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AN INTEGRATED AI-BASED APPROACH TO TRANSFORMING ENERGY SYSTEMS FOR SUSTAINABILITY AND EFFICIENCY

Abstract: *This paper explores the transformative role of artificial intelligence (AI) in modernizing energy systems to enhance efficiency, sustainability, and resilience in response rising global energy demands and environmental concerns. A comprehensive literature review and systematic analysis highlight how AI-driven innovations impact energy generation, distribution, consumption, and system operations. Key AI techniques such as machine learning, deep learning, reinforcement learning, and optimization algorithms play pivotal roles in enhancing renewable energy integration, optimizing smart grid functionalities, improving energy storage solutions, and redefining energy market dynamics. A structured approach was presented for AI-based energy system transformation, emphasizing the importance of setting clear goals, selecting strategic directions, implementing AI applications, and establishing continuous feedback loops for verification and improvement. By segmenting the energy system into functional components, production, transportation, distribution, consumption, and system operations, an in-depth analysis of AI applications was provided relevant to each segment. Specific AI technologies, models, and algorithms suitable for various applications are identified, along with associated challenges and considerations. AI is a transformative force capable of reshaping energy systems to meet contemporary demands for sustainability and efficiency. By thoughtfully integrating AI technologies across the various components of energy systems and addressing associated challenges, the energy sector can unlock new levels of performance and innovation, contributing significantly to global sustainability objectives.*
Keywords: energy system, energy security, energy transformation, energy market, energy services, artificial intelligence.

1. Introduction

The energy sector is undergoing a substantial transformation driven by global efforts to achieve sustainability, efficiency, resilience, and equity. Artificial Intelligence (AI) is playing a crucial role in enabling these transformative processes across various segments of the energy industry. AI's role in the modernization of energy systems encompasses several key areas: optimizing renewable energy integration, enhancing smart grid functionalities, improving energy storage solutions, and redefining energy market dynamics.

The analytical report [1] provides a comprehensive examination of AI applications in Ukraine’s energy sector, emphasizing its transformative potential for sustainability and efficiency. These insights underscore the critical need for an integrated AI-based approach to modernize energy systems for transforming Ukraine’s energy sector in the context of post-conflict reconstruction. It is underscored in [2] that transforming Ukraine’s energy systems via energy management systems (EMS) is vital for sustainability and efficiency. This emphasizes the critical role of AI-driven EMS in fostering resilient, sustainable energy systems in Ukraine.

One critical area of transformation is the integration of renewable energy sources into the existing power systems. AI has shown significant potential in addressing challenges such as variability, unpredictability, and grid integration associated with renewables. Forecasting renewable energy generation with AI, for instance, helps in optimizing hybrid systems that comprise a mix of renewable energy sources and other technologies, improving the overall efficiency and reliability of the energy grid [3–5]. AI's predictive capabilities in this domain are further emphasized in studies focusing on demand forecasting and real-time energy management, illustrating the importance of integrated data analytics and predictive modeling [6, 7].

The development of smart grids is another transformative direction facilitated by AI. AI technologies enable real-time monitoring, decentralized control, and provide advanced functionalities such as fault detection, load balancing, and predictive maintenance. These capabilities contribute to making energy systems more reliable and adaptable to disruptions [8–10]. By using techniques such as behavior trees, AI can introduce innovative control strategies to enhance the adaptability and efficiency of smart grid systems [11] and can enhance the efficiency of renewable energy systems by optimizing energy storage through predictive charge-discharge cycle management, improving battery performance, and addressing challenges related to storage capacity and cost-effectiveness in the context of Ukraine's increasing adoption of RES technologies, e.g for heat supply [12].

In terms of energy market optimization, AI has revolutionized pricing dynamics and demand-response systems. With AI-powered tools, dynamic pricing models are more accurately tailored to supply and demand fluctuations, leading to reduced price volatility and enhanced market transparency. This fosters an environment where smaller players and households can engage in energy trading, thus contributing to a more decentralized and democratized energy market [13, 14]. Moreover, AI facilitates the integration of intermittent renewable energy sources, supporting their economic viability and influence on the cost structure of energy production [15]. AI also plays a pivotal role in enhancing energy efficiency by optimizing operations in generation, transmission, and distribution. AI and IoT-enabled smart infrastructures, such as buildings, advance energy efficiency further by real-time adjustments based on usage patterns [16].

Environmental sustainability is significantly impacted by AI-driven initiatives, which prioritize low-emission and renewable sources, consequently reducing carbon footprints. AI aids in the assessment and optimization of waste management systems, and predictive analytics for waste heat recovery, particularly in district heating systems [17–19]. AI's integration into the energy market brings about substantial regulatory and governance challenges and opportunities. AI enables sophisticated modeling of policy effects, aiding regulators in informed decision-making [20].

AI's transformative capabilities offer substantial benefits across various facets of the energy sector, from technological advancements in grid management to economic optimization of energy markets. The integration of AI within energy systems not only leads to operational improvements but also supports the global transition towards more sustainable energy solutions, aligning with strategic objectives outlined for future developments.

The aim of this paper is to develop a holistic approach to enhancing the transformative role of artificial intelligence in modernizing energy systems by exploring models and algorithms that facilitate this transition.

To achieve the task, the following objectives were set:

- conduct a review of the existing literature to identify the state-of-the-art advancements and gaps in the application of AI for energy systems transformation;
- delineate the key stages in the transformation of energy systems, highlighting how AI technologies enable and enhance each stage;
- segment the energy system into functional components and provide an in-depth analysis of AI-based applications relevant to each segment and propose a conceptual framework or roadmap for the integration of AI-driven approaches across energy systems.

According to the defined objectives, the research methodology is structured into four sequential stages, as illustrated in Fig. 1. This systematic approach ensures a comprehensive exploration of the ways and means to transform energy systems using AI. Each stage contributes uniquely to achieving the study’s goals by addressing key aspects such as literature analysis, identification of transformation phases, AI applications, and the development of a conceptual framework.

The proposed research methodology systematically addresses the objectives of the study. Starting with a thorough literature review to identify current advancements and gaps, the methodology delineates the transformation stages of energy systems with a focus on AI integration. It further explores AI methods and applications across system components and concludes with the development of a conceptual framework to ensure scalability and sustainability. This structured approach provides valuable insights and practical guidelines for advancing energy system transformations powered by AI.

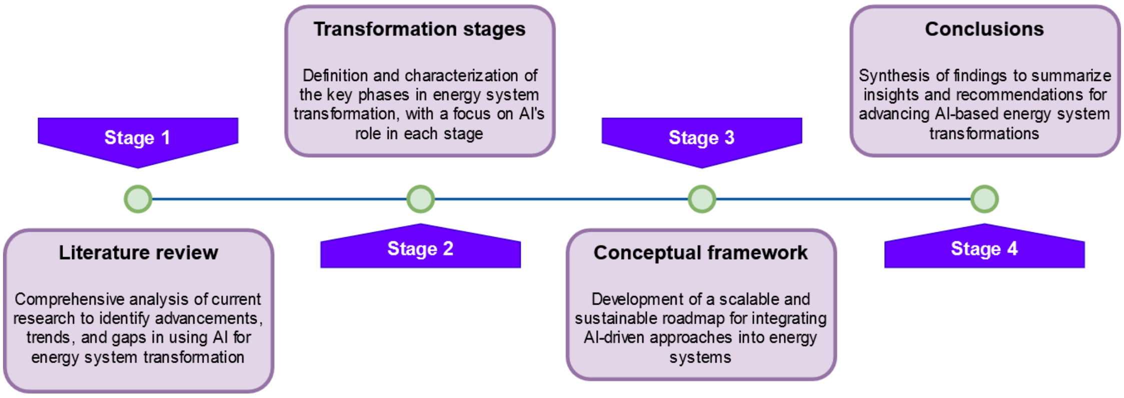

Figure 1. Methodology of research

2. Methods and materials

Literature review. The literature on transforming energy systems using AI reflects a burgeoning field that aims to revolutionize how energy is generated, distributed, and consumed. The convergence of AI with energy systems offers innovative solutions but also poses complex challenges. This review synthesizes insights across several studies to delineate the core developmental trends, applications, challenges, and future directions associated with AI in energy transformation.

Advancements in AI applications have led to significant improvements in various domains of the energy sector. The integration of AI into energy systems has facilitated automation and optimization of power grids. For instance, AI algorithms have been applied to automate power grid management, perform multidimensional data analysis, and optimize decision-making processes. Machine learning methods, metaheuristic algorithms, and intelligent fuzzy inference systems enhance operations such as cybersecurity, smart grid management, energy saving, power loss minimization, fault diagnosis, and renewable energy integration, as highlighted in [21]. In distributed smart grids, AI techniques support applications including distributed energy management, generation forecasting, grid health monitoring, fault detection, and home energy management. The integration of renewable energy sources and energy storage systems is optimized through AI, enhancing the reliability and efficiency of the future power system, as discussed in [22].

The digital transformation of microgrids through AI technologies like distributed energy resource management systems, the Internet of Things (IoT), big data analytics, blockchain, and digital twins improves performance, efficiency, and resilience. AI enables advanced control and optimization strategies for microgrid operations [23, 24]. In the domain of electric vehicles, the integration of AI into energy management systems has led to advancements in energy management optimization, route planning, energy demand forecasting, and real-time adaptation to driving conditions. This enhances vehicle performance, energy efficiency, and range, as analyzed in [25]. Expanding the scope to critical infrastructure, AI has been instrumental in optimizing energy systems within railway transport. An innovative model of deep mutual integration of the architecture of an intelligent computer environment for managing objects in the power supply system of railway transport has been proposed in [26]. By integrating AI, the management systems of power supply facilities become more flexible and adaptive to changes in load and working conditions.

Despite these advancements, several gaps and challenges hinder the full potential of AI in energy systems transformation. The incorporation of AI into existing energy infrastructures faces technical complexities, interoperability issues, and a lack of standardization, making implementation difficult [27]. Increased reliance on digital technologies introduces vulnerabilities to cyberattacks. AI systems themselves can be targets of attacks or may inadvertently introduce security loopholes [28, 29]. Policy and regulatory barriers, such as inadequate policies, regulations, and institutional hindrances, impede the integration of AI into the energy sector. There is a need for supportive regulatory frameworks that facilitate innovation while ensuring security and privacy. Additionally, the vast amounts of data required for AI applications raise concerns about data privacy and ethical use. Strategies for secure data handling and compliance with privacy laws are essential.

The transformation of energy systems involves several key stages where AI technologies play a crucial role. Digitalization of energy systems is foundational for integrating AI technologies [30, 31]. Power grid enterprises are adopting digital transformation management modes based on AI algorithms to improve management and service levels. For instance, enterprises employing AI-based digital transformation have shown significant improvements in informatization project management and operation and maintenance service management indices [32]. In intelligent buildings, AI enhances robustness, reliability, automation, and flexibility by applying smart controls, fault detection, diagnosis, and optimization techniques, while AI-driven energy management systems enable better demand response and load management. Moreover, AI can significantly reduce excess energy generation by accurately predicting energy consumption patterns [33]. By analyzing data and forecasting energy demand, AI helps optimize energy system operations, ensuring efficient use of resources and avoiding overproduction. Research indicates that methods like deep learning significantly enhance the accuracy of electricity demand predictions, a cornerstone for the reliable operation of future power systems [34]. This aspect is particularly crucial in contexts like Ukraine's recovery, where efficient resource utilization and reduction of greenhouse gas emissions are paramount [35].

The transition to smart grids represents a prominent area where AI is making a substantial impact. Smart grids incorporate high levels of renewable energy, which introduces variability due to the intermittent nature of resources like solar and wind. AI-powered methods, such as machine learning and data-driven approaches, help manage and predict the behaviors of such systems, improving their efficiency despite these variabilities. These predictive analyses are propelled by the integration of digital technologies such as the Internet of Things (IoT), blockchain, and AI itself, collectively referred to as the Internet of Energy [36]. AI is instrumental in developing smart grids and transitioning towards the Energy Internet, which envisions a decentralized, efficient, and sustainable energy system. Smart grids utilize real-time data and intelligent algorithms to optimize operations, enhance energy distribution, and integrate prosumers into the energy market [37–39].

AI enables the transformation of energy markets by optimizing trading, forecasting prices, and facilitating new market models like local electricity markets. AI-based computational models support the sustainable transformation of energy markets, improving operations and accelerating the transition to cleaner energy sources [40, 41]. A significant aspect of the energy sector's transformation involves the integration of AI, which is facilitating the flow of information and enabling more efficient operations. The use of AI in the power sector is evidenced by a survey that covered hundreds of companies globally, highlighting a significant level of adoption and showcasing how these technologies are pivotal in supporting energy supply chains and digital solutions [42].

Short-term load forecasting is another domain where AI, particularly machine learning, plays a crucial role in smart grids. Accurate forecasting of load, photovoltaic production, and electricity sales is critical for grid management and demand-side optimization. Advanced AI models, including LSTMs and ensemble methods, have been developed to enhance prediction accuracy across these domains [43, 44]. Supporting these models, Big Data technologies enable the processing of vast real-time data streams, ensuring that forecasts are based on the most current and comprehensive information available [45]. Furthermore, AI-driven optimization techniques, such as genetic algorithms for solar panel configuration, contribute to maximizing renewable energy output, thereby promoting sustainability [46].

The integration of AI into energy systems is emerging as a transformative force, poised to reshape the way energy is generated, distributed, and consumed. This comprehensive literature review reveals that AI offers numerous opportunities to enhance efficiency, reliability, and sustainability within energy systems, yet it also brings about complex challenges that need addressing. By deploying AI-driven digital transformation strategies, power grid enterprises are capable of elevating their operational efficacy significantly. This transformation is evident in the transition towards smart grids, where AI empowers intelligent networks to self-optimize and better assimilate renewable sources, thereby fostering improved grid reliability and security. Moreover, methodological challenges in managing the complex and often stochastic nature of energy systems, particularly with regards to renewable energy sources, must be mitigated to fully harness the benefits AI can provide.

Key stages of AI-based energy system transformation. The necessity for transforming energy systems stems from the pressing challenges of climate change, resource scarcity, and the increasing complexity of energy demand and supply dynamics. Traditional energy systems, reliant on fossil fuels and centralized structures, are no longer sustainable or efficient in meeting the needs of a rapidly evolving world. The integration of renewable energy sources, electrification of sectors, and decarbonization goals require innovative approaches that go beyond conventional methods. AI provides a pivotal solution by enabling predictive analytics, real-time decision-making, and system optimization. These advancements address critical issues such as reducing greenhouse gas emissions, enhancing energy access and equity, and improving the resilience of energy infrastructure against disruptions.

The fig. 2 outlines key stages in the AI-based energy system transformation cycle, offering a structured approach to transforming energy systems using AI technologies.

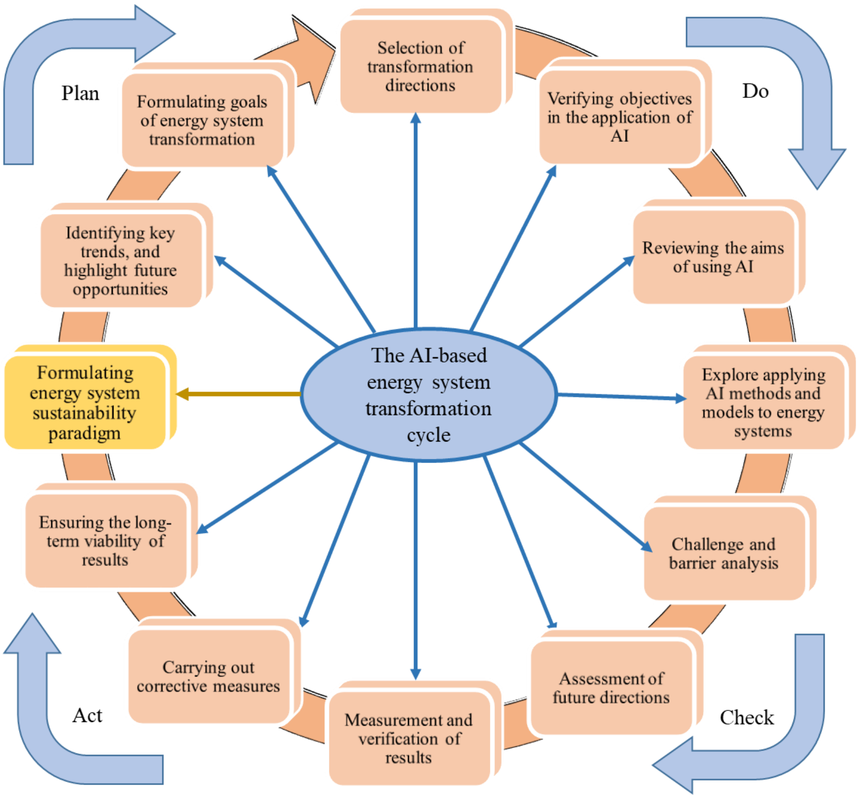

Figure 2. Key stages of a closed-loop energy system transformation based on artificial intelligence

Formulating goals of energy system transformation stage in the transformation cycle involves defining clear and actionable goals for energy system transformation. Leveraging AI's capabilities in data analysis, predictive modeling, and optimization, energy systems can identify precise objectives. For instance, goals might include achieving net-zero emissions, enhancing grid reliability, or improving energy efficiency. Recent advancements in AI-driven forecasting and scenario analysis provide actionable insights, enabling energy planners to set realistic and impactful objectives.

Selection of transformation directions stage prioritizes areas within energy systems where AI interventions will yield the most significant impact. AI algorithms can analyze historical data and predict future trends to identify transformation opportunities in energy production, distribution, or consumption. For example, AI can guide investments in renewable energy integration or energy storage systems by evaluating their potential impact on grid stability and cost efficiency.

Verification ensures that the application of AI aligns with the predefined objectives. This involves using AI tools to continuously monitor progress, identify deviations, and refine strategies. For example, machine learning models can track energy efficiency improvements over time, providing feedback on whether the implemented measures meet the intended goals.

Periodic reviews are essential to evaluate the effectiveness of AI applications in addressing energy system challenges. By integrating feedback loops, energy planners can reassess the relevance of AI-driven initiatives. This iterative process ensures adaptability to changing circumstances, such as evolving energy demands or technological advancements.

AI methods, such as deep learning, reinforcement learning, and optimization algorithms, play a pivotal role in energy system transformation. Applications include load forecasting, predictive maintenance, and smart grid management. For example, reinforcement learning has been successfully applied to optimize energy dispatch in microgrids, while deep learning models enhance demand-side management by predicting consumption patterns.

Identifying and addressing challenges is critical to the success of AI-based energy transformations. Common barriers include data scarcity, high computational costs, and resistance to change among stakeholders. AI can also help overcome these barriers by automating data collection, optimizing resource allocation, and demonstrating clear benefits through pilot projects.

Assessment of future directions involves forecasting emerging trends and identifying opportunities for AI integration in energy systems. Recent advancements, such as AI-enabled energy trading platforms and autonomous grid operation technologies, highlight the potential for transformative innovation. By synthesizing insights from existing literature, future research can focus on scaling these technologies and addressing implementation challenges.

AI tools facilitate accurate measurement and verification of energy system performance metrics, such as energy savings, emission reductions, and system reliability. Techniques like digital twins and real-time analytics enable energy operators to validate the impact of AI-driven interventions and ensure continuous improvement.

Corrective measures are essential to address any gaps or inefficiencies identified during the transformation process. AI systems can dynamically adjust operational strategies based on real-time data, ensuring optimal performance. For instance, adaptive control systems can reconfigure energy flows to mitigate bottlenecks or balance supply and demand.

The long-term success of AI-based energy transformations depends on maintaining system resilience and adaptability. AI can support this by enabling predictive maintenance, optimizing resource allocation, and fostering collaboration across stakeholders. By continuously evolving with advancements in technology and shifting energy needs, AI ensures the sustainability of transformation efforts.

The final stage synthesizes insights from the entire transformation cycle to establish a sustainability paradigm. AI plays a central role in fostering sustainable practices, such as maximizing renewable energy utilization, minimizing waste, and optimizing lifecycle costs. By integrating sustainability considerations at every stage, the transformation cycle ensures that energy systems contribute to a resilient and low-carbon future.

The schema of an AI-based energy system transformation cycle provides a comprehensive framework for addressing the complex challenges of energy transition. By systematically applying AI methods and models across each stage, energy systems can achieve transformative goals that align with sustainability objectives. This closed-loop approach ensures continuous improvement and adaptability, paving the way for resilient and future-ready energy systems.

AI-based methods, models, and applications in energy systems. The challenges in leveraging AI for energy transformation include issues such as data quality and availability, ethical and regulatory concerns, security and privacy, scalability, and interoperability in legacy systems. Meanwhile, emerging opportunities focus on adaptability in forecasting, optimization of energy markets, hybrid algorithm development, fault detection, and operations in smart grids and microgrids, alongside improved interactions with energy storage systems and enhanced cybersecurity measures. This conceptual framework underscores the potential and complexity of using AI to address the evolving demands of modern energy systems.

By segmenting the energy system into distinct groups, the unique requirements, inefficiencies, and opportunities inherent to each component can be identified. Segmentation analysis is provided in Fig. 3 and highlights the interconnected nature of these components, emphasizing the need for AI-driven approaches that ensure interoperability and scalability across the entire energy system [47]. It enables the identification of critical data flow pathways and control mechanisms, which are essential for designing integrated AI solutions that align with the system's long-term sustainability goals. Additionally, this analytical framework serves as a foundation for proposing conceptual roadmaps and frameworks, as the segmentation aligns with the hierarchical and functional structure of energy systems.

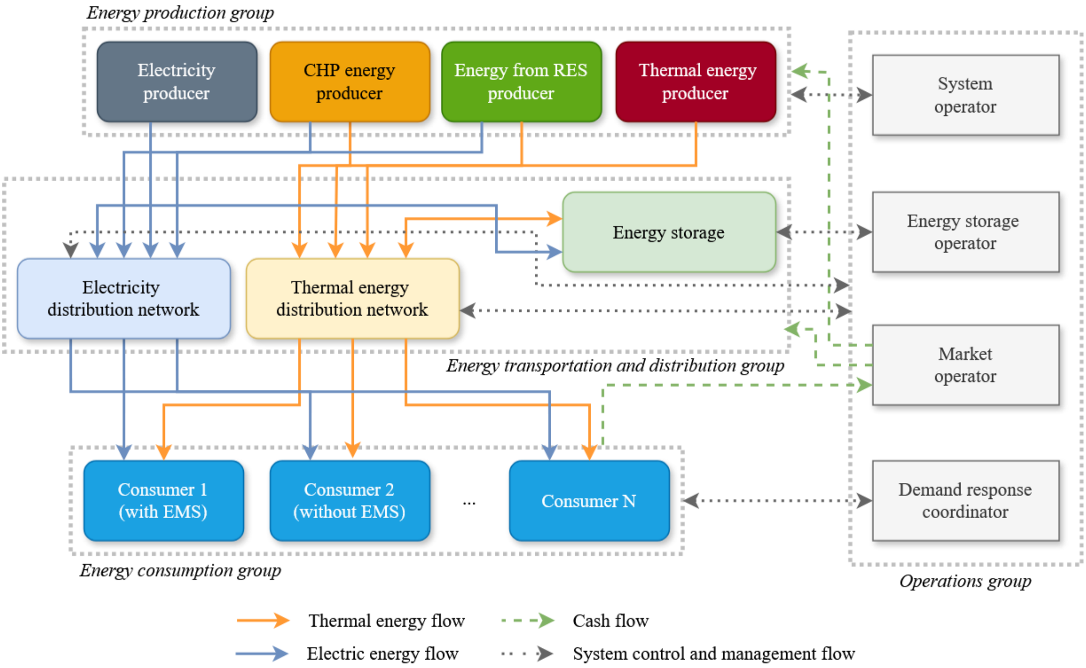

Figure 3. Functional segmentation of a local energy system (based on [47])

The “Energy production” group is responsible for generating energy, encompassing both thermal and electric forms. This group includes several key components. The electricity producer supplies electrical energy directly to the electricity distribution network, ensuring the availability of power for downstream systems. Combined Heat and Power (CHP) energy producers play a dual role, generating both electricity and thermal energy, thereby contributing to the efficiency of the overall energy system. Renewable energy sources (RES) producers provide electricity derived from sustainable resources, such as solar and wind, thus promoting the decarbonization of energy systems. Additionally, thermal energy producers generate heat for various applications, including residential heating and industrial processes, further diversifying the energy portfolio.

The “Energy transportation and distribution” group serves as the intermediary between energy producers and end-users, focusing on the efficient and reliable delivery of energy. This group includes the electricity distribution network, which facilitates the transfer of electricity from production units to consumers, ensuring grid stability. Similarly, the thermal energy distribution network ensures the delivery of heat to consumers for residential, commercial, and industrial use. Energy storage systems are integral to this group, acting as buffers to store excess energy during periods of low demand and release it during peak consumption. These systems enhance the flexibility and resilience of the energy system by mitigating supply-demand imbalances.

The "Energy consumption" Group comprises the end-users of the energy system, categorized based on their level of energy management capability. Consumers equipped EMS actively optimize their energy usage and, in some cases, interact with other system components, such as storage or demand response programs. In contrast, consumers without EMS exhibit traditional consumption patterns with limited flexibility in managing their energy use.

The "System operations" group plays a critical role in coordinating and managing the overall energy system, ensuring seamless integration of production, distribution, and consumption components. The system operator oversees the balance and stability of energy flows, maintaining operational reliability. The energy storage operator manages the charging and discharging of storage systems to optimize their utilization and enhance system flexibility. The market operator facilitates economic transactions within the energy system, ensuring the viability of energy trade and market operations. Finally, the demand response coordinator interacts with consumers to adjust their energy usage patterns dynamically in response to real-time supply conditions, thereby contributing to system efficiency and demand-side flexibility.

The diagram in Fig. 4 delineates the energy system into functional components where AI can significantly enhance transformation. In energy production, AI improves efficiency through renewable forecasting and maintenance strategies. For energy transportation and distribution, AI optimizes grid management, storage operations, and smart grids. On the consumption side, it enables demand-side management and efficiency through forecasting and personalized recommendations. System operations benefit from AI in grid balancing, market optimization, and cybersecurity. The framework underscores the potential of AI to enhance scalability, interoperability, and sustainability, offering a roadmap for integrating AI into energy systems transformation.

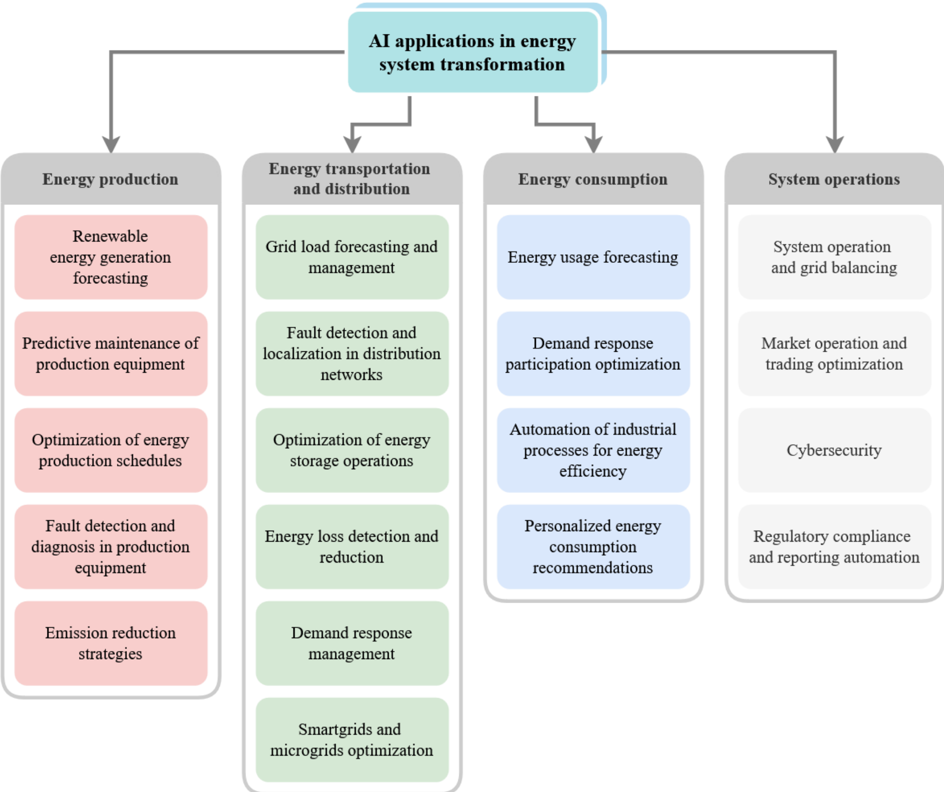

Figure 4. AI applications in energy system transformation

The energy sector is inherently complex, involving a multitude of interconnected components that range from production to consumption and system operations. Without a structured segmentation of the energy system, it becomes challenging to identify and address the specific areas where AI can be most effectively applied. By segmenting the energy system into functional components, such as production, transportation and distribution, consumption, and system operations, we create a clear framework that facilitates targeted analysis and application of AI technologies.

In energy production, AI enhances the efficiency of both renewable and traditional sources. For instance, in solar and wind farms, it predicts generation patterns based on historical weather data, enabling better maintenance scheduling and reducing reliance on backup fossil fuels. This ensures a more reliable integration of renewable energy into the grid. In traditional power plants, such as those using coal, AI forecasts energy demand using consumption and weather data, optimizing fuel usage and cutting operational costs while maintaining stable output. Additionally, AI monitors equipment health in renewable installations, predicting failures before they occur and extending the lifespan of critical components like turbine blades.

AI plays a crucial role in managing the transportation and distribution of energy. It forecasts load distribution across transmission lines, anticipating peak demand to prevent overloads and enhances grid stability. In distribution networks, AI quickly detects faults in power lines, significantly reducing downtime and improving service reliability for customers. It also optimizes the management of battery storage systems connected to the grid, extending battery life and supporting renewable energy integration during off-peak hours. Furthermore, AI identifies energy losses due to leakage in distribution lines, enabling targeted repairs that improve overall efficiency and lower operational costs.

On the consumption side, AI helps end-users reduce energy usage and costs across residential, commercial, and industrial settings. Energy apps leverage AI to analyze consumption patterns and provide personalized recommendations, such as adjusting thermostat settings, to help users reduce energy usage. In factories, AI monitors machine schedules in real-time, detecting inefficiencies and minimizing waste, which enhances operational competitiveness.

AI ensures the overall stability, security, and compliance of the energy system. It predicts system-wide load across large networks, improving resource allocation and reducing the costs of integrating renewable energy. In substations, AI localizes faults quickly, minimizing disruptions during peak usage. AI also enhances cybersecurity by detecting anomalies, such as cyber threats, in real-time, preventing potential outages and maintaining trust in the system. Additionally, it automates compliance reporting for power plants, ensuring adherence to environmental regulations while reducing administrative workloads.

This analysis presented in Table 1 allows to delve deeply into each segment and uncover the unique challenges and opportunities present. By identifying these specific needs and potential solutions within each group, AI applications can be proposed that are not only innovative but also highly relevant and impactful.

Table 1. AI applications, technologies, challenges and benefits in energy system transformation

AI Application	**AI technologies, models, and algorithms**	**Challenges and considerations**	**Expected benefits and impact**
Energy production			
Renewable energy generation forecasting	Long short-term memory (LSTM) networks, recurrent neural networks (RNN), time series analysis, gradient boosting machines, convolutional neural networks (CNN)	Weather data accuracy, complex patterns in data, computational intensity, integration into operational planning	Improved integration of renewables, enhanced scheduling and dispatching, reduced reliance on fossil fuels
Predictive maintenance of production equipment	Machine learning algorithms, support vector machines (SVM), random forests, anomaly detection algorithms, autoencoders, multilayer perceptron (MLP)	Data quality and availability, sensor integration for real-time monitoring, need for explainable AI for regulatory compliance	Reduced downtime and maintenance costs, extended equipment lifespan increased reliability of energy supply
Optimization of energy production schedules	Reinforcement learning (RL), genetic algorithms, optimization algorithms, swarm intelligence	High computational requirements, real-time optimization needs, balancing multiple objectives, regulatory and market constraints	Increased operational efficiency, cost savings, lower emissions, enhanced response to demand fluctuations

Table 1 continued

AI Application	AI technologies, models, and algorithms	Challenges and considerations	Expected benefits and impact
Fault detection and diagnosis in production equipment	CNN, SVM, decision trees, clustering algorithms, computer vision (CV)	Need for large labeled datasets, real-time processing, integration with monitoring systems, data privacy concerns	Early fault detection, prevention of failures, improved safety, reduced repair costs
Emission reduction strategies	RL for adaptive control, support vector regression (SVR)	Regulatory compliance, accurate emission measurements, trade-offs between efficiency and emissions, adoption barriers	Lower greenhouse gas emissions, regulatory compliance, improved public health outcomes
Energy transportation and distribution			
Grid load forecasting and management	LSTM networks, time series forecasting models; SVR, ARIMA models	Accurate demand prediction, integration of distributed resources, data latency, scalability for large grids	Improved grid stability, efficient load balancing, reduced operational costs, better renewable integration
Fault detection and localization in distribution networks	Anomaly detection algorithms, SVM, decision trees, clustering algorithms, CV	Limited data from sparse sensors, real-time processing needs, sensor deployment costs, system interoperability	Faster fault resolution, reduced downtime, improved reliability, customer satisfaction
Optimization of energy storage operations	RL, particle swarm optimization, predictive modeling, deep learning (DL)	Battery degradation, charge/discharge balancing, integration with grid and market signals, storage technology constraints	Enhanced storage utilization, improved grid flexibility, cost saving, increased renewable integration
Energy loss detection and reduction	SVM, anomaly detection, pattern recognition algorithms, CV	Measuring losses accurately, complex network topologies, data quality issues, real-time analytics needs	Reduction in losses, cost savings, improved distribution efficiency
Demand response management	RL, agent-based modeling	Consumer participation rates, privacy concerns, communication infrastructure, regulatory compliance	Better demand-side flexibility, reduced need for peaking plants, improved grid stability, cost savings
Smartgrids and microgrids optimization	RL, multi-agent systems, predictive analytics, optimization models	Coordinating multiple DERs, data interoperability, AI model scalability, regulatory and market barriers	Improved DER utilization, enhanced grid resilience, lower operational costs, support renewable targets
Energy consumption			
Energy usage forecasting	Time series analysis, LSTM networks, ARIMA models, SVR, CV, DL	Accurate consumption modeling, external factors (weather, occupancy), scalability, data privacy concerns	Better energy planning, cost savings with optimized tariffs, market participation, sustainable consumption
Demand response participation optimization	RL, game theory models, optimization algorithms, transformers	Incentivizing participation, communication infrastructure, real-time data processing, regulatory constraints	Improved grid flexibility, financial incentives, enhanced supply-demand balance, peak load reduction
Automation of industrial processes for energy efficiency	CV, RL, predictive maintenance algorithms, optimization algorithms	High initial costs, legacy system integration, skilled workforce needs, safety and compliance regulations	Increased efficiency, significant energy savings, reduced operational costs, enhanced competitiveness
Personalized energy consumption recommendations	Data mining, transformers	Data privacy and protection, need for quality user data, ethical considerations, user engagement strategies	Increased user engagement, energy savings, enhanced customer satisfaction, support for demand management
System operation and grid balancing	RL, predictive modeling, transformers	Real-time data processing, data source integration, cybersecurity risks, large-scale system modeling complexity	Enhanced grid stability, reduced blackout risks, optimal resource use, better renewable energy integration

Table 1 continued

AI Application	AI technologies, models, and algorithms	Challenges and considerations	Expected benefits and impact
System operations			
Market operation and trading optimization	Algorithmic trading systems, LSTM, DL, agent-based modeling, game theory	Market volatility, regulatory constraints, high-frequency data needs, ethical considerations in trading	Increased market efficiency, optimized trading strategies, better price discovery, enhanced market liquidity
Cybersecurity	Anomaly detection systems, ML for intrusion detection, threat intelligence, blockchain technology	Evolving cyber threats, legacy system integration, security vs. efficiency balance, regulatory compliance	Enhanced cyber protection, safeguarding infrastructure, maintaining trust, compliance with security regulations
Regulatory compliance and reporting automation	Transformers, data validation ML models	Keeping up with regulations, ensuring data accuracy, reporting system integration, data privacy concerns	Reduced administrative burden, increased reporting accuracy, timely compliance, adaptability to changes

This analysis directly supports the objective of proposing a conceptual framework and roadmap for AI integration. By thoroughly examining each segment and identifying how AI can enhance scalability, interoperability, and sustainability, a solid foundation is provided upon which a cohesive and strategic plan can be built. This roadmap is essential for guiding policymakers, industry leaders, and other stakeholders in making informed decisions about investing in and implementing AI technologies within the energy sector. In essence, this analysis serves as the bridge between theoretical understanding of AI's capabilities and the practical steps needed to transform energy systems. It ensures that proposed roadmap is grounded in a thorough understanding of the energy system's intricacies and is tailored to address the specific challenges and opportunities within each segment.

3. Discussion

The integration of AI into energy systems represents a significant transformation in how energy is produced, distributed, and consumed. This study highlights the multifaceted roles AI can play in enhancing efficiency, sustainability, and resilience within the energy sector.

AI integration has profound implications. It enhances efficiency through improved energy forecasting and optimized resource utilization, leading to reduced operational costs and better load management. In the realm of renewable energy, AI manages the intermittent nature of sources like solar and wind power, enhancing predictability and facilitating seamless integration into the grid. Grid reliability is bolstered by AI-driven predictive maintenance and fault detection, which reduce downtime and improve stability. Consumers are empowered by AI applications that enable personalized energy management and participation in demand response programs, fostering active engagement and energy conservation. Economically, AI optimizes market operations, improves price discovery, and has the potential to lower energy costs for consumers.

Given the ongoing war and the urgent need to recover Ukraine's energy systems, AI offers transformative potential to improve the efficiency, reliability, and sustainability of the energy sector. The war has caused extensive damage to generation facilities and transmission networks, with significant losses reported by [48]. As Ukraine seeks to rebuild and modernize its energy infrastructure, particularly by integrating renewable energy sources, AI can play a crucial role in addressing current challenges and shaping a resilient energy future.

One of the most immediate and impactful applications of AI in Ukraine’s energy sector is forecasting energy production and consumption, especially as the country plans to massively install renewable energy sources like solar and wind. Accurate forecasting is essential for balancing the grid, particularly in a post-war context where energy supply and demand can fluctuate unpredictably. Similarly, AI can predict energy demand by processing consumption patterns, weather data, and economic indicators. This dual forecasting capability enables grid operators to maintain stability across local and unified energy systems, ensuring reliable power delivery as Ukraine transitions to a greener energy mix.

As Ukraine reconstructs its energy systems with an emphasis on decentralization and renewable integration, AI can optimize energy distribution and consumption. Smart grid management powered by AI can predict load distribution, manage energy storage, and implement demand response programs.

Also, the war has left Ukraine's energy infrastructure vulnerable, with frequent disruptions due to damaged equipment and networks. AI-based fault detection and predictive maintenance can significantly enhance system resilience. This is critical for minimizing downtime in a recovery phase where resources are stretched thin.

Policymakers have a critical role in creating an enabling environment for AI-driven energy transformations. Updating regulations to accommodate AI technologies, while ensuring ethical standards and data security, is essential. Financial incentives and subsidies can promote innovation and support infrastructure upgrades in the energy sector. Investing in education and training programs will develop a skilled workforce capable of driving and managing these technological advancements. While AI holds immense promise, its implementation in Ukraine faces challenges. Data availability and quality are critical, as AI relies on large, accurate datasets that may be disrupted by the war. Rebuilding data collection infrastructure and training skilled professionals to develop and maintain AI systems will be essential.

Future research should focus on developing robust data management frameworks to improve data quality and availability for AI applications. Advancing AI algorithms that are more efficient and require less computational power will facilitate broader adoption. Creating AI-driven cybersecurity solutions is crucial to protect energy infrastructure from emerging threats. Encouraging interdisciplinary collaboration among technologists, energy experts, policymakers, and social scientists can lead to holistic solutions that consider technical feasibility, regulatory compliance, and societal impact. Implementing pilot projects and case studies will provide valuable insights into practical challenges and effective strategies for AI integration in real-world settings.

4. Conclusions

This paper has explored the transformative potential of AI in modernizing energy systems, with a particular emphasis on addressing Ukraine's pressing challenges of efficiency, sustainability, and resilience amid post-war recovery and growing demands for renewable energy integration. Through a holistic approach that encompassed a comprehensive literature review, delineation of transformation stages, functional segmentation of energy systems, and the proposal of a conceptual framework, we have demonstrated how AI can drive significant advancements across the energy sector tailored to Ukraine's unique context.

By delineating the key stages of AI-based energy system transformation, this study provided a structured framework that illustrates how AI enables each phase, particularly in Ukraine's post-war context. These stages include setting goals for resilient infrastructure reconstruction, strategically prioritizing renewable energy integration, implementing AI-driven solutions like fault detection and load forecasting, and establishing feedback loops for continuous improvement. This approach ensures that AI integration is purposeful and adaptable to Ukraine's evolving energy needs, facilitating a transition from recovery to sustainability.

The functional segmentation of the energy system into production, transportation and distribution, consumption, and system operations allowed for an in-depth analysis of AI applications relevant to each segment. This detailed analysis culminated in the development of a conceptual framework that serves as a roadmap for integrating AI-driven approaches across energy systems. By identifying specific AI technologies, models, and algorithms suitable for various applications, and by acknowledging the challenges and considerations associated with each, practical guidelines were provided for stakeholders aiming to implement AI solutions. The expected benefits and impacts, such as improved efficiency, cost savings, enhanced reliability, and reduced emissions, highlight the significant potential of AI to contribute to sustainable energy objectives.

AI emerges as a pivotal force in reshaping Ukraine's energy systems to meet modern demands. Future research should refine AI methodologies for post-conflict settings, improve data management, and develop regulatory frameworks to ensure secure, equitable, and sustainable energy transformations.

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ІНТЕГРОВАНИЙ ПІДХІД ДО СТАЛОГО РОЗВИТКУ ТА ЕФЕКТИВНОСТІ ТРАНСФОРМУВАННЯ ЕНЕРГЕТИЧНИХ СИСТЕМ НА ОСНОВІ ШТУЧНОГО ІНТЕЛЕКТУ

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Анотація: *У статті досліджено трансформаційну роль штучного інтелекту (ШІ) у модернізації енергетичних систем для підвищення ефективності, стійкості та резильєнтності у відповідь на зростаючий глобальний попит на енергію та екологічні проблеми. Завдяки комплексному огляду літератури та систематичному аналізу висвітлено, як інновації, керовані ШІ, впливають на виробництво, розподіл, споживання та роботу системи енергії. Ключові методи штучного інтелекту, такі як машинне навчання, глибоке навчання, навчання з підкріпленням і алгоритми оптимізації, відіграють ключову роль у покращенні інтеграції відновлюваної енергетики, оптимізації функціональних можливостей інтелектуальної мережі, покращенні рішень для зберігання енергії та переосмисленні динаміки енергетичного ринку. Було представлено структурований підхід до трансформації енергетичної системи на основі штучного інтелекту з наголошенням на важливості встановлення чітких цілей, виборі стратегічних напрямків, впровадженні програм штучного інтелекту та встановленні постійних циклів зворотного зв'язку для перевірки та вдосконалення. Завдяки сегментуванню енергетичної системи на функціональні компоненти: виробництво, транспортування та розподіл, споживання енергії та управління системою, було забезпечено поглиблений аналіз застосувань ШІ щодо кожного сегмента. Визначено конкретні технології штучного інтелекту, моделі та алгоритми, придатні для різних застосувань. ШІ виступає як інтегрований підхід, здатний змінювати енергетичні системи відповідно до вимог стійкості та ефективності. Системна інтеграція технологій штучного інтелекту в різні компоненти енергетичних систем і вирішення пов'язаних з цим проблем дасть змогу енергетичному сектору отримати новий рівень продуктивності та інновацій, зробить значний внесок у глобальні цілі сталого розвитку.*

Ключові слова: енергетична система, енергетична безпека, енергетична трансформація, енергетичний ринок, енергетичні послуги, штучний інтелект.

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