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Artificial Intelligence in the Power Industry

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ABSTRACT

Artificial intelligence (AI) refers to the science and engineering of making machines intelligent. The introduction of AI is igniting a revolution in the dynamic world of power systems. AI is revolutionizing the power sector by enabling intelligent data analysis for grid management, predictive maintenance, and optimization of energy consumption. Owners and operators of buildings, homes, and power grids can all benefit from the advances in AI that potentially improve building-to-grid-operator communication. AI applications are transforming business operations and processes in the power sector, leading to greater cost savings, increased efficiency, and new services for consumers. This paper highlights the transformative potential of AI in the power systems.

KEYWORDS: *power, power industry, artificial intelligence, machine learning, AI, generative AI*

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INTRODUCTION

The power sector worldwide is going through fundamental changes due to the urgency to decarbonize, improve resilience against climate-induced extreme weather events, and provide affordable, reliable energy access to at-risk communities. The sector faces growing challenges related to rising demand, efficiency, changing supply and demand patterns, and a lack of analytics needed for optimal management. These challenges are more acute in emerging market nations. Artificial intelligence (AI) has a significant impact on power industries, helping to overcome these challenges. AI is an umbrella term for various software-based systems that use data inputs to make decisions on their own. It is a multi-purpose technology which is gaining increased attention and is now widely used across all sectors of the economy. You may have experienced AI in a voice search with Amazon's Alexa or Apple's Siri. Figure 1 shows AI symbol [1].

From lighting our homes and putting food on our tables to providing warmth during winters and keeping us cool during scorching summers, the power sector is an indispensable part of modern society. The power industry also empowers other industries to manufacture goods and enables businesses and institutions to operate seamlessly.

The past ten years have seen an explosion in the amount of data generated by power companies, mostly due to the rise of the IoT. Although the power industry has been one of the slower adopters of AI, the industry continues to be a hotbed of innovation. Activity is driven by intelligent processing, automation, enhancement of the performance of the power distribution networks, and growing importance of technologies such as AI and machine learning. Leading adopters of artificial intelligence in the power sector include Duke Energy, ABB, E.ON, Enel, Électricité de France (EDF), Iberdrola, Exelon, Schneider Electric, Dubai Energy & Water Authority (DEWA), National Grid, Siemens Energy, Schneider Electric, and Southern Company [2].

WHAT IS ARTIFICIAL INTELLENCE?

The term "artificial intelligence" (AI) is an umbrella term John McCarthy, a computer scientist, coined in 1955 and defined as "the science and engineering of intelligent machines." It refers to the ability of a

computer system to perform human tasks (such as thinking and learning) that usually can only be accomplished using human intelligence [3]. Typically, AI systems demonstrate at least some of the following human behaviors: planning, learning, reasoning, problem solving, knowledge representation, perception, speech recognition, decision-making, language translation, motion, manipulation, intelligence, and creativity.

The 10 U.S. Code § 2358 define artificial intelligence as [4]:

1. "Any artificial system that performs tasks under varying and unpredictable circumstances without significant human oversight, or that can learn from experience and improve performance when exposed to data sets.
2. An artificial system developed in computer software, physical hardware, or other context that solves tasks requiring human-like perception, cognition, planning, learning, communication, or physical action.
3. An artificial system designed to think or act like a human, including cognitive architectures and neural networks.
4. A set of techniques, including machine learning, that is designed to approximate a cognitive task.
5. An artificial system designed to act rationally, including an intelligent software agent or embodied robot that achieves goals using perception, planning, reasoning, learning, communicating, decision making, and acting."

AI provides tools creating intelligent machines which can behave like humans, think like humans, and make decisions like humans. The main goals of artificial intelligence are [5]:

1. Replicate human intelligence
2. Solve knowledge-intensive tasks
3. Make an intelligent connection of perception and action
4. Build a machine which can perform tasks that requires human intelligence
5. Create some system which can exhibit intelligent behavior, learn new things by itself, demonstrate, explain, and can advise to its user.

AI is not a single technology but a range of computational models and algorithms. The concept of AI is an umbrella term that encompasses many different technologies. AI is not a single technology but a collection of techniques that enables computer systems to perform tasks that would otherwise require human intelligence. The major disciplines in AI include [6]:

- *Expert systems*
- *Fuzzy logic*
- *Neural networks*
- *Machine learning (ML)*
- *Deep learning*
- *Natural Language Processors (NLP)*
- *Robots*

These computer-based tools or technologies have been used to achieve AI's goals. Each AI tool has its own advantages. Using a combination of these models, rather than a single model, is recommended. Figure 2 shows a typical expert system, while Figure 3 illustrates the AI tools. These tools are gaining momentum across every industry. Analytics can be considered a core AI capability.

GENERATIVE AI

Artificial Intelligence (AI) is increasingly a part of our world and it is rapidly changing our lives. Generative AI (GenAI) is a subset of artificial intelligence that uses generative models to produce text, images, videos, or other forms of data. Generative AI (GenAI) is a term for any type of AI system capable of using generative models to create new forms of humanlike creative content, like text, images, music, audio, video and more. GenAI models include various algorithms able to learn the various patterns and structures of input training data before generating novel outputs with similar characteristics. It is essentially a narrow type and application of the broader artificial intelligence umbrella of technologies. It describes algorithms (such as ChatGPT) that can be used to create new content, including audio, code, images, text, simulations, and videos. It is specifically designed and trained to generate new content. The versatility and potential of GenAI to transform various aspects of business operations make it an attractive investment for companies across industries. GenAI uses neural networks, machine learning, deep learning models, complex algorithms, and large and varied training datasets to produce original content based on user input and how to reason in ways akin to a human brain. The technology is built on AI tools shown in Figure 4 [7]. It uses neural networks to identify the patterns and structures within existing data to generate new and original content.

Generative AI can be thought of as a machine-learning model that is trained to create new data, rather than making a prediction about a specific dataset. Since its inception, the field of machine learning used both discriminative models and generative models, to model and predict data. A

generative AI system is constructed by applying unsupervised machine learning or self-supervised machine learning to a data set. The most common way to train a generative AI model is to use supervised learning. Generative AI can also be trained on the motions of a robotic system to generate new trajectories for motion planning or navigation. Generative AI models are used to power chatbot products such as ChatGPT [8].

Generative AI is transforming nearly all aspects of the pharmaceutical industry, revamping the way companies operate and potentially unlocking billions of dollars in value. The pharmaceutical-operations value chain encompasses sourcing, manufacturing, quality, and the supply chain—and gen AI is expected to improve them all

AI IN POWER SYSTEMS

Power systems are utilized to transmit and distribute electricity to all machines. A typical power system is shown in Figure 5 [9]. The current trend observed in many power systems around the world is a transformation of the functioning of electricity wholesale and retail markets. Power systems are progressively incorporating AI to improve sustainability, dependability, and efficiency.

The incorporation of AI into power systems marks a paradigm shift, allowing utilities to switch from reactive to proactive and intelligent management tactics. AI technologies used in the power industry include [10]:

- *Machine Learning:* Used for predictive maintenance, load forecasting, and anomaly detection.
- *Deep Learning:* Can be applied for complex data analysis, such as identifying patterns in sensor data from power plants.
- *Natural Language Processing* (NLP): Can be used to analyze text data from reports and customer feedback to identify potential issues.

Conventional artificial intelligence is a familiar tool used in grid planning, line routing, and transformer placement. In the power industry, AI is primarily used to optimize energy distribution, improve grid reliability, predict potential issues with power infrastructure, and reduce energy waste. The integration of AI in power system is represented in Figure 6 [11]. AI allows for better decision-making and proactive maintenance across power generation, transmission, and distribution networks. It essentially makes the grid "smarter" and more efficient. It is now frequently suggested that generative artificial intelligence could place within the power sector's grasp the dream of fully automated electricity supply chains.

In power generation, applications generally seek to optimize power plant operations and maintenance (O&M) or detect anomalies, exploiting advances in deep learning. Artificial intelligence (AI) is emerging as a transformative technology within generation. A typical example of power generation is shown in Figure 7 [12]. AI applications in power transmission networks currently revolve heavily around transmission system expansion planning. Power distribution networks are exploiting learning and planning, using various types of optimization algorithms for line routing and substation placement.

APPLICATIONS OF AI IN POWER SYSTEMS

As shown in Figure 8, artificial intelligence is making an impact into power systems for predictive maintenance, fault detection, smart grid management, and grid optimization [13]. The following examples illustrate the range of potential applications [13]:

- *Predictive Maintenance*: A proactive method called predictive maintenance uses AI to foresee equipment breakdowns before they happen. AI is used to anticipate when power system components like transformers, generators, and turbines need maintenance. AI algorithms can analyze data from power plants and equipment to identify potential failures before they occur, allowing for preventative maintenance and minimizing downtime. To forecast when maintenance is necessary, machine learning algorithms examine past data, sensor readings, and performance patterns. With this strategy, downtime is kept to a minimum, expenses are cut, and equipment lifespan is increased. In power systems, AI is in use to control voltage and reactive power.
- *Fault Detection:* Traditional fault detection encounters issues like limited real-time monitoring, slow response times, and the difficulty of spotting minute irregularities. Reactive techniques could result in more maintenance requirements and downtime. By examining real-time data, AI excels at finding faults early on. Power system component problems and anomalies are found using artificial intelligence. Real-time data is analyzed by advanced algorithms to spot errors or possible problems. This enhances system reliability by enabling proactive action before a significant issue happens.
- *Grid Optimization:* AI algorithms can analyze grid data to identify bottlenecks and

inefficiencies, allowing for optimized power flow and reduced transmission losses. They enhance the reliability and efficiency of power grid operations. They evaluate information from a variety of sources, such as demand trends, generation capacity, and weather forecasts. The distribution of power is optimized using this information, resulting in a grid that is reliable and effective. As a result, adjustment of electricity distribution is possible in real time, resulting in a grid that is reliable and effective.

- *Load Forecasting:* To estimate loads accurately and support resource allocation, AI is used. AI helps in precise load forecasting. To forecast future power consumption, machine learning models use previous data and outside variables. To estimate future power demand, machine learning models use historical data, weather patterns, and other factors. This aids utilities in planning for adequate generation capacity and optimizes resource allocation.
- *Integration of Renewable Energy*: Despite regulatory efforts aimed at incentivizing clean energy investments, the diffusion and expansion of renewable energy remains a challenge. AI can help with planning, permitting, and operation of renewable power projects. It can optimize the integration of variable renewable energy sources like solar and wind power into the grid by forecasting production and adjusting power flows accordingly. It can help improve power management, efficiency, and transparency, and increase the use of renewable energy sources. It predicts the generating patterns of renewable energy sources, making it easier to integrate them. Based on the weather and other variables, AI algorithms forecast the production of renewable energy. Utilizing this data, one may control the unpredictability of renewable energy sources and guarantee a steady and dependable supply of electricity. Figure 9 shows a wind power generation [14].
- *Cybersecurity:* Cyber threats to power systems are constantly changing. Grids are vulnerable to cyberattacks because of the way their interconnection exists. To safeguard power systems from online attacks, AI is used in cybersecurity. Network traffic is analyzed by AI algorithms, which may spot odd patterns that could be signs of a cyberattack. Power systems are better protected against cyber threats due to AI-driven cybersecurity solutions. Cybersecurity protects important utility data. Conversely, AI can be used to augment cybersecurity by helping to monitor network connections and traffic more effectively.
- *Smart Grid Management:* Smart grids are electrical grids that allow two-way communication between utilities and consumers. For grid stability, AI is essential. AI is in use for managing and controlling the smart grid. AI algorithms provide the real-time monitoring and management of smart grid components. This entails controlling distributed energy supplies, improving grid functionality, and adapting to sudden changes in demand. By avoiding overloads and improving overall grid stability, distribution of power is done effectively.

Figure 10 evaluates the performance of five AI-driven applications—Predictive Maintenance, Smart Grid Optimization, Demand Response System, Renewable Integration, and Fault Detection [15].

BENEFITS

The advantages of incorporating AI into power systems are many and quantifiable. They include decreased downtime, reduced maintenance costs, increased grid efficiency, and improved cybersecurity. The use of AI in power systems will significantly advance preventive maintenance, effective grid management, and improved cybersecurity. AI can improve the transmission and distribution of electric power. Other benefits include the following [10]:

- *Lack of Power Access:* Access to energy is critical both for survival and development. Sadly, even in today's age, power is not accessible to all. This is the reality for one billion people, mostly in Sub-Saharan Africa and South Asia. It is a fundamental impediment to progress, one that has an impact on health, education, food security, gender equality, livelihoods, and poverty reduction. Universal access to affordable, reliable, and sustainable modern energy is one of the Sustainable Development Goals (SDGs). Power-related obstacles that plague emerging markets include a lack of sufficient power generation, poor transmission and distribution infrastructure, affordability, and climate concerns. Renewables will play an important role in increasing access to electricity.
- *Automation:* Automating tasks enables plant operational and grid integration efficiency improvements. AI can help to achieve the required automation of decision making in such increasingly complex market environments. When designed carefully, AI systems can be particularly useful in the automation of routine

and structured tasks, leaving humans to grapple with the power challenges of tomorrow. For example, Azuri's HomeSmart solution is built on AI. It learns home energy needs and adjusts power output accordingly—by automatically dimming lights, battery charging, and slowing fans, for example—to match the customer's typical daily requirements.

- *Price Forecasting:* A popular application for AI in market operations and trading is price forecasting, e.g., electricity wholesale market prices. In particular, AI technologies utilizing probabilistic time series forecasting have grown rapidly, as they are highly relevant for many applications in energy trading risk management and electricity price forecasting.
- *Equipment Reliability*: AI improves equipment reliability by identifying when maintenance is necessary. The availability and reliability of the equipment increase multifold by limiting downtime and increasing the life of important assets.
- *Improved Grid Efficiency*: AI-driven insights improve grid efficiency by minimizing losses and maximizing resource use. It adjusts to shifting circumstances to make sure the grid runs as efficiently as possible. AI can be applied in buildings and industrial processes to optimize energy consumption.
- *Demand Management:* By analyzing real-time energy consumption patterns, AI can optimize energy usage during peak demand periods, allowing utilities to better manage load fluctuations.
- *Increased Sustainability:* AI can facilitate the integration of renewable energy sources into the grid, contributing to a cleaner energy mix. AI technologies are closely tied to the ability to provide clean and cheap energy that is essential to development. AI technologies can help power system operators mitigate negative environmental impacts through more effective planning and operations.
- *Research and Development:* AI is accelerating research in energy-related fields, including materials science and energy storage technologies. AI-driven simulations and data analysis are helping scientists discover more efficient and sustainable energy solutions.
- *Energy Storage:* AI can improve energy storage. AI can help integrate energy storage into power grids, predicting when renewable power will be curtailed and supporting energy storage scheduling more broadly.
- *Waste:* AI is significantly powering the waste-to-energy revolution by enabling smart waste sorting systems that can accurately categorize waste into recyclable, organic, or landfill materials using advanced machine learning and vision systems. AI is making waste sorting and energy generation from waste significantly more efficient and effective than traditional methods.

CHALLENGES

There are some challenges confronting the power industry. These include insufficient power generation, infrastructure deficiencies, affordability issues, environmental concerns, complexities of diversifying energy production, and adapting to changing demand patterns. The biggest challenge to generative AI enabling full automation is that power grids operate under strict physical constraints imposed by the need for reliability and the laws of physics. Generative AI is also "black box" technology whose inner workings are opaque and not easily understandable to those deciding on its deployment. Other challenges include [16,17]:

- *High Costs*: On the business side of AI, costs are also a growing concern. There are high costs of designing, testing, and deploying generative AI and ensuring that the skills for using it are available in a market where they are in short supply.
- *Data Quality:* There are data quality and data format issues to consider, especially given the degree of collaboration implicit in the notion of fully automated, integrated value chains. Then there are questions of data privacy and cyber security, which are increasingly regulated for.
- *Energy Consumption:* AI requires significant computing power. Training generative AI, in particular, is extremely energy intensive and consumes much more electricity than traditional data-center activities. AI systems vary widely in energy consumption depending on their complexity and usage, but they generally require significant amounts of electricity to process and analyze data efficiently.
- *Emissions:* Tech companies are reporting increased emissions due to running the data centers that power AI. Yet a clean, modern and decarbonized grid will be vital in the broader move to a net-zero emissions economy.
- *Power Demand:* Power demand has increased significantly in recent years. In many places, the

lack of power supplies is an important constraint on the growth of data centers to train and run AI models. AI can help accelerate the growth of renewables, improve transmission and distribution, deploy virtual power plants, revolutionize energy storage, and much more.

- *Breaches:* The use of AI in the power sector could result in privacy breaches. AI systems require large amounts of data to function well. Data collection on topics such as energy consumption patterns and customer payment histories may be important for some AI applications but creates a risk of unauthorized access, identity theft, and related problems. AI systems are susceptible to cyberattacks, including attacks where malicious actors manipulate the AI's input data to cause harmful outputs.
- *Catastrophic Failures:* These could result if an AI system recommends or makes an incorrect decision due to a flaw in its algorithm or an unforeseen situation. Such failures could include equipment damage, power outages or worse.
- *Regulation:* Electricity regulators should create clear regulatory frameworks to support using AI in energy management. The frameworks should address risks related to data privacy, safety and cybersecurity. Utilities and electricity regulators should launch programs for training workers in the power sector to assess and use AI-driven technologies. Utilities, regulatory agencies, and academic experts should work together to develop AI-driven models and solutions.
- *Trust:* Another challenge is trusting the data. Data is at the heart of all AI technologies. Without sufficient quantity, quality, and cleanliness of data, AI systems can potentially produce erroneous results. This concern is especially growing prevalent as generative AI gains traction in the power industry. To boost the consumer engagement, we urgently need to build relationships based on trust, ensuring the protection of privacy and data, as well as making sure that those who are vulnerable and less tech-savvy are not left behind.
- *Bias:* Another glaring issue concerns bias. The datasets that are used to train AI models may suffer from bias, which is then transferred into the AI model. This can cause existing biases in data to be perpetuated or reinforced in the AI models used. AI practitioners need to be aware of such potential biases and attempt to remove or eliminate their effects.

CONCLUSION

The adoption of AI in the power sector has experienced a remarkable surge. The integration of AI in the power sector has shown significant potential for enhancing operational efficiency, cost savings, reliability, and user satisfaction. The power sector has a promising future with the advent of solutions such as AI-managed smart grids. AI has the potential to transform many parts of the power system, if barriers can be overcome and risks can be addressed. While renewables are expected to cover over 80% of the electricity mix by 2050, coupling their deployment with AI applications can lead to an efficient integration of variable sources of energy. More information on artificial intelligence in the power industry is available from the books in [18-24] and the following related journals:

- *The AI Journal*
- *AI Magazine*
- *Energy and AI*
- *Journal of Intelligence*

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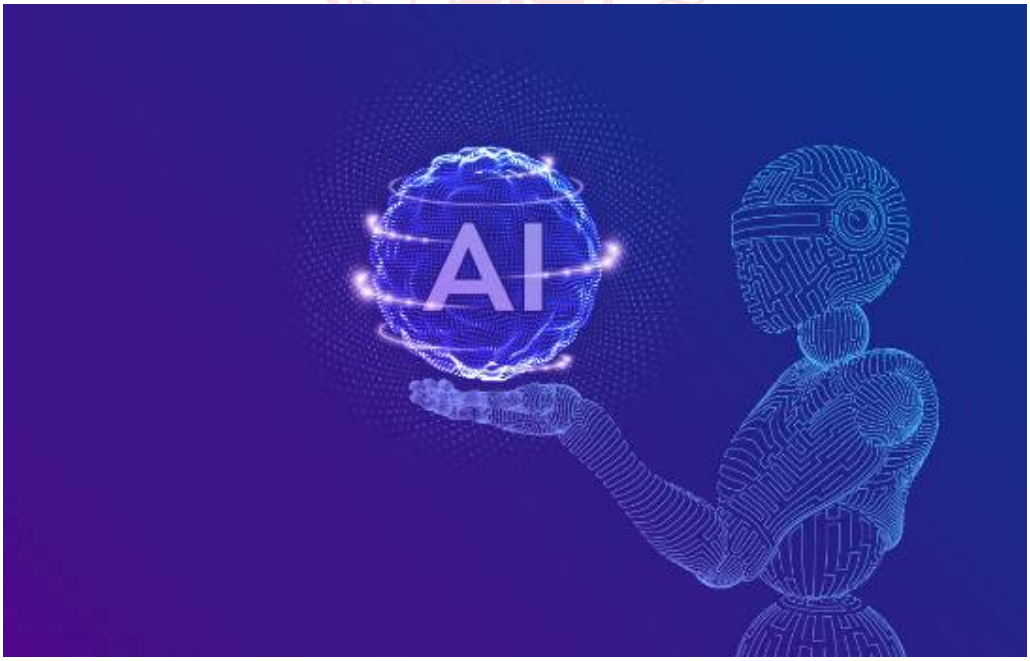

Figure 1 AI symbol [1].

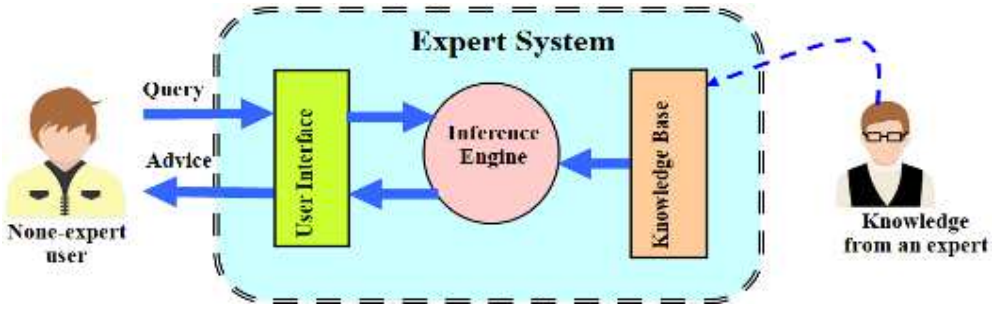

Figure 2 A typical expert system.

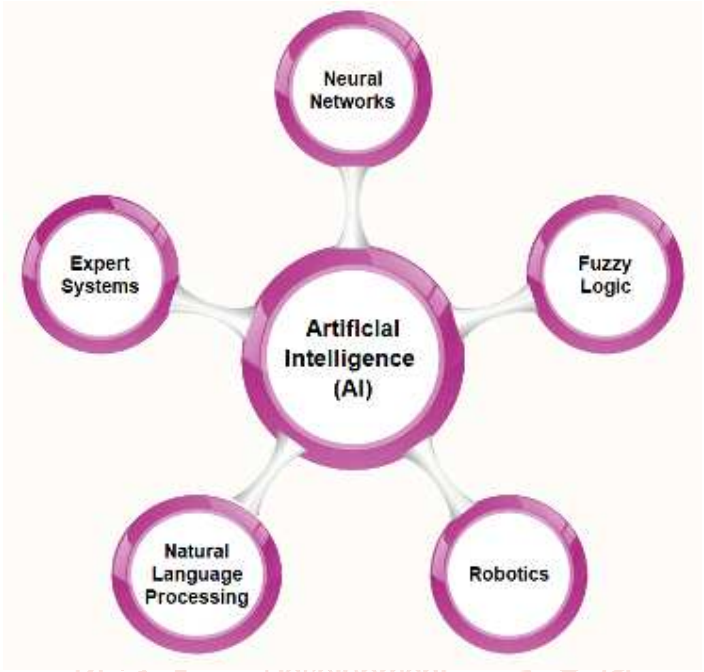

Figure 3 AI tools.

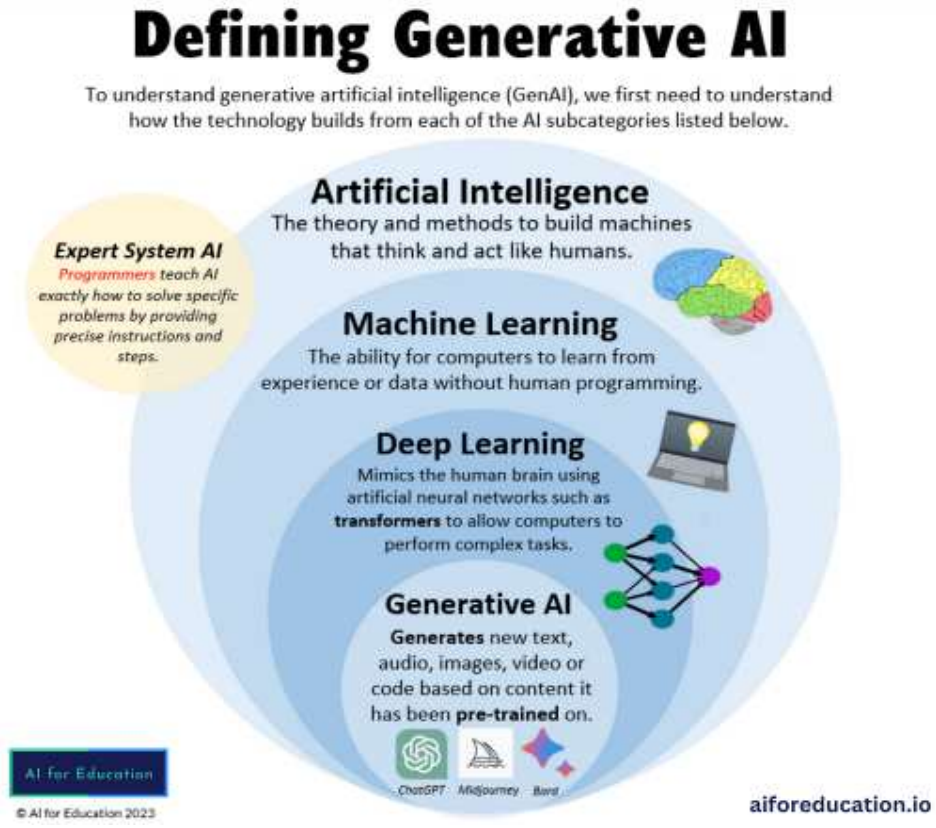

Figure 4 GenAI built on AI tools listed above [7].

Figure 5 A typical power system [9].

Figure 6 Representation of AI in power system [11].

Figure 7 A typical power generation [12].

Figure 8 Applications of AI in power systems [13].

Figure 9 Wind power generation [14].

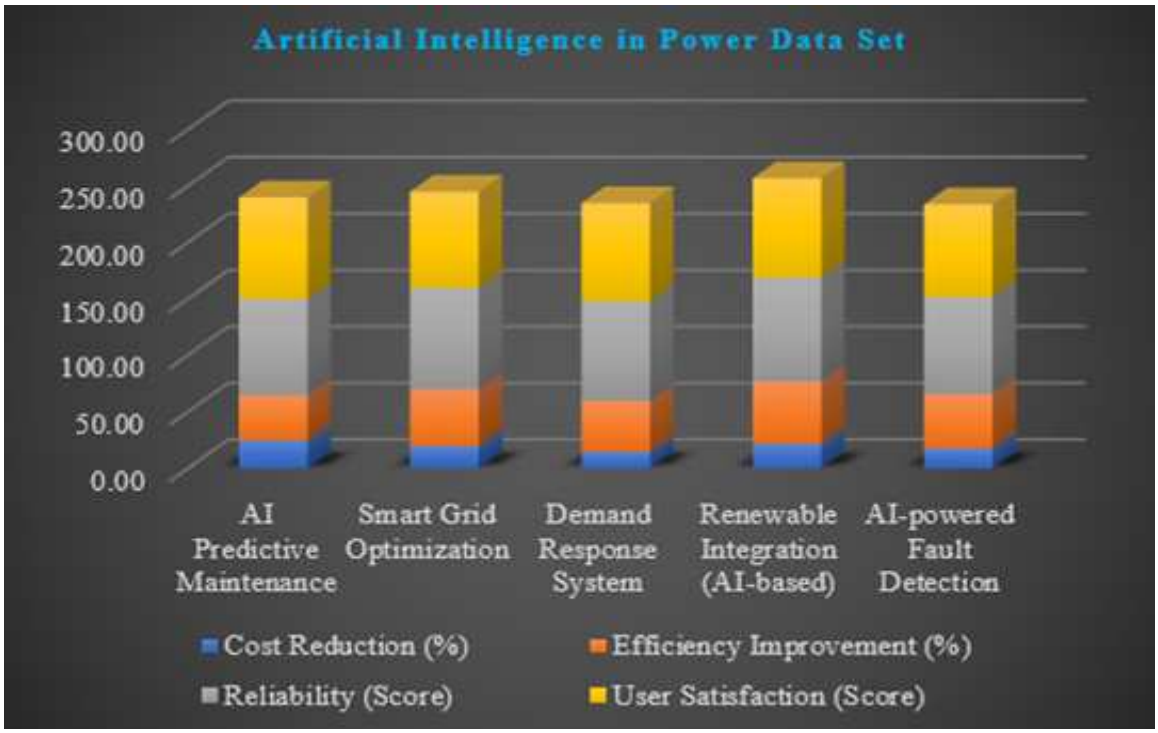

Figure 10 Performance evaluation of five AI-driven applications [15].