Artificial Intelligence and Energy Security
Intelligent Solutions for a Sustainable and Resilient Future
الذكاء الإصطناعي والامن الطاقوي-حلول ذكية من اجل مستقبل مستدام ومرن

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Abstract:The transition to renewable energy sources is crucial for addressing climate change and achieving sustainable development.

However, ensuring continuous and reliable energy supply remains a challenge due to dependency on traditional fuels and market fluctuations.

Artificial Intelligence (AI) presents innovative solutions by enhancing predictive analytics, optimizing energy storage, managing smart grids, and securing energy infrastructure. This paper explores how AI contributes to energy security by improving efficiency, reliability, and sustainability in the energy sector, highlighting real-world applications such as Germany's advancement in AI-powered smart grids.

Keywords: Artificial Intelligence, Energy Security, Smart Grids, Predictive Analytics, Energy Storage Optimization, Germany Smart Grid.

JEL Classification Codes :Q43, Q47, Q54, O33, C63

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1. Introduction

The world is witnessing a rapid shift toward renewable energy sources in its pursuit to address the challenges of climate change and achieve sustainable development goals. However, ensuring a stable energy supply remains a major concern for countries, especially given the heavy reliance on traditional energy sources and the volatility of global markets. Energy security here is defined as the assurance of a continuous flow of energy supplies from diverse and reliable sources.

Therefore, investing in renewable energy capabilities becomes the only path to achieving both energy security and sustainability.

In this context, artificial intelligence (AI) emerges as a powerful tool that can play a pivotal role in overcoming these challenges and enhancing energy security.

Through its diverse applications in areas such as predictive analytics, smart grid management, energy storage optimization, and cybersecurity for energy systems, AI offers innovative solutions to ensure sustainable and reliable energy supplies.

This research paper seeks to answer the following question: ***How does artificial intelligence contribute to achieving energy security across these various domains?*** It will also present real-world examples of AI applications in the energy sector, such as Germany's pioneering experience in developing smart grids using AI technologies.

2. Current Challenges in Energy Security

2.1. Energy Security definition

Energy security is determined by how diversified and politically secure a country's energy sources are. For our purpose, energy security is defined as security of supply. That is, ceteris paribus, high-energy security is observed if there is a diversified portfolio of suppliers.(MAZARAKI & MELNYK , 2024, p. 3)

Distinguish between energy independence and energy security, with the former only focused on reducing the share of imported energy in the national energy mix. Increasing energy independence through investments into domestic fossil fuel production, however, conflicts with the Paris Agreement and efforts to reach net zero emissions. This means that energy security and sustainable investment can be achieved jointly only through investments into renewable energy capacity.(Augustus J & Schwerhoff, 2024, p. 8)

The center of Asia-Pacific Energy Researchhas developed the 4A model of Energy Security, which is based on four principles:(MAZARAKI & MELNYK , 2024, p. 11)

-Availability (availability of energy resources);
- Accessibility (physical availability of energy for consumers);
- Affordability (financial availability of energy for consumers);
- Acceptability (acceptability of consumption conditions).

2.2. Energy Security obstacles

Despite the global shift towards renewable energy, several obstacles continue to hinder the achievement of full energy security:(11 صفحة ،،2016 أكتوبر 25-26 يومي ،بن جديد)

- The heavy reliance of oil-based economies on traditional energy sources leads in some cases to a reluctance to shift towards renewable energy, due to fears of negatively affecting the oil production system.
-The high capital requirement for renewable energy projects makes countries in need of foreign investment dependent on foreign capital grants that may not align with development priorities, especially since investment in this field requires a longer return period compared to investment in traditional energy sources.
-The large land areas required for wind and solar energy projects pose a challenge in countries with limited land suitable for such uses, especially in densely populated countries or those with high agricultural needs and urban expansion.
-Many countries, especially developing ones, lack advanced technology needed to invest in energy storage, particularly for renewable energy sources, which hinders optimal utilization.
-The renewable energy industries, and the shift towards them, are heavily dependent on electricity and certain rare elements such as lithium, cadmium, and others, which are mainly concentrated in specific regions around the world. Extracting these elements is often environmentally damaging due to the nature of the land and the extraction methods, especially in terms of pollution.

3. How Artificial Intelligence Helps Energy Security – An Overview

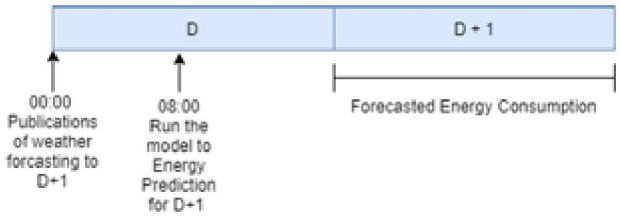
3.1. Predictive Analytics

The forecasting of demand plays an essential role in the electric power industry, the prediction of power consumption has been tackled from different perspectives using different forecasting methodologies.

Traditional machine learning models are data-driven techniques used to model complex relationships between inputs and outputs... modern deep learning techniques... integrate feature learning and model. (Alejandro J & Fernando Dorado, 2022, pp. 01-03)

Thanks to their good generalization ability, ANNs have received considerable attention in smart grid forecasting and management.

Figure 1. Real setting of the energy demand-forecasting problem.



Source: **Energy Demand Forecasting Using Deep Learning Models" – IEEE Access, 2022. Scopus: doi:10.1016/j.apenergy.2023.121907, p :06**

This **Figure** presents a **daily timeline** illustrating how **weather forecasts** are used in **predicting energy consumption** for the following day (D+1) using a predictive model.

Step 1: Publication of Weather Forecast – 00:00 (Midnight)
-At the start of the current day (**D**), **weather forecasts for the next day (D+1)** are published by meteorological services (such as ARPEGE).
-The data includes: temperature, humidity, pressure, etc.

-Temperature is considered the **most influential factor** in predicting energy demand due to its direct correlation with consumption (heating in winter and cooling in summer).

Step 2: Running the Forecasting Model – 08:00 AM
-At this point, the deep learning-based predictive model is executed using the weather data released at midnight.
-The model uses:Forecasted weather data for D+1.
-Additional contextual data such as: day of the week, hour of the day, holiday indicators.
-The goal is to accurately forecast energy demand for the entire next day (D+1).

Step 3 : Forecasted Energy Consumption Period
-This period spans the entire next day (**D+1**).

-After D+1 ends, the **forecasted values** are compared with the **actual recorded energy Relevance of the Diagram to Predictive Analytics:**
-This diagram demonstrates how **predictive analytics is applied in real-world operations**.
-It shows the **importance of timely and accurate input data**.
-It illustrates how predictive models rely on **forecasted inputs (like weather)** to generate **predicted outputs (like energy consumption)**.
-Timing is critical: any delay in obtaining weather data can delay the forecasting process and reduce the effectiveness of decision-making based on the predictions.
-Consumption, allowing researchers to **evaluate the model's performance**.

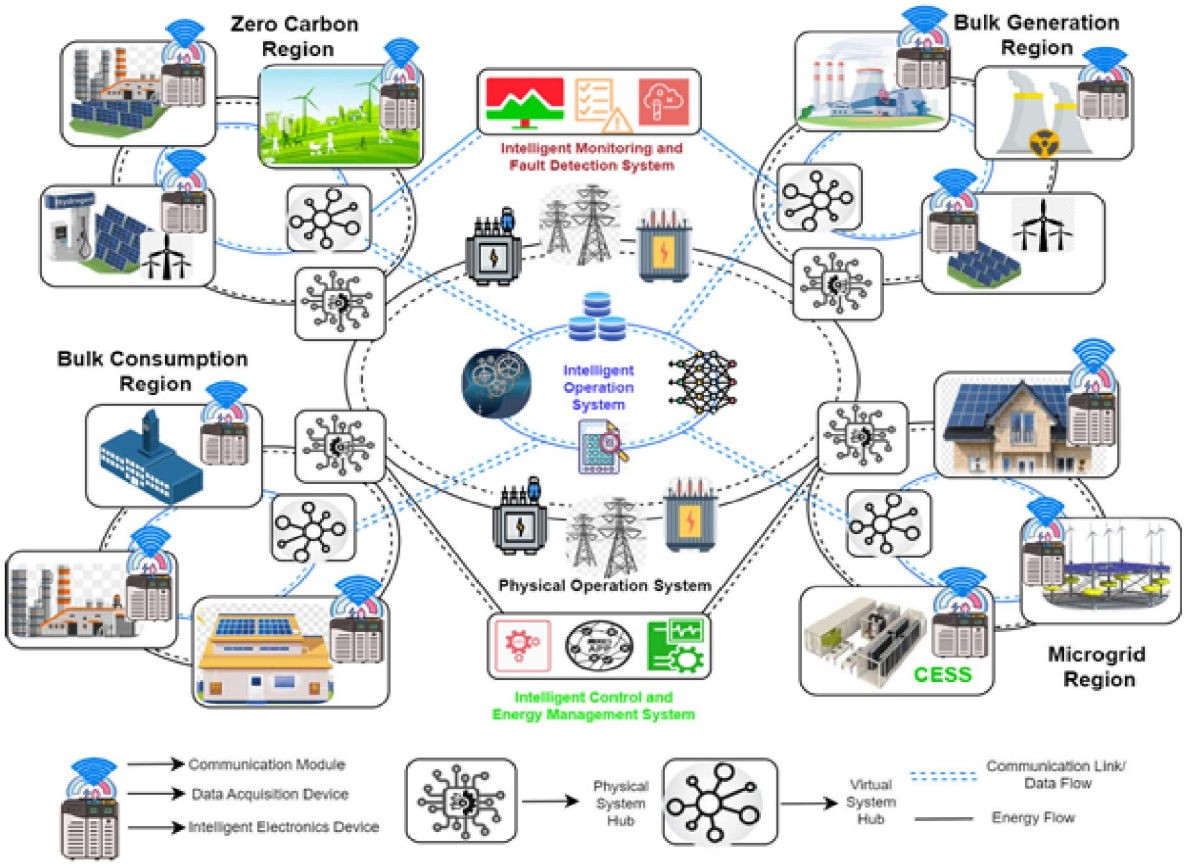
3.2. Smart Grid Management

Smart Grid (***SG***) is a sophisticated electricity distribution system that improves efficiency, sustainability, and reliability through real-time data exchange, Renewable Energy Sources integration. (Alama, Hossaina, & Md Ahasan, p. 05)

Smart Grid Advantages

Key advantagesOF AI-based Intelligent Grid Systems ARE:(Alama, Hossaina, & Md Ahasan, p. 07)
- Improved security and reliability by enabling automated fault detection and restoration, reducing outage duration, and allowing predictive maintenance.
- Reduced costs through optimizing grid operations, load management, minimizing losses, and improving energy distribution.
- Improved sustainability by providing real-time insights for decision-making and optimizing grid operations.
- Wide range of scalability for RES integration.

Figure 2. Framework of AI-based intelligent grid system.



Source: **Md Morshed Alama,M.J. Hossaina, ,Md Ahasan Habiba,M.Y. Arafata,M.A. Hannanb, "Artificial intelligence integrated grid systems: Technologies, potential frameworks, challenges, and research directions", RenewableandSustainableEnergyReviews, https://doi.org/10.1016/j.rser.2024.115251, p:04.**

Figure 2. Appears to present an integrated framework for an AI-based intelligent grid system, focusing on intelligent monitoring and fault detection, all the way to energy management and the realization of zero-carbon regions.

Key Elements in the Framework:

1. Regions: The framework illustrates several interconnected regions, each with its own characteristics and role within the grid:

- **Zero Carbon Region:** This region focuses on renewable energy sources such as wind and solar power. We see wind turbines and solar panels connected to energy storage units and residential and industrial buildings. The apparent goal is to achieve self-sufficiency in clean energy within this region.
- **Bulk Generation Region:** This region includes traditional power generation plants (such as nuclear or fossil fuel-based plants) in addition to large-scale renewable sources like wind farms and solar panel arrays. This region is responsible for supplying a significant portion of the energy to the grid.
- **Bulk Consumption Region:** This region represents the major energy consumers, such as factories and large industrial facilities.
- **Microgrid Region:** This region displays a smaller, local power grid that may include residential buildings equipped with solar panels and energy storage units (CESS - Community Energy Storage System).
- This micro grid can operate independently or connected to the main grid.

2. Intelligent Monitoring and Fault Detection System: Located in the upper central part of the diagram, this system appears to monitor the performance of the grid in different regions. The diagram indicates that it receives data from various elements (such as transformers and transmission lines) and uses it to detect any potential faults or issues.

3. Intelligent Operation System: Situated at the heart of the framework, this seems to be the brain of the grid. This system likely uses artificial intelligence to analyze the data received from the monitoring system, make decisions to optimize grid performance, distribute energy efficiently, and respond to various events.

4. Physical Operation System: This system represents the physical infrastructure of the grid, including transformers, high-voltage transmission lines, and other equipment necessary for energy distribution.

5. Intelligent Control and Energy Management System: Located within the Physical Operation System, this system appears to be responsible for the actual control of energy flow and the efficient management of its use.

Communication and Data Transmission Components:
- Communication Module: Represented by a small device with an antenna, it seems responsible for sending and receiving data between different elements in the grid.
- Data Acquisition Device: Collects data from various equipment (such as solar panels, wind turbines, transformers).
- Intelligent Electronics Device: Appears to be a local processing and control device that interacts with communication modules and data acquisition devices.
- Physical System Hub and Virtual System Hub: Represent data and information aggregation and distribution points at the physical and digital levels of the grid.
- Communication Link/Data Flow: Represented by a dashed line, indicating the exchange of information between different components.
- Energy Flow: Represented by a solid line with an arrowhead, illustrating the direction of electrical energy flow.

3.3. Energy Storage Optimization

Optimization techniques can be classified into mathematical optimization (alternatively, mathematical programming) and AI-based optimization approaches (mainly computational intelligence-based optimization and RL-based methods).

Mathematical optimization methods focus on the selection of the best solution based on some criteria from a set of available alternatives so that they work well for smooth unimodal problems, such as linear programming (LP), MIP, non-linear programming (NLP), DP, stochastic programming (SP), etc.

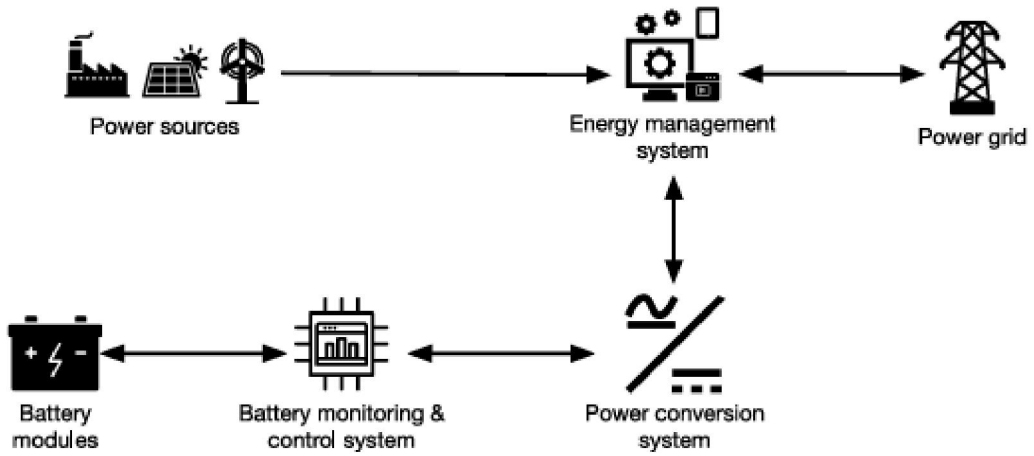
AI-based optimization methods mainly refer to EAs, such as genetic algorithm (GA), differential evolution (DE), particle swarm optimization (PSO), etc., which use heuristic search as the local search to find the global optimum and are more suitable for the complex optimization problems, e.g., non-convex, non-differentiable, or multi-modal problems.

It also includes RL-based models, particularly DRL-based models developed using NNs, wherein optimization techniques primarily rely on gradient descent (GD)-based methods, such as deep Q-networks (DQN).(Song &&all, p. 06)

Components of the Battery Energy Storage Systems (BESS)

It can be illustrated by the figure below

Figure 3.The major components of the BESS.



*Source:*Hui Song , Chen Liu , AliMoradi Amani , Mingchen Gu , Mahdi Jalili, Lasantha Meegaha pola , Xinghuo Yu , George Dickeson, **" Smart optimization in battery energy storage systems: An overview",Energy and AI,** https://doi.org/10.1016/j.egyai.2024.100378, p :04.

Figure 3. Illustrates a simplified system for managing and integrating energy, likely within a smart grid or a renewable energy setup.

It shows the flow of energy from sources to the power grid, and the role of battery storage in conjunction with an energy management system.

Components and Connections:

1. Power Sources:

This represents the various sources that generate electricity. It includes traditional sources like factories (which might have their own generators or represent industrial power usage), as well as renewable energy sources like solar panels and wind turbines. This indicates a mixed energy generation environment.

Connection: An arrow points from "Power sources" to "Energy management system," indicating that the electricity generated flows into the energy management system.

2. Energy Management System:

This is the central control hub of the system. It monitors, controls, and optimizes the flow of energy.

The gears suggest processing and automation, while the mobile phone could imply remote monitoring or control capabilities. This system likely makes decisions about how to distribute energy, when to use battery storage, and how to interact with the power grid.

Connections:

Receives input from "Power sources."

Sends output to "Power grid."

Has a two-way connection with the "Power conversion system," indicating it both sends commands and receives data.

3. Power Grid:

This represents the traditional electrical grid that distributes electricity to consumers. It's the destination for the energy after it's been managed by the system.

Connection: Receives output from the "Energy management system."

4. Battery Modules:
These are the batteries used for energy storage. They store electricity for later use, which is especially important for managing intermittent renewable energy sources like solar and wind.
Connection: Connects to the "Battery monitoring & control system."

5. Battery Monitoring & Control System:
This system manages the charging and discharging of the battery modules. It monitors parameters like voltage, current, temperature, and state of charge to ensure safe and efficient operation. The graph suggests data logging and analysis.
Connection:
Connects to "Battery modules" to control and monitor them.
Connects to the "Power conversion system" to regulate the flow of energy to and from the batteries.

6. Power Conversion System:
This system converts the form of electrical energy. It likely includes inverters (DC to AC conversion for batteries to grid), rectifiers (AC to DC for charging batteries), and possibly DC-DC converters to adjust voltage levels. The symbol suggests the conversion between different types of electrical power.
Connections:
Two-way connection with the "Energy management system" for control and data exchange.
Two-way connection with the "Battery monitoring & control system" to manage battery charging/discharging.

3.4. Cybersecurity in Energy Systems

Many traditional industry companies are embracing the digital transformation of Internet of Things (IoT).

Critical infrastructure (gas, oil, manufacturing, transportation, and electricity) networks need to be constantly operated and monitored to ensure sustainability and security in industrial control systems (ICSs)

A supervisory control and data acquisition (SCADA) system is designed and implemented to increase energy efficiency, reduce energy losses, and monitor and analyze operational features within the specific industrial automation system.(Yalçın & Sibel Ünaldı, 2024, p. 01)

SCADA systems automate the gathering of real-time data, the management of industrial processes, and the observation of distributed industrial machinery based on location. SCADA systems can communicate through wireless or cable.

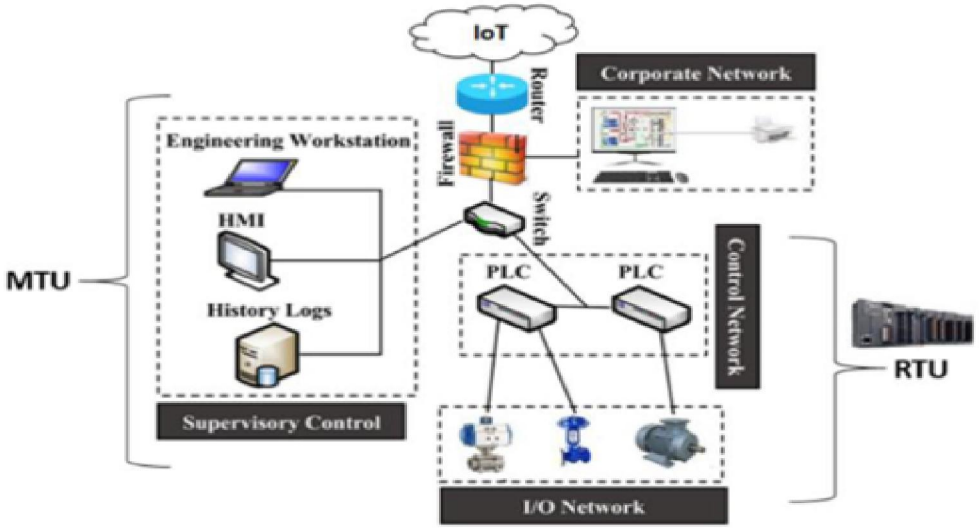
The ability to communicate is crucial for SCADA systems. SCADA has experienced a significant evolution from an isolated environment to an interconnected network.

Despite the advantages of this evolution, SCADA systems have become more vulnerable to cyber-attacks (data theft, data manipulation, and data transfer over idle network traffic to different locations).

Therefore, a cyber-attack on a SCADA system can be disastrous: it may disrupt power, gas, and water supplies, damage important military facilities, and affect significantly public health and safety.

As a result, analyzing cyber risks associated with the SCADA system is critically important.(Yalçın & Sibel Ünaldı, 2024, p. 02)

Figure 4. Schematic representation of an ICS/SCADA system.



Source: Nesibe Yalçın, SemihÇakır, Sibel Ünaldı, **"Attack Detection Using Artificial Intelligence Methods for SCADA Security",** IEEE INTERNET OF THINGS JOURNAL, VOL. 11, NO. 24, 15 DECEMBER 2024, p: 01.

Figure 4represents a typical architecture of an Industrial Control System (ICS), a type of system widely used in the energy sector to manage and operate critical infrastructure such as power generation plants, electricity distribution networks, and pipelines. Let's break down the diagram into its main components:

- Master Terminal Unit (MTU): Represents the left side of the diagram and is the central hub for monitoring and controlling industrial processes.
Components:
Engineering Workstation: A computer used by engineers to configure and program the control system.
Human Machine Interface (HMI): A screen that displays industrial process data and allows operators to interact with the system.
History Logs: A database that stores historical data of industrial operations for analysis and reporting purposes.
Supervisory Control: A primary function in an ICS that allows operators to monitor and adjust set points and control operations.

-Programmable Logic Controller (PLC): Specialized industrial computers that control the actual equipment and processes on-site.
Function: Receives signals from sensors (e.g., pressure, temperature sensors) and issues commands to actuators, valves, and other equipment based on programmed logic.

- Remote Terminal Unit (RTU): A device that controls equipment remotely at distant locations.
Function: Collects data from the remote site and sends it to the MTU, and receives commands from the MTU to execute at the remote site.

- Communication Networks:
I/O Network: Connects the PLCs to sensors, actuators, and other equipment in the industrial process.
Router, Firewall, and Switch: Network devices used to route traffic, secure the network, and connect different devices.

-Internet of Things (IoT): Refers to internet-connected devices that collect and transmit data, it include smart sensors and other equipment that provide real-time data about operations.

4. Real-World Examples *"Germany's Smart Grids using AI"*

4.1. The German Electricity Market - A Brief Overview

The German electricity market is Europe's largest, with annual power generation of around 625 TWh and a capacity of around 200 GW.

Germany's domestic electricity market was fully liberalized in 1998 (Energy Industry Act), opening the market for new players and stimulating new business opportunities. Prior to liberalization, a defined supply area was typically served by a single supplier (e.g. local utility).

More than one thousand market participants are active in the fully liberalized German electricity market, with new market actors – who do not own power plants or supplier networks successfully entering the domestic electricity market.

The creation of ***the Bundesnetztagentur*** ("Federal Network Agency") regulatory office for electricity, gas, telecommunications, post, and railway markets in 1998 further opened up the power market.

A raft of measures promoting competition – including legal unbundling for suppliers with more than 100,000 customers – was introduced.

The agency is responsible for ensuring non-discriminatory third party access to power network.

The fluctuating supply of electricity from renewables requires upgrades to be made to the entire power grid.

An investment of over 35 billion euros is planned for the construction of high-voltage transmission lines - "electricity autobahns" - from the wind-rich north to major industrial regions.

Transmission system operators (TSOs) keep control power available to maintain stable and reliable supply.

Demand for control energy is created when the sum of power generated varies from the actual load (due to for example unforeseeable weather fluctuations).(Germany Trade & Invest)

4.2. Smart Grids and Energy Storage

Germany is at the forefront in international smart grid development. Intelligent networks or "smart grids" allow fluctuating renewable energy power generation and consumption to be optimally managed by allowing a shift from "consumption-oriented generation" to "generation-optimized consumption."

Information and communication-based technologies (ICT) will play a central role in connecting the different parts of the energy system. Intelligent ICT solutions will allow smart grids to efficiently manage power generation, consumption and storage in tandem with so-called "***smart meters***"

Germany Trade & Invest helps open up a vista of opportunities for companies looking to cooperate with German partners, become involved in demonstration projects, and expand through direct investment.(Germany Trade & Invest)

4.3.Research and Funding Programs

-Kopernikus: Germany's Largest Research Initiative for the Energy Transition

The four Kopernikus-Projects aim to develop technological and economic solutions for the transition of the German energy system, from basic research to real-life application.

As part of the energy research program "Research for an environmentally-friendly, reliable and affordable energy supply", the government plans to fund the projects with EUR 400 million between 2016 and 2025.

The research is conducted in four key areas of the energy transition:

1. ENSURE: The project aims to identify an efficient structure of the energy grid by integrating new technologies and combining centralized and decentralized energy supply to an integrated system.

2. P2X: Development of innovative solutions for "Power-to-X"-technolgies to efficiently store, distribute and convert renewable energies to gas, heat or chemicals.

3. SynErgie: Customization of traditional production processes in energy-intensive industries to synchronize the energy demand with the volatile supply by renewable energies.

4. ENavi: Development of a navigation instrument to assess the short- and long-term impact of economic and political measures on the energy system. (Germany Trade & Invest)

-The 6th Energy Research Program

Between 2006 and 2015, the German government has provided about EUR 6.4 billion in energy research funding to promote the research and development of modern energy technology. In this way, the energy research program is making an important contribution to ensuring that the restructuring of the power supply in Germany is carried out in a secure and economical manner.(Germany Trade & Invest)

5. Conclusion

Transforming geopolitical and technological world. As pressures persist due to resource scarcity, price volatility, and climate change, promising technological solutions such as artificial intelligence (AI) are emerging and revolutionizing the ways energy is produced, distributed, and predicted.

This study has shown that AI can play a pivotal role in enhancing energy security by improving operational efficiency, reducing costs and risks, and supporting the transition towards smarter and more sustainable energy sources. However, this shift also brings real challenges, including investment requirements, data protection concerns, and the need for capacity building.

Recommendations:

-Invest in digital infrastructure for the energy sector, including smart grids and big data analytics platforms.

-Train and upskill human resources in the energy sector to efficiently use AI technologies.

-Encourage scientific research and development in AI applications for energy, particularly in universities and research centers.

-Establish regulatory and legal frameworks to ensure ethical and secure use of AI, while protecting infrastructure-related data.

-Promote international cooperation and knowledge exchange on using AI in renewable energy and energy security.

-Support startups offering innovative AI-based energy management solutions.

-Develop national energy strategies that integrate AI as a key element in energy security and energy transition planning.

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