

The Role of Artificial Intelligence Techniques as a Modern Approach to Improving Energy Efficiency and Supporting the Energy Transition

Dr. Argillos Amal
Oran Graduate School of Economics
argiamal@gmail.com

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Abstract:

Artificial intelligence techniques have emerged as a technological tool that contributes to improving the management of energy systems and enhancing their efficiency. This study aims to analyze the role of AI techniques in improving energy efficiency and supporting the path of energy transition towards more sustainable energy systems. The study adopts an analytical approach by reviewing and analyzing the most important scientific literature related to AI applications in the energy sector. The findings of the study show that the use of AI techniques, such as big data analytics, effectively contributes to improving the management of electrical grids, forecasting energy demand, reducing energy waste, and enhancing the integration of renewable energies into energy systems. The study concludes that promoting the use of AI in energy management represents one of the promising pathways to support energy efficiency and accelerate the energy transition towards a low-carbon economy.

Keywords: Artificial Intelligence; Energy Resources; Energy Transition, Energy Efficiency ; Renewable Energies.

JEL Classification : Q40- Q 42 – C45

Introduction:

In recent decades, the world has witnessed profound transformations in patterns of energy production and consumption as a result of growing environmental challenges, foremost among them climate change, rising greenhouse gas emissions, and the continuous increase in energy demand.

In this context, improving energy efficiency has become one of the most important pillars for achieving sustainable development and ensuring the optimal use of energy resources. The concept of energy transition has also emerged as a strategic path aimed at shifting from traditional fossil-fuel-based energy systems to more sustainable systems based on renewable energies and clean technologies.

Against the rapid development of digital technologies, artificial intelligence has emerged as one of the most important technological tools capable of bringing about a qualitative shift in the energy sector. AI techniques, such as machine learning and big data analytics, provide advanced possibilities for improving the management of energy systems, forecasting energy demand, enhancing the efficiency of electricity grid operations, reducing energy waste, and improving the performance of industrial systems and smart buildings.

AI also facilitates the integration of renewable energies into electricity grids by improving production forecasting and managing the fluctuations associated with these sources.

From this standpoint, employing AI techniques in the energy sector is gaining increasing importance as an effective tool to enhance energy efficiency and support the energy transition towards a low-emission economy. This approach also opens new horizons for improving the energy performance of institutions and various economic sectors, and for fostering innovation in energy management systems.

In light of the above, the research problem can be formulated as follows:

To what extent can AI techniques contribute to improving energy efficiency and supporting the energy transition path?

To clarify the study further, the following sub-questions are posed:

1. What are the most important applications of AI in the field of energy management and consumption?
2. How does AI contribute to improving energy efficiency in different economic sectors?
3. What are the challenges facing the use of AI in the energy sector?

Hypotheses:

1. The use of AI techniques contributes to improving energy consumption efficiency by optimising the management of energy systems.
2. AI helps enhance the integration of renewable energies into electricity grids.
3. The use of intelligent systems leads to a reduction in energy losses and improves the energy performance of institutions.

Objectives of the study:

This study aims to analyse the role of AI techniques in improving energy efficiency and supporting the energy transition, by highlighting the most important applications of AI in the energy sector, demonstrating its contributions to enhancing the efficient use of energy resources, as well as discussing the main challenges and future prospects associated with the adoption of these techniques in modern energy systems.

Literature review:

In recent years, there has been growing interest in studying the relationship between technological development, especially AI techniques, and improving energy efficiency, in light of the challenges associated with increasing global energy demand and the need to reduce carbon emissions. Many recent studies have focused on analysing the role that AI techniques can play in improving the management of energy systems and enhancing their efficiency across various economic sectors.

In this context, the study by Chatterjee and Dethlefs (2022) indicates that the use of AI techniques in the renewable energy sector, particularly in the maintenance and operation of wind turbines, contributes to improving operational efficiency and reducing failures, thereby increasing energy production and lowering maintenance costs. The study also shows that machine learning algorithms enable the prediction of failures before they occur, which enhances the reliability of renewable energy systems.

On the other hand, a study by Ding et al. (2024) confirms that applying AI techniques in smart buildings can lead to significant improvements in energy consumption efficiency, through the use of intelligent control systems based on big data analytics and consumption pattern prediction. The study shows that these systems can notably reduce energy consumption and carbon emissions in commercial buildings.

Similarly, a study by Xie et al. (2025) examined the impact of developing AI techniques on energy efficiency at the economic level. The results showed that investment in AI contributes to improving energy efficiency by enhancing technological innovation, developing digital infrastructure, and improving the management of energy resources in industrial sectors.

In the same context, a study by Gunasinghalge et al. (2025), based on a systematic review of a large number of studies, indicates that the use of AI algorithms, especially reinforcement learning, can achieve significant energy savings in smart buildings, with savings ranging between 10% and 30% compared to traditional energy management systems.

Some studies have also focused on the role of AI in supporting the energy transition. For instance, a study by Yasmeeen and Tao (2026) points out that integrating AI techniques into energy systems can enhance the operational efficiency of electricity grids and facilitate the integration of renewable energies, in addition to improving energy security and supporting the achievement of sustainable development goals.

Overall, the above literature shows a consensus among most studies on the growing importance of AI in improving energy efficiency and enhancing the sustainability of energy systems. However, there are still some challenges related to data availability, digital infrastructure, and investment costs in these technologies, which calls for further studies exploring the potential of AI in supporting the transition towards more efficient and sustainable energy systems.

Structure of the study:

-Axis 1: Conceptual framework of artificial intelligence and energy efficiency

1. Concept of artificial intelligence
2. Concept of energy efficiency

3. Concept of energy transition

4. The relationship between AI and the energy transition

- Axis 2: Applications of AI in improving energy efficiency

1. Size of the AI market in the energy sector

2. Uses of AI in the energy sector

- Axis 3: The role of AI in supporting the energy transition

1. Management of smart electricity grids

2. Enhancing the efficiency of renewable energies

3. Rationalising consumption in smart cities

- Axis 4: Challenges and future prospects

1. Technical and economic challenges

2. Prospects for developing AI in the energy sector

3. International experiences in using AI for energy security

Axis 1: Conceptual framework of artificial intelligence and energy efficiency

1) Concept of artificial intelligence

Artificial intelligence is one of the computer sciences aimed at developing systems and programs capable of simulating human intelligence, i.e., having the ability to think in a way similar to humans.

AI consists of two words: the first is “intelligence”, meaning the ability to know, understand, and think; the second is “artificial”, derived from the verb “to imitate”, referring to something made in a non-natural way through human intervention. AI is distinguished from traditional software by its ability to learn and adapt by analysing data and using it in decision-making (Al-Wahab, 2024).

2) Concept of energy efficiency

Energy efficiency is defined as the optimal use of energy with the highest level of loss reduction, using only what is necessary to achieve a specific goal. It is not limited to a particular application but can be employed in all areas of energy use, whether electrical or thermal (Dardouri, 2022).

It can also be said that it means using less electricity or fuel to perform the same tasks. Simply put, it is “doing more with less energy”, which directly leads to lower consumption bills, reduced energy waste, and reduced carbon emissions harmful to the environment (Star, 2024).

3) Concept of energy transition

Energy transition is defined as the gradual abandonment of fossil fuel sources alongside the development of renewable energies, accompanied by measures to improve energy efficiency. The concept of energy transition, which emerged in the 1980s in Germany, is part of the concern for environmental and climate issues. It also has economic and social dimensions and moves towards a more sustainable energy system within the framework of sustainable development.

According to the International Energy Agency (ARENA), it is the transformation of the global energy sector based on fossil fuels into a zero-carbon energy sector by the second half of this century (Bilal, 2024).

4) The relationship between AI and the energy transition

AI represents a fundamental element in supporting the energy transition process, as it enhances the production efficiency of renewable energies (solar and wind) and intelligently manages energy consumption. At the same time, modern technologies themselves require massive energy consumption to operate data centres. To address climate challenges, AI contributes to:

1. Enhancing the efficiency of renewable energies

- **Weather and production forecasting:** AI algorithms analyse climate data to predict the amount of solar and wind energy expected to be generated, thereby preventing grid fluctuations.

- **Battery management:** Optimising charging and discharging cycles of energy storage systems, thereby doubling their lifespan and effectiveness in grid stabilisation.

2. Smart grids and consumption management

- **Real-time balancing:** AI can read consumption patterns and accurately distribute electrical loads, reducing waste and lowering electricity bills by rates between 10% and 20%.

- **Smart transport management:** AI-based transport systems help improve traffic flow and reduce congestion, lowering carbon emissions by up to about 60%.

3. Reducing industrial emissions

- AI is used to design factories and production processes to reduce the carbon footprint and reduce consumption in heavy industrial sectors.

4. Reciprocal environmental challenges

- This sector faces a double challenge: training large AI models requires massive energy and water resources.

- Experts are working to develop “green algorithms” that operate according to sustainability principles to ensure that the benefits of AI outweigh its environmental cost.

Axis 2: Applications of AI in improving energy efficiency

AI in the energy sector has become one of the most important factors that may reshape this vital sector by 2025, offering innovative solutions to improve processes and increase efficiency.

AI is no longer just a complementary technology; it has become an essential element in improving production efficiency, reducing costs, and achieving sustainability goals that are increasingly important in light of current environmental and economic challenges.

With the advancement of AI techniques in the energy sector, future opportunities look promising; AI has begun to revolutionise software, hardware, and system integration, covering all sectors from downstream to upstream in the oil and gas industry, as well as many other sectors, according to a report reviewed by the Energy Research Unit (Washington, D.C.).

This rapid growth is due to the increasing spread of AI techniques that contribute to improving operational processes, enhancing safety standards, and decision-making processes, thereby increasing performance effectiveness.

1) Size of the AI market in the energy sector

The value of the AI market in the energy sector is expected to rise from \$8.91 billion in 2024 to \$58.66 billion by 2030, at a compound annual growth rate of 36.9%.

North America leads the adoption of AI technologies in the energy sector, representing more than 38% of the global AI market in this sector.

This is due to the race among major energy companies and technology leaders, especially in Canada and the United States, to develop AI solutions.

Non-traditional methods of oil and gas production have also been one of the main drivers for adopting AI techniques to improve performance.

In 2023, the North American oil and gas market was estimated at about \$2.8 billion, and is expected to rise to \$5.96 billion by 2028, according to the Energy Research Unit.

2) Uses of AI in the energy sector

The role of AI in the energy sector is expected to expand significantly by 2025; its integration into various fields such as oil, gas, and renewable energies will bring about a fundamental transformation in the way resources are produced, consumed, and managed (Majdi, 2025).

According to the Energy Research Unit, these are the top 6 applications:

1. Enhanced Oil Recovery (EOR)

EOR is a set of techniques used to increase the amount of recoverable crude oil from oil fields.

Thanks to machine learning techniques, algorithms, digital twins, and AI integration, companies can optimise the extraction process with precision and enhance productivity. AI helps in:

- Identifying reservoir characteristics: providing detailed information about porosity, geological properties, rock permeability, and fluid properties, enabling accurate reservoir simulation and performance prediction.
- Intelligent reservoir monitoring and management: both contribute to improving productivity.
- Selecting appropriate EOR techniques based on reservoir conditions: helps improve recovery rates.
- Optimising processes to reduce costs: AI techniques enable optimisation of EOR processes to maximise oil extraction while reducing operating costs.

2. Predictive maintenance

Unexpected maintenance problems are common in the oil and gas industry. Machine learning algorithms are currently used to analyse data collected from sensors and examine historical records.

AI also provides insights that enable prediction of equipment failures before they occur, and can be applied in the field to monitor equipment performance and detect problems early, thereby reducing downtime and maintenance costs, according to the Energy Research Unit.

3. Improving drilling operations

AI stands out as a powerful solution for improving drilling and exploration operations through real-time data analysis and precise control of drilling systems. This helps in:

- Reducing time spent on unnecessary or inefficient activities, thereby enhancing productivity.
- Improving safety standards and preventing accidents or failures.
- Improving drilling efficiency.
- Training systems to detect anomalies and take immediate corrective actions.
- Analysing historical data to make decisions related to the selection of drilling rigs.

4. Environmental, social, and governance (ESG) goals

With increasing global awareness of environmental concerns, oil and gas companies are under growing pressure to align their operations with ESG principles. Integrating AI into the energy sector contributes to:

- The Internet of Things (IoT) is a valuable tool for companies to achieve ESG goals.
- Machine learning algorithms process data from sensors and geological surveys to monitor emissions and detect leaks.
- AI can optimise energy consumption in oil and gas operations to reduce the carbon footprint.
- AI also helps forecast energy demand and identify opportunities to integrate renewable energy into operations.

5. Digital twins

A digital twin is a virtual digital replica of a physical asset, system, or process.

In the context of the oil and gas industry, companies rely on digital twins alongside real-time data collection to monitor and simulate assets. They can improve performance through predictive maintenance and process management.

British BP relies on digital twins to monitor offshore platforms in real time and improve their performance. Chevron also uses them to optimise refining processes and improve efficiency.

6. Logistics

The integration of AI into logistics has been a game changer, especially in the energy sector. It helps in:

- Forecasting demand fluctuations, enabling companies to adjust operations.
- Managing inventory levels, reducing the risk of overstocking or stockouts.
- Analysing market trends and external factors to forecast future demand, ensuring procurement and logistics accuracy.
- Automating procurement processes by analysing supplier performance, market conditions, and historical data.

Axis 3: The role of AI in supporting the energy transition

1. Management of smart electricity grids

- **Balancing supply and demand:** Integrating renewable energy sources (e.g., solar and wind) depends on weather forecasting and production quantities. AI algorithms match production with actual demand with high precision.

- **Real-time response:** Modern technologies enable prediction of grid failures and automatic load redirection to prevent outages, thereby increasing grid flexibility and reliability.

2. Enhancing the efficiency of renewable energies

- **Predictive maintenance:** Wind turbines and solar panels use monitoring systems based on machine learning to detect potential failures before they occur, reducing maintenance costs and increasing asset lifespan.

- **Eco-design:** AI is used to optimise the design of energy facilities to reduce the carbon footprint and increase sustainability rates.

3. Rationalising consumption in smart cities

- **Green buildings:** Sensors and intelligent control systems analyse energy use patterns in buildings (lighting, heating, cooling), leading to significant consumption reductions.

- **Transport management:** AI helps improve the efficiency of public transport and electric vehicle charging networks to reduce emissions.

Axis 4: Challenges and future prospects

1) Technical and economic challenges

Although integrating AI into the energy sector holds promising potential, many obstacles must be addressed. Among these are:

1. Current datasets used to train AI models are often incomplete and limited, restricting the scope of discoveries. Collaboration between global laboratories through platforms such as “Mission Innovation M4E” can play a pivotal role in bridging this gap by organising data and creating common protocols.
2. The need to enable AI to optimise outcomes for a wide range of characteristics and to consider the requirements for integrating materials into practical products. Currently, human intervention is still needed to validate AI results, such as verifying performance across different environments or interactions with hardware systems.
3. Translating AI designs into manufacturable materials imposes additional complexities and efforts. Although AI can manage these challenges, it requires significant computational resources and costs that need careful consideration.
4. AI can accelerate the discovery of new materials, but subsequent stages – prototyping, marketing, and scaling up for production – take a long time, sometimes decades. Fortunately, AI tools are currently being developed that will accelerate these stages, such as digital twins – virtual digital replicas that reduce the costs and risks associated with scaling up energy technologies, especially in sectors like nuclear fusion and geothermal energy.

To enhance the impact of AI, the International Energy Agency has pointed out the need for governments to prioritise building unified data platforms and global collaboration between laboratories, along with investment in skills and equipment.

In addition, policies must ensure that AI tools are available to innovators and help investors adapt to risks.

Integrating AI into the energy sector can accelerate progress, improve outcomes, and enhance economic competitiveness by analysing data for new products and increasing their value.

2) Prospects for developing AI in the energy sector

The role of AI in the energy sector, particularly in the oil and gas industry, is expected to grow. This is reflected in the following roles:

- **Sustainability:** AI is expected to play a vital role in reducing the environmental footprint of oil and gas operations by optimising resource consumption and reducing waste.
- **Safety:** AI can enhance safety standards through real-time monitoring and identifying potential hazards before they occur.
- **Operational efficiency:** AI helps streamline logistics and improve decision-making to ensure smooth operations.

- **Increased automation:** Companies will seek to automate as many processes as possible to achieve greater efficiency.

- **Evolution of predictive analytics:** AI will help accurately forecast needs, improving demand forecasting and inventory management.

- **Carbon capture and storage:** Investments and innovations in these technologies are increasing, demonstrating their enormous potential and role in combating climate change.

3) International experiences in employing artificial intelligence for energy security

In this section, we will shed light on the Swiss experience in exploiting artificial intelligence technology and its various applications in order to preserve energy security.

1. The Swiss experience in using artificial intelligence in the energy sector

The Swiss state aspires to rely entirely on renewable energies by 2050 by building more solar panels and wind turbines, as they play a decisive role in achieving this goal, while at the same time relying on artificial intelligence in this matter to achieve its long-term energy security.

Electricity consumption is a very ordinary and constantly recurring matter, but what is noteworthy about these simple behaviours is that we do not notice the source of the electricity used for these things, nor whether its quantity is sufficient to operate all devices.

The same issue arises with regard to institutions, companies and public facilities. In the past, economic researchers did not worry about the source of electricity supplies. However, with the Swiss state's attempt to increase its stock of renewable energies, the issue of providing a sufficient quantity of electricity to benefit from it when needed has become important.

The sun does not shine every day and continuously, nor does the wind blow constantly. On the other hand, the demand for electricity has increased more than ever before. When Switzerland completely abandons fossil fuels, cars will run on batteries, and heat pumps will replace oil- and gas-fired heating systems in buildings (Hashem, 2020). Switzerland has embarked on a very ambitious programme towards clean energy: by the end of 2022, it expected to utilise about 1,500 MW of photovoltaic solar energy.

The energy mix is also increasing; about 76% of the electricity that supplies sockets in Switzerland comes from renewable sources, especially hydroelectric power plants, while nuclear energy produces about 20% of electricity. Only a few major public utilities in Switzerland do not use power plants and nuclear plants; these institutions know exactly how much energy they must generate and at the right time (Kamal, 2025).

Nuclear energy is gradually being phased out and replaced by renewable sources. Thus, families use electricity generated by solar panels installed on rooftops, and wind power plants contribute to feeding the electricity grid throughout the country, which changes the way the grid works.

Examples of this include the construction of a large pumped-storage hydroelectric battery to stabilise energy supply, and the use of electric car batteries to supply homes with electricity.

But to apply these solutions, a set of measures must be taken, such as trying to understand the behaviour of people and citizens, because imbalances in supply and demand may arise.

What matters here is that public utilities do not know the extent of people's energy consumption – that is, they know the quantity consumed but do not know when people consume electricity, when it is high and when it is low. It is necessary to focus on analysing energy-related data and trying to understand people's behaviours through algorithms. The devices that collect data throughout Switzerland to solve this problem are called smart meters, replacing traditional ones. According to the Federal Office of Energy, 80% of homes will be equipped with smart electricity meters by 2027. These meters monitor the electricity use of these homes and continuously send the results to electricity suppliers every minute. In this way, utilities can identify peak hours – for example, the company can know when electrical appliances are turned on.

The goal of this project is to control people's behaviour and understand their electricity consumption in order to be able to solve and understand many problems.

As another step in this field, Switzerland has relied on so-called new-generation batteries. As sales of electric cars increase, putting more and more pressure on electricity supply, this step materialises in taking advantage of a dual benefit:

By charging car batteries to avoid a severe shortfall in electricity supplies. That is, when electricity demand is low, cars are charged at smart charging stations; when demand is high, the energy stored in the car batteries can be discharged and sold back to the electricity grid.

Among the practical applications of this project, we find the two companies Tiko and Centovalli, which collaborated on a pilot project at the University of Lucerne. The project will be tested on 24 vehicles from Mobility, a company that provides car-sharing services.

This whole process is accompanied by a set of measures, such as obtaining better data on how people use cars, knowing the times of sunshine and car-charging times, so that artificial intelligence can analyse the data. This type of pilot project is increasing over time, especially in European countries.

Nevertheless, it is still early and the road is long for vehicle-to-grid energy transfer technology before its accuracy is confirmed and before it moves from the testing stage to actual use, especially since there are not yet a large number of electric cars that we can charge. Nissan, Volkswagen and Fiat are among the very few brands that are adopting this type of vehicle. The aforementioned Mobility company owned no more than 150 electric cars in Switzerland in 2021, but it plans to equip its entire fleet – more than 3,000 vehicles – with this electric technology by 2030 (Arabiya, 2023), and only then does it plan to create smart charging stations like those built by the Swiss company Centovalli.

Also, what could hinder these projects is the question of how to use data and information securely, especially data that shows when people will use electricity and when they turn on their electrical appliances, without violating privacy protection laws.

In this regard, US-based start-ups believe they can help. VIA Science has developed a programme to be tested in the smart meter project at the University of Lucerne. Instead of extracting and viewing people's data, researchers in these projects can analyse the data directly on the meters. In addition, people can be encouraged to share their data voluntarily, because such data helps establish a stable energy system. Participants – researchers, professors, students and the general public – at the Hackdays conference created a project called "Read your own smart meter". This allows homeowners to view the data from their meters,

thus knowing how much electricity they consume, controlling their usage, and saving energy and money. Then they can share this data with specialised companies without revealing their identity, thus solving the problem of hiding personal data.

2. The experience of the United States of America in using artificial intelligence in the energy sector

The United States is one of the leading countries in integrating AI into the energy sector, especially in the field of smart grids and electricity demand forecasting systems. American energy companies rely on predictive analytics technologies to reduce power outages and improve the efficiency of energy distribution.

AI technologies are also used to protect energy facilities from cyber-attacks, as smart systems help detect suspicious activities and respond quickly to electronic threats. Reports from the International Energy Agency indicate that cyber-attacks on energy companies have multiplied in recent years due to digital expansion (IEA, 2025).

3. The Chinese experience in using artificial intelligence in the energy sector

China has adopted a broad digital transformation strategy in the energy sector, employing AI to manage huge electricity grids and improve the efficiency of conventional and renewable power plants.

China also uses AI technologies to forecast industrial energy consumption, improve the efficiency of smart cities, and monitor energy supply chains. This has helped raise energy efficiency and reduce electrical losses.

4. The German experience in using artificial intelligence in the energy sector

Germany is one of the most prominent European countries in the field of energy transition, having relied on AI as part of the “Energiewende” (energy transition) project aimed at integrating renewable energies into the electricity grid.

Smart systems are used for:

- Forecasting solar and wind energy production.
- Improving energy storage processes.
- Balancing supply and demand.
- Reducing carbon emissions.

AI has contributed to increasing the efficiency of electricity grids and reducing operating costs.

5. The Japanese experience in using artificial intelligence in the energy sector

After the Fukushima nuclear disaster in 2011, Japan moved towards developing a smart energy system based on digitalisation and artificial intelligence.

The most prominent applications include:

- Early warning systems for failures.
- Managing electricity consumption during crises.
- Using smart robots to monitor nuclear facilities.
- Developing low-energy smart buildings.

6. The UAE experience in using artificial intelligence in the energy sector

The United Arab Emirates is one of the most prominent Arab experiences in employing AI in the energy sector, having adopted a national AI strategy that includes developing smart electricity grids and enhancing energy efficiency.

The UAE also relies on smart meters and big data analytics to rationalise consumption, in addition to developing smart city projects and solar energy.

7. The Saudi experience in using artificial intelligence in the energy sector

Within the framework of Vision 2030, the Kingdom of Saudi Arabia has expanded the use of AI in the oil and energy sector, especially through Saudi Aramco.

Applications include:

- Predictive maintenance of oil facilities.
- Monitoring pipelines.
- Analysing geological data.
- Improving production and refining processes.

This has contributed to raising operational efficiency and reducing maintenance costs and failures.

Conclusion:

At the conclusion of this study, it is clear that artificial intelligence has become one of the most important modern tools capable of bringing about a qualitative transformation in the energy sector, by improving the efficiency of energy resource use, enhancing the flexibility of electricity grids, and supporting the integration of renewable energies into modern energy systems. Smart technologies have also contributed to developing methods for forecasting energy demand, reducing operational costs, and raising the level of energy security in light of increasing economic and environmental challenges.

International experiences have shown that relying on AI in the energy sector is no longer merely a technological choice, but has become a strategic necessity for achieving the transition towards more sustainable and efficient energy systems. Despite the great advantages of these technologies, their successful use remains linked to the availability of digital infrastructure, investment in scientific research, the

development of human skills, as well as the establishment of regulatory legislation that ensures the safe and effective use of AI.

Accordingly, achieving a successful and sustainable energy transition requires enhancing integration between technology and energy policies, encouraging digital innovation, and expanding international cooperation in the fields of AI and energy, so as to contribute to building a more sustainable and secure energy future for generations to come.

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