-Context (PCC) framework, recommended for scoping reviews. The population or area of interest consisted of the energy systems and sectors related to the energy transition. The central concept corresponded to generative artificial intelligence, which comprised deep generative models and architectures capable of producing synthetic data, simulations, or optimized designs applied to the energy domain. The context comprised scientific publications in the fields of energy, engineering, and computer science.

Peer-reviewed studies published in English between 2020 and 2026 that explicitly addressed applications of generative AI in energy systems or processes related to the energy transition were included. Studies focused exclusively on conventional machine learning without a generative component, duplicate publications, documents outside the energy domain, and studies without full-text access were excluded.

The 2020–2026 period was selected due to the recent emergence of generative artificial intelligence as a field applied to the energy sector. The restriction to the English language was based on its predominance in international scientific production in engineering and energy. The exclusive inclusion of peer-reviewed articles was adopted to ensure the methodological quality and academic rigor of the analyzed evidence.

Information Sources and Search Strategy

The literature search was carried out in the scientific databases IEEE Xplore, Scopus, Web of Science, and Springer Nature on December 17, 2025, with the aim of identifying publications related to the use of generative artificial intelligence in the field of renewable energy and the energy transition. The search strategy was designed by combining terms associated with generative artificial intelligence models and energy systems using Boolean operators.

The Boolean search string used was: ("generative AI" OR "large language model" OR "foundation model") AND ("energy transition" OR "renewable energy" OR "clean energy" OR "low-carbon energy" OR "decarbonization") AND ("energy system" OR "power system" OR "smart grid*" OR "energy planning" OR "energy management").

Selection filters were then applied to narrow down the study corpus. Only publications from the past five years were considered, and studies on renewable energy and the energy transition involving the application of generative artificial intelligence were selected. Peer-reviewed articles published in scientific journals or edited volumes with full-text access in PDF format, including review articles, were given priority, so the final corpus ended up comprising analytical, conceptual, and modeling studies.

The information gathered was managed through Mendeley software, which made it possible, ahead of the screening and selection of studies, to identify and remove duplicate articles in line with the PRISMA-ScR protocol.

Study Selection Process

The selection process was carried out in two consecutive stages. In the first stage, titles and abstracts were screened to identify eligible studies. In the second stage, a full-text review was conducted to verify compliance with the established inclusion and exclusion criteria.

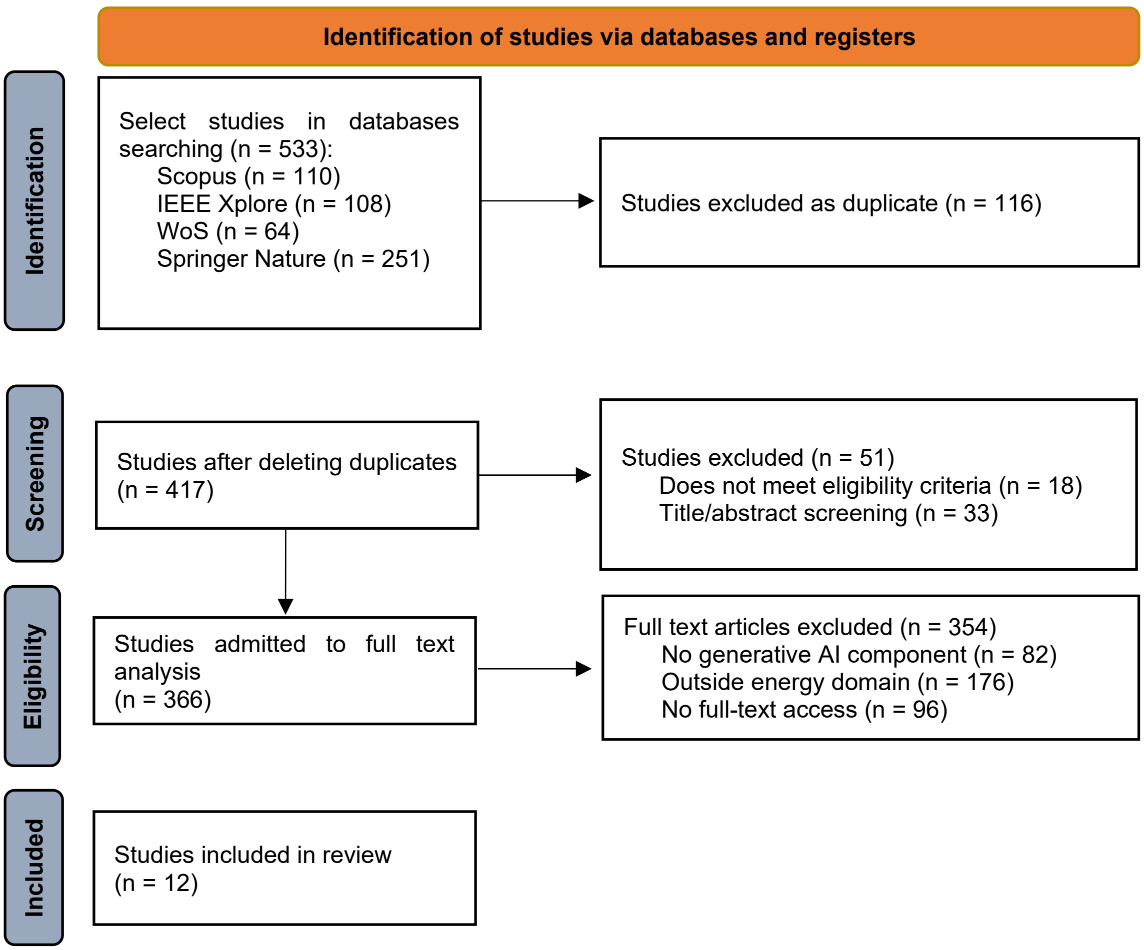
The evaluation was carried out independently by two reviewers, and any discrepancies arising during the selection process were resolved through discussion and consensus.

The complete process of identification, screening, eligibility, and inclusion was documented using a flow diagram in accordance with PRISMA-ScR.

Initially, 533 records were identified across the four databases; 116 duplicates were then removed, and 417 titles and abstracts were screened, of which 51 articles were excluded for not meeting the eligibility criteria. The 366 full-text articles were assessed, of which 354 were excluded due to the absence of a generative component, a focus outside the energy domain, or lack of full-text access; as a result, a total of 12 studies met the inclusion criteria and were incorporated into the synthesis, as shown in Figure 1.

Figure 1

Identification of studies via databases and registers.



Data Extraction and Synthesis

A structured information extraction matrix was designed for all the studies, gathering data on the type of publication, the year, the energy domain addressed, the generative AI approach used, the stage of the energy system, and the main contribution of the study.

Data extraction was carried out independently by two researchers; any discrepancies that arose were discussed until consensus was reached and then adjusted in the matrix.

The information was analyzed using a qualitative and descriptive approach and subsequently organized into synthesis tables that made it possible to identify common patterns, emerging trends, and research gaps. Finally, the studies were grouped according to energy domain, type of generative model, and the stage of the energy system addressed.

Methodological Considerations

In line with the PRISMA-ScR guidelines, the absence of a formal risk-of-bias assessment and a comparative analysis of technical metrics across different models is not regarded as a methodological shortcoming, but rather as a core feature of the scoping review approach. This approach favors broad coverage and conceptual mapping of the field over the critical appraisal of individual study quality that is typical of systematic reviews. Accordingly, these methodological choices were aligned with the exploratory aim of the study, which focused on mapping the field and identifying potential research areas rather than quantitatively assessing the effectiveness of specific generative AI methods.

Results

Following the PRISMA-ScR methodology, 12 scientific articles addressing the use of generative artificial intelligence in the energy transition process were identified; the selected studies showed a diversity of methodological approaches, energy sectors, and generative AI techniques, which facilitated the mapping of the current state of the evidence.

General Characterization of the Study Corpus

The publications analyzed span the period from 2020 to 2026, reflecting the relevance of the content and the nature of the research on generative artificial intelligence applied to the energy transition. The characterization of the studies included in the review, considering their application domain, energy sector, generative AI technique, study type, and data source, is presented in Table

1.***Table 1***

General characterization of the studies included in the review.

Article	Application Domain	Energy Sector	Generative AI Technique	Study Type	Data Source
(Velmurugan et al., 2026)	Consumption analysis	Final energy consumption	Generative models	Analytical / modeling	Energy consumption databases
(Rane, 2024)	Decision support	Renewable energy systems	Language models (ChatGPT)	Conceptual / review	Scientific literature
(Glaws et al., 2025)	System design	Integrated energy systems	Generative design models	Conceptual	Simulated scenarios
(Erdiwansyah et al., 2025)	Forecasting and optimization	Solar and wind energy	GANs, diffusion models	Review	Historical generation data
(Benchikh et al., 2024)	Performance improvement	Renewable generation	Hybrid generative models	Review	Scientific literature
(Haputhanthri et al., 2025)	Predictive maintenance	Solar photovoltaic energy	Generative AI agents	Modeling / simulation	Sensor and operational data
(Selvakumar et al., 2026)	System design	Bioenergy	Generative design models	Modeling	Energy process data
(Thirupathi et al., 2026)	System resilience	Renewable grids	Multimodal generative AI	Review	Scientific literature
(Mousavi et al., 2025)	Storage optimization	Energy storage systems	Predictive generative models	Analytical	Battery performance data
(Annapareddy y Seenu, 2023)	Resilience planning	Smart grids	Spatiotemporal generative models	Modeling	Spatial and temporal data
(Briceño et al., 2025b)	Security and reliability	Industrial photovoltaic systems	Security generative models	Case study	Operational data
(Gao et al., 2022)	System efficiency	Solar energy	Generative optimization models	Review	Scientific literature

Within a technological framework, the studies encompassed various generative AI approaches, such as deep generative models, intelligent agents, and language models. The corpus covered different stages of the energy cycle from planning, design, and operation to decision-making and included multiple domains such as solar energy, bioenergy, energy storage, and intelligent energy systems, as detailed in Table 1.

To synthesize the main results identified in the literature, Table 2 summarizes the contributions and limitations reported in the analyzed studies, allowing for the identification of methodological contributions, application areas, and research gaps in the use of generative artificial intelligence within the energy transition.

Table 2*Main contributions and limitations of the analyzed studies.*

Article	Main Contribution	Limitations / Identified Gaps
(Velmurugan et al., 2026)	Models patterns of energy consumption behavior using generative AI	Limited validation in real-world scenarios
(Rane, 2024)	Explores the potential of language models for energy planning and decision-making	Lack of quantitative evaluation
(Glaws et al., 2025)	Proposes the use of generative AI for the design of future energy systems	Conceptual framework at an early stage
(Erdiwansyah et al., 2025)	Demonstrates improvements in renewable forecasting and system optimization	Heterogeneous methodologies
(Benchikh et al., 2024)	Identifies opportunities to improve the performance of renewable systems using AI	Limited comparison between technologies
(Haputhanthri et al., 2025)	Improves fault prediction and maintenance planning in solar systems	Dependence on high-quality data
(Selvakumar et al., 2026)	Optimizes bioenergy system configurations using generative models	Limited sectoral scope
(Thirupathi et al., 2026)	Links generative AI with the resilience of intelligent energy systems	Limited empirical evidence
(Mousavi et al., 2025)	Improves reliability and lifetime of energy storage systems	Applicability restricted to certain technologies
(Annapareddy y Seenu, 2023)	Supports resilience planning in renewable energy grids	High computational complexity
(Briceño et al., 2025a)	Improves security and reliability design in industrial photovoltaic systems	Limited scalability
(Gao et al., 2022)	Demonstrates improvements in efficiency and sustainability of solar systems	Mainly conceptual approach

To synthesize the main application areas identified in the literature, Table 3 presents a classification of the applications of generative artificial intelligence in energy systems, organized according to their domain of use and the techniques employed.

Table 3

Main contributions and limitations of the analyzed studies.

Application Category	Description	Generative AI Techniques Used	Representative Studies
Energy forecasting and scenario generation	Use of generative models to simulate the variability of renewable resources and generate alternative energy scenarios that improve system planning and operation	GANs, deep generative models	(Erdiwansyah et al., 2025; Mousavi et al., 2025)
Analysis of energy consumption and behavior	Application of generative AI to analyze consumption patterns, generate synthetic data, and support energy efficiency strategies and demand management	Generative data models, LLMs	(Rane, 2024; Velmurugan et al., 2026)
Design and planning of energy systems	Use of generative models to explore alternative configurations of energy systems, optimize technological architectures, and support the design of complex energy infrastructures	Generative design models, deep generative models	(Glaws et al., 2025; Selvakumar et al., 2026; Thirupathi et al., 2026)
Operation and predictive maintenance	Application of generative AI to detect potential failures, optimize maintenance, and improve the operational performance of energy infrastructures	Generative agents, predictive	(Annapareddy y Seenu, 2023;

		generative models	Haputhanthri et al., 2025)
Security and resilience of energy systems	Use of generative AI to improve operational resilience, assess vulnerabilities, and strengthen the security of complex energy systems	Spatiotemporal generative models	(Briceño et al., 2025a; Dui et al., 2025)
Optimization and sustainability of renewable systems	Application of generative AI to improve efficiency, sustainability, and management of renewable-based energy systems	Hybrid generative models	(Benchikh et al., 2024; Gao et al., 2022)

Discussion

Interpretation of the Main Findings

In line with the general objective of this review, the included studies evidenced that generative artificial intelligence intervened at multiple stages of the energy cycle from planning, design, and operation to decision support without being limited to a single application domain (Benchikh et al., 2024; Glaws et al., 2025; Mousavi et al., 2025). This cross-cutting presence was associated with the capacity of generative models to manage uncertainty and complexity in energy systems with high renewable penetration (Dui et al., 2025; Silva et al., 2025). This finding is consistent with previous reviews that identified AI as a cross-cutting tool for energy systems management, although those reviews emphasized predominantly predictive rather than generative approaches (Adewoyin et al., 2025).

A relevant finding was that most of the included studies did not use generative AI as a direct substitute for physical models or classical methods, but rather as a complementary tool that expanded the space of possible solutions, enabling the exploration of alternative scenarios and non-trivial configurations (Figliola et al., 2025; Selvakumar et al., 2026; Thirupathi et al., 2026). This pattern was evident in applications such as energy forecasting, system design, and predictive maintenance (Briceño et al., 2025a; Haputhanthri et al., 2025), a result that is consistent with recent literature on artificial intelligence applications in renewable energy forecasting and system optimization (James, 2025).

Implications for the Energy Transition

From a systemic perspective, the research findings indicate that generative artificial intelligence could help address key challenges of the energy transition, especially those linked to the variability of renewable resources, planning uncertainty, and the need for operational resilience (Benchikh et al., 2024; Erhinyodavwe et al., 2024; Mousavi et al., 2025; Saif-Alyousfi y Alshammari, 2026).

Generative models make it possible to identify and reproduce complex, non-linear patterns in the availability of resources such as solar energy, creating synthetic series and different operating-condition scenarios. This allows system performance to be analyzed against realistic variations, moving beyond historical averages or deterministic assumptions, a capability also highlighted in broader reviews on AI applications in renewable energy systems (Ghazi Bishaw et al., 2024; Xiang et al., 2025).

Regarding planning uncertainty, generative AI reflects a shift in approach by allowing the simultaneous exploration of diverse system development pathways, rather than relying on a limited number of predefined scenarios. By generating sets of plausible scenarios, these models support the evaluation of investment, expansion, and operating decisions under different future contexts for long-term energy planning (Figliola et al., 2025; Glaws et al., 2025).

With regard to operational resilience, the reviewed literature shows that generative AI can flag vulnerable system configurations ahead of time and assess how the system might respond to extreme events or operational failures. By simulating adverse scenarios and behaviors not previously recorded, this made it possible to design more flexible operational strategies and improved the recovery capacity of energy systems (Annapareddy y Seenu, 2023; Silva et al., 2025).

Finally, the reviewed studies indicate that generative AI can help integrate energy technologies through the design and coordination of hybrid systems that combine renewable generation, storage, and demand. By generating a range of configurations and jointly evaluating multiple components, these models enable the optimization of decentralized energy infrastructures and improve the different layers of the system (Saif-Alyousfi y Alshammari, 2026; Selvakumar et al., 2026).

Relationship with Existing Literature

Unlike earlier reviews that focused on traditional machine learning methods, current results reveal a progressive, structural shift toward generative artificial intelligence approaches, driven by recent advances in deep architectures and large language models (Mousavi et al., 2025; Rane, 2024; Saif-Alyousfi y Alshammari, 2026; Xiang et al., 2025). Whereas traditional machine learning approaches were oriented toward specific predictive tasks, such as point estimation of energy variables or classification of system states, recent studies point to a growing role for artificial intelligence within energy systems.

The studies reviewed show that generative AI enables a shift away from an approach centered on predicting individual outcomes, moving instead toward exploring sets of possible solutions, scenarios, and configurations. This capability shows up in applications such as the generation of energy scenarios for planning, the design of complex energy systems, and support for strategic decision-making processes under low uncertainty (Benchikh et al., 2024; Glaws et al., 2025; Thirupathi et al., 2026).

Recent literature shows that generative AI plays a key role in knowledge management and intelligent information systems in the energy sector, drawing on technical knowledge and the application of operational data for energy system planning and management (Alsayegh y Masood, 2024; Lin et al., 2023).

This shift in approach makes it possible to connect different research domains for energy planning, operation, and governance within a common framework enabled by generative AI (Dui et al., 2025; Ghazi Bishaw et al., 2024).

Practical and Decision-Making Implications

The findings drawn from conceptual, modeling, and simulation studies carry implications for system designers and operators; in particular, generative AI could strengthen strategic and long-term planning processes through the generation of multiple alternative energy scenarios that account for the uncertainty associated with renewable resource variability, demand evolution, and system operating conditions (Erdiwansyah et al., 2025; Mousavi et al., 2025; Xiang et al., 2025).

In the operational domain, its application in predictive maintenance and performance optimization contributes to improved reliability of critical infrastructures and reduced downtime (Annapareddy y Seenu, 2023; Briceño et al., 2025a; Haputhanthri et al., 2025). Recent studies highlight the growing role of artificial intelligence techniques in the predictive maintenance and operational optimization of renewable energy systems (James, 2025; Silva et al., 2025).

Generative learning techniques are increasingly applied to optimize renewable energy production, manage hybrid systems, and improve decision-making in complex energy infrastructures (Chatterjee et al., 2024; Khan et al., 2026; Zinoviev et al., 2026).

The use of generative and language models as decision-support tools raises challenges related to transparency, explainability, and governance, particularly in critical energy systems (Briceño et al., 2025a; Rane, 2024). These concerns are increasingly highlighted in the literature addressing the

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security, interpretability, and governance challenges associated with the deployment of AI in renewable energy systems.

Application Areas of Generative AI in the Energy Transition

Energy Forecasting and Scenario Generation

In 2025, Erdiwansyah et al. examined the emerging role of generative AI in renewable forecasting and system optimization, while Mousavi et al. (2025) reported its contribution to the sustainability and efficiency of solar resources through the generation of advanced scenarios. Glaws et al. (2025) examined the use of generative models in the design and planning of future energy systems, showing that these approaches enabled the evaluation of multiple configurations under uncertainty. Dui et al. (2025) applied generative AI to strengthen spatiotemporal resilience and support low-carbon transformation strategies in intelligent energy systems.

Analysis of Energy Consumption and Behavior

Two studies addressed this topic. In 2026, Velmurugan et al. used generative models to analyze consumption patterns and generate synthetic data supporting the characterization of energy demand, while in 2024, Rane examined the contribution of generative and language models, such as ChatGPT, to consumption analysis and decision-making oriented toward energy efficiency. Benchikh et al. (2024) analyzed the use of AI tools to optimize the integration of renewable energy into power grids.

Design and Planning of Energy Systems

In 2026, Selvakumar et al. applied generative AI to the design of bioenergy systems to explore complex configurations and optimize resource use. Additionally, Thirupathi et al. (2026) examined the use of generative models in intelligent and resilient renewable systems, addressing multiple technical variables from data to deployment. In 2025, Glaws et al. also examined the early evaluation of technological and architectural alternatives using generative AI as a codesign tool for future energy systems.

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Operation and Predictive Maintenance

In 2025, Haputhanthri et al. proposed the use of generative AI agents for the predictive maintenance of solar systems, reporting improvements in early fault detection and operational efficiency. In 2023, Annapareddy y Seenu analyzed the application of generative AI in solar battery storage systems for performance and reliability. Briceño et al. (2025a) examined the use of generative AI in industrial photovoltaic systems to improve operational safety and risk management, reporting its usefulness for anticipating potential failures.

Governance for Decision-Making

One study specifically addressed aspects of security, governance, and decision-making; in 2024, Rane reported the use of generative and language models as cognitive support tools in the energy sector, considering both the opportunities and the challenges associated with their integration into complex systems.

Trends and Challenges of Generative AI

The analysis of the 12 studies revealed a shift from traditional predictive approaches toward generative models, the growing use of synthetic data, and the integration of generative AI throughout the entire energy cycle (Benchikh et al., 2024; Selvakumar et al., 2026).

However, the literature revealed gaps in the application of generative AI to the energy transition, such as limited validation in real-world settings and scalability issues when applying models to complex energy systems (Thirupathi et al., 2026). Likewise, the absence of clear regulatory and governance frameworks hindered the adoption of generative artificial intelligence, creating challenges in terms of transparency and accountability in decision-making processes (Rane, 2024).

Synthesis of the Role of Generative AI in the Energy Transition

The 12 studies described applications of generative AI across different stages of the energy cycle, including planning, design, operation, and maintenance of renewable systems. The most relevant approaches are based on the generation of alternative energy scenarios, the probabilistic modeling of uncertainty, and the development of optimized techniques for complex environments.

Throughout the literature, three main axes were identified:

- The use of generative models for simulation and synthetic data generation;
- Integration into optimization and predictive maintenance processes; and
- Support for technical and strategic decision-making in intelligent energy systems.

Recurring challenges were also identified, particularly those related to empirical validation, scalability in real-world systems, data quality, and the absence of specific regulatory frameworks. Overall, the evidence made it possible to map generative AI as an emerging approach with diversified applications, although still in a consolidation phase within the energy transition.

Study Limitations

This study presents limitations inherent to its approach as a scoping review. No quantitative critical assessment of the performance of the included models was conducted, since the objective was to map trends and application areas rather than to evaluate methodological quality. Additionally, no formal quality assessment of the included studies was performed, which is consistent with the exploratory nature of scoping reviews; however, this is acknowledged as a limitation and highlights the need for future systematic reviews that incorporate a rigorous quality assessment. The search was restricted to English-language publications indexed in specific databases (IEEE Xplore, Scopus, Web of Science, and Springer Nature), which may have excluded relevant literature published in other languages or sources. Likewise, the analysis period was limited to studies published between 2020 and 2026, in keeping with the emerging nature of the topic. The methodological heterogeneity of the studies makes direct comparisons and broad generalizations difficult. These limitations are consistent with the exploratory nature of the review and reinforce the need for more specific complementary studies.

Future Research Directions

The findings point to several directions for future research. First, there is a need to validate generative models in real operational settings, particularly in large-scale energy systems (Annapareddy y Seenu, 2023; Haputhanthri et al., 2025). Second, there is a clear need to develop governance regulations to accompany the adoption of generative AI in critical energy infrastructures (Briceño et al., 2025a; Rane, 2024; Zinoviev et al., 2026).

In addition, future research could explore the integration of generative AI with energy markets, the assessment of ethical and security risks, and its interaction with human actors in decision-making processes. Other research avenues could focus on generative models for synthetic data generation, digital twins, and intelligent information systems for renewable energy infrastructures.

Conclusions

This scoping review is grounded in the general objective of analyzing and synthesizing the scientific evidence on the application of generative artificial intelligence in energy systems related to the energy transition. The evidence indicates that generative approaches are applied mainly to scenario generation, uncertainty management, the design of complex energy systems, and the strengthening of operational resilience, pointing to a shift away from conventional predictive models toward more flexible and exploratory approaches. However, the literature on generative AI in the energy sector is still at an early, conceptual stage, with limited validation in real-world settings, constraints on model scalability, and an absence of clear governance frameworks; this gap defines the practical limits of its use in the energy transition. The main scientific contribution of this scoping review is the identification of generative AI as a cross-cutting paradigm in energy systems research, distinct from conventional predictive AI approaches. Future research should prioritize real operational settings and the development of specific governance frameworks to broaden the practical application of generative AI in the energy transition.

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