

Empowering “Energy” with “Numbers”: Mechanism, Challenges, and Path Selection of Digital and Intelligent Enablement Across the Energy Industry Chain

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ABSTRACT

Currently, the energy industry is at a critical stage of transformation and upgrading. Amid the shifts in global energy structures, mounting environmental pressures, and rapid technological changes, advancing the energy industry towards high-efficiency, clean, and low-carbon development has become a major technical challenge that must be addressed. The widespread application of digital and intelligent technologies provides new opportunities and driving forces for innovative development within the energy industry. However, substantial challenges and bottlenecks exist across technical, managerial, policy, and economic dimensions in the digital and intelligent empowerment of the entire energy industry chain. Strategies such as exploring automated production control, innovating in smart operations, enhancing the safety of new productive force empowered by digitalization and intelligentization, and strengthening the "green" edge of the entire industry chain should be actively promoted to advance the high-quality development of the energy industry chain.

KEYWORDS

Digitalization; Intelligentization; Energy industry chain; Path selection

1. INTRODUCTION

In March 2023, the *National Energy Administration* issued opinions on accelerating the digital and intelligent development of energy systems, stating [1]: “Achieving deep integration of digital technologies with the real economy and promoting the digital and intelligent transformation of traditional industries is a strategic measure to seize new opportunities brought by the new wave of technological and industrial revolution [2].” Enhancing digitalized demand response alone is projected to reduce the curtailment rate of photovoltaic and wind power in the EU from the current 7% to 1.6% by 2040, cutting carbon emissions by 30 million tons. Meanwhile, the global process of digitalizing power plants is also accelerating, with digital adoption expected to reach 19% by 2025, helping power generation companies reduce operating costs by 27% and global sector emissions by 4.7% [3]. In the context of this new era, energy, as the cornerstone of economic and social stability and development, has witnessed its deep integration with digital technologies, which has become key to elevating China’s energy systems to advanced stages and modernizing industrial chains. This integration is not only pivotal for implementing the “Four Revolutions and One Cooperation” strategy for energy security and building modernized energy systems, but also for enhancing competitiveness in the energy industry and advancing its high-quality development. This paper explores the mechanism, challenges, and path choices for enabling the high-quality development of China's energy industry chain through digital and intelligent technologies, aiming to provide policy suggestions.

2. THEORETICAL MECHANISM OF DIGITAL AND INTELLIGENT ENABLEMENT ACROSS THE ENERGY INDUSTRY CHAIN

The energy full industry chain covers the entire process from the extraction, processing, and trade of energy resources to their final purchase and utilization by consumers in the consumer market. It includes both the core basic industry chain and the auxiliary and related industry chain closely linked to it. The basic industry chain extracts and processes resources such as oil, natural gas, coal, and electricity, transforming them into tradeable and usable forms, which ultimately enter the terminal consumer market. The auxiliary related industry chain provides fundamental support for the basic industry chain and expands its breadth. Auxiliary industry chains include information consulting, manufacturing of production equipment, financial services, environmental protection, and other auxiliary industries that cooperate in a forward manner with the basic industry. Related industry chains include electric power, wind energy, water energy, solar energy, nuclear energy, and other related industries that cooperate in a backward manner with the basic industry. In the power industry, upstream includes various manufacturers and suppliers of power generation equipment. Figure 1 is a diagram of the entire energy industry chain, where the primary downstream industries of coal include electricity, building materials, chemicals, metallurgy, iron and steel, machinery, and chemical fibers. The direct downstream of the power industry is the grid companies, while the indirect downstream includes high energy-consuming industrial enterprises, such as electrolytic aluminum and steel companies. The downstream of the oil industry includes engineering construction, metallurgy, electricity, chemicals, shipping, metal processing manufacturing, logistics, and daily chemical products industries. With continuous technological advancements and the deepening of digital transformation, digitalization and intelligence are gradually changing the landscape of the entire energy industry chain. This is specifically manifested in the deep mining and processing of massive amounts of data using technologies such as the internet and big data analytics, providing accurate data support for energy decision-making. At the same time, it promotes the balanced development and efficient operation of the energy system through intelligent management and scheduling of various links in energy production, transmission, and consumption, thereby achieving overall optimization and collaborative development [4-5].

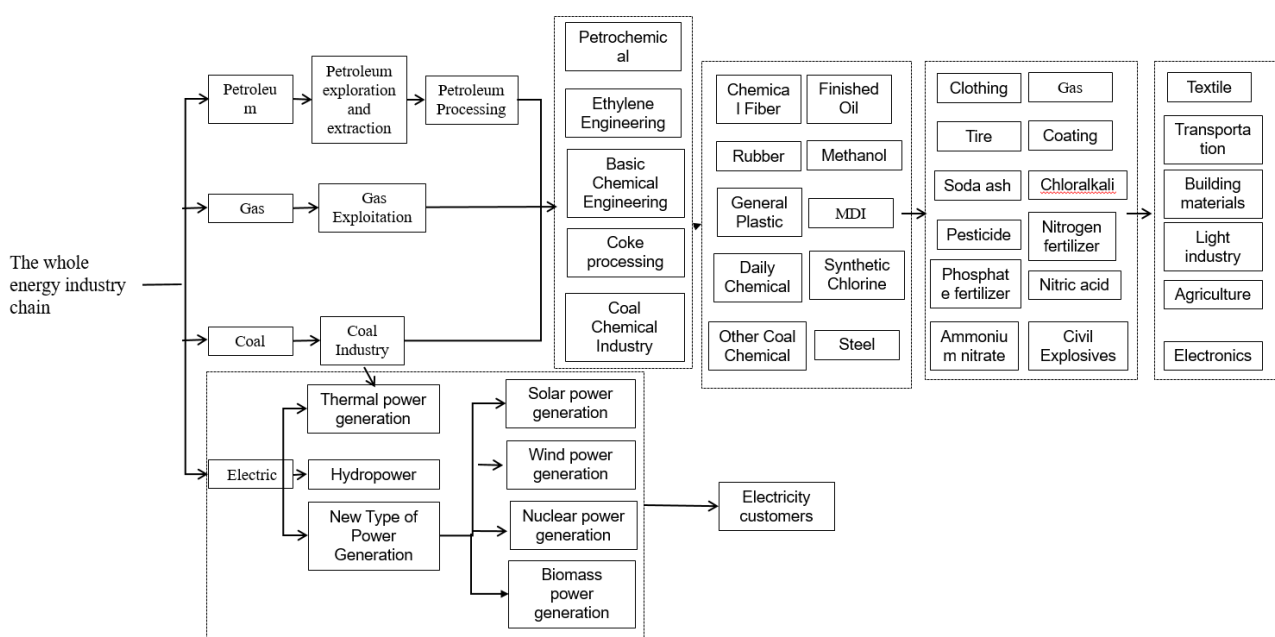


Figure 1. Energy Full Industry Chain Map

2.1. Structural Composition of the Energy Industry Chain

The digital and intelligent transformation of the entire energy industry chain is not only a technological upgrade and innovation, but also a profound change to the traditional energy industry model [6]. On one hand, the traditional energy industry model focuses on the extraction and utilization of resources while neglecting the importance of technological innovation. The digital and intelligent transformation signifies that the energy industry places greater emphasis on technological innovation and research and development, promoting the development of areas like 'new energy', 'new materials', and 'new technologies', injecting a continuous driving force for the sustainable development of the energy industry. On the other hand, the digital and intelligent transformation also reshapes the development philosophy of the entire energy industry chain. The traditional energy industry often emphasizes short-term economic benefits while neglecting environmental protection and social responsibility. The digital and intelligent transformation and upgrading will integrate environmental protection, social equity, and other factors into the development considerations. Through technological innovation, it will improve the energy-saving and carbon-reduction efficiency of the entire energy industry chain, optimize the structure of energy production, storage, and consumption, and promote the green, low-carbon, integrated, and sustainable development of the energy industry.

2.2. Digitalization and Intelligentization Reshaping the Development Paradigm of the Energy Industry Chain

Digitalization and intelligence are becoming new driving forces for the transformation and upgrading of the entire energy industry chain. Emerging hotspot technologies such as cloud computing, blockchain, and digital twins are bringing new development momentum for innovation and change in the energy sector, providing technological support for accelerating the digital transformation across the entire chain of energy production, transmission, storage, consumption, and energy markets. For example, in oilfield extraction and the power industry, the application of digital technologies enables companies to understand production status in real-time and make adjustments and optimizations based on data, thereby improving energy utilization efficiency. The "14th Five-Year" Energy Sector Technology Innovation Plan proposes to prioritize digital and intelligent technologies in energy systems as a key task, focusing on the integration of new generation information technology and energy development. It calls for research on common key technologies in the energy sector utilizing digitalization and intelligence. The National Energy Administration has issued several opinions on accelerating the development of energy digitalization and intelligence, which specifically emphasize hastening the integration of digital and intelligent technologies in areas such as electricity, coal, and oil and gas, to promote the construction of intelligent energy regulation systems, thereby enhancing the precise and efficient allocation of resources. The introduction of these policies provides strong support and guarantees for the digital and intelligent transformation of the energy industry. New generation information technologies represented by the Internet, big data, and artificial intelligence are accelerating the green, low-carbon, and intelligent transformation of industries such as electricity, coal, and petroleum and petrochemicals, bringing new engines and new momentum to technological innovation and high-quality development across the entire energy industry chain.

2.3. Data Elements Activate The Multiplier Effect of the Entire Energy Industry's Value Chain: The Far-Reaching Impact of Digital and Intelligent Transformation

On one hand, the open sharing of data elements promotes cost reduction and efficiency enhancement for energy companies, facilitating the integration of meteorological data by wind and solar energy companies, thereby optimizing site selection, layout, equipment operation and maintenance, and energy scheduling. This improves energy utilization efficiency, promotes the integration and innovation of manufacturing and energy data, and facilitates the connection of order, production scheduling, and electricity consumption data between energy companies and high-energy-consuming

enterprises. It enhances carbon emission management levels, supports the integration of carbon emission data related to materials, auxiliary materials, and energy across the entire production cycle of key products, as well as industry carbon footprint data, conducting calculations and evaluations of product carbon footprints, and guiding enterprises to save energy and reduce carbon emissions. On the other hand, the application of data elements also drives the intelligent and digital transformation of the energy industry. By introducing technologies such as intelligent control systems, the Internet of Things, and cloud computing, energy equipment can achieve remote monitoring, automatic adjustments, and optimized operations, improving the efficiency and safety of production and maintenance. Based on real-time data for forecasting and planning, it helps enterprises respond to market changes and risk challenges. By fully exploring and applying the value of data elements, it promotes the efficient operation of the energy industry chain and value enhancement, achieving sustainable development for the energy industry and creating effects that far exceed the initial changes across the entire industry chain.

3. CHALLENGES AND BOTTLENECKS IN DIGITAL AND INTELLIGENT ENABLEMENT FOR THE ENERGY INDUSTRY CHAIN

3.1. Technical Aspect: The Digital and Intelligent Transformation Empowering The Entire Energy Industry Chain Faces Challenges of "Development" and "Safety"

Currently, the technical challenges faced by the digital and intelligent empowerment of the entire energy industry chain mainly consist of two aspects. The first is development issues, including advanced technology research and innovation in data collection and integration, as well as efficient data processing. The entire energy industry chain involves many links and complex equipment, and the accuracy and completeness of data collection face challenges. At the same time, there may be differences in data formats, communication protocols, and so on across different links and equipment, leading to difficulties in data integration and sharing. How to quickly and accurately process and analyze this data to extract valuable information and support decision-making is a challenge. Additionally, due to potential discrepancies in technical standards and specifications across different fields and links of the energy industry chain, how to achieve interconnection and data sharing between different systems during the process of digitalization and intelligence, as well as establish unified technical standards and specifications, poses another challenge.

3.2. Management Level: Threefold Development Obstacles of Organizational Structure Adjustment, Process Optimization, and Collaborative Cooperation

Firstly, organizational structure adjustment is a key link in the process of digital and intelligent transformation. Traditional energy enterprises often have relatively fixed organizational structures, while digital and intelligent transformation will inevitably bring new business models or optimize and reorganize existing internal processes, breaking down original departmental barriers and establishing a more flexible and efficient organizational structure to adapt to the rapidly changing market environment. Secondly, process optimization is also an important task in the digital and intelligent transformation process. The application of digital technology enables enterprises to more accurately grasp various links in business processes, thereby identifying potential optimization space. To ensure smooth communication between different links, mutual cooperation across functional departments is required, along with the establishment of effective collaborative mechanisms to ensure that digital and intelligent transformation is truly implemented. Lastly, collaborative cooperation is also an important management challenge that needs to be addressed during the digital and intelligent transformation process. In the context of digital intelligence, due to the differences in interests and technological levels among different links in the entire energy industry chain, collaboration,

communication, and cooperation often face certain difficulties, and there are issues of information delay, absence, and asymmetry among various links.

3.3. Policy Level: More Policy Support is Urgently Needed for the Digital and Intelligent Empowerment of the Entire Energy Industry Chain

Insufficient Policy Support: Local energy authorities lack comprehensive strategies to incentivize digital and intelligent innovation, with policies for financing, technology equipment prioritization, financial aid, tax benefits, and intellectual property protections not sufficiently robust.

Regulatory Standards: The absence of unified standards for digitalized intelligent energy systems across different zones and operational segments restrict interconnectivity and long-term collaboration.

Fiscal Incentives: Limited fiscal mechanisms like subsidies, tax deductions, and insurance safeguards impede business readiness for high-risk breakthroughs.

3.4. Economic Aspect: There are Dual 'Fog' Issues of Uncertain Investment Returns and Unclear Profit Models

The uncertainty surrounding the investment return and profitability of digitalized energy solutions poses concerns:

Investment Uncertainty: Digital and intelligent application demands substantial funding. However, disparities across conversion efficiency and lifecycle of high-tech tools inhibit widespread adoption by smaller enterprises lacking capital buffers.

Market Acceptance: Despite cost reductions from digital models (e.g., blockchains for energy flow), integrating these measures into traditional incumbents' business pathways has been slow.

4. PATH SELECTION FOR HIGH-QUALITY DIGITAL AND INTELLIGENT DEVELOPMENT ACROSS THE ENERGY INDUSTRY CHAIN

4.1. Strategic Basis for Path Selection

Path Selection for Digital and Intelligent Empowerment of High-Quality Development in the Entire Energy Industry Chain: A Comprehensive Consideration

The path selection for achieving high-quality development of the entire energy industry chain through digital and intelligent empowerment should be evaluated and balanced based on the following aspects:

Current Status and Development Trends of the Energy Industry:The first step is to conduct an in-depth analysis of factors such as the scale, structure, technological level, and market demand of the energy industry. Such analysis will contribute to identifying the potential applications and improvement opportunities of digital and intelligent technologies within the energy sector. Additionally, attention should be placed on the development trends of emerging fields like clean energy and distributed energy, as these trends can provide directional guidance for path selection.

Technological Feasibility and Economic Benefits.While digital and intelligent technologies are advancing rapidly, not all of them can be directly applied to every segment of the energy industry chain. Therefore, the selection of these technologies should involve rigorous evaluations of their stability, maturity, and reliability to ensure that their expected outcomes can be achieved in practical applications. Furthermore, a comprehensive cost-benefit analysis of technology implementation should be conducted to ensure the selected path is economically viable and reasonable.

Policy Environment and Market Demand:On one hand, the government's supportive policies, legal frameworks, and relevant industry standards for the energy sector will have a direct impact on the

path selection. On the other hand, market demand reflects consumer expectations for energy products and services. Understanding market demand thoroughly is critical when making decisions about the path forward.

Energy Security and Sustainable Development Requirements:As a critical component of national security, energy security should focus on the stability and reliability of energy supply within the path selection process. Simultaneously, sustainable development, a key principle of modern societal progress, must be incorporated into the planning process. Factors such as environmental protection, resource conservation, and social responsibility should be taken into account to promote a green, low-carbon, and sustainable energy industry.

4.2. Path Framework Design

Optimal Path Design for Digital and Intelligent Empowerment of High-Quality Development in the Entire Energy Industry Chain

The optimization path for digital and intelligent empowerment of high-quality development in the entire energy industry chain is designed across three dimensions: the status layer, the path layer, and the target layer [7].

Status Layer: This dimension addresses the challenges and bottlenecks faced in the process of digital and intelligent empowerment of the entire energy industry chain.

Path Layer: Based on the current status and development trends of the energy industry, the feasibility of technologies, economic benefits, policy environment, market demand, as well as energy security and sustainability requirements, this layer analyzes the path selection for digital and intelligent empowerment. The goal is to seek strategies that include automated production control, innovative practices for smart operations, strengthening digital information security, and promoting green energy development.

Target Layer: The final basis for selection lies in the transformation and upgrading of the entire energy industry chain through digital and intelligent empowerment. This aims to achieve digitized and intelligent development of the full energy industry chain (see Figure 2).

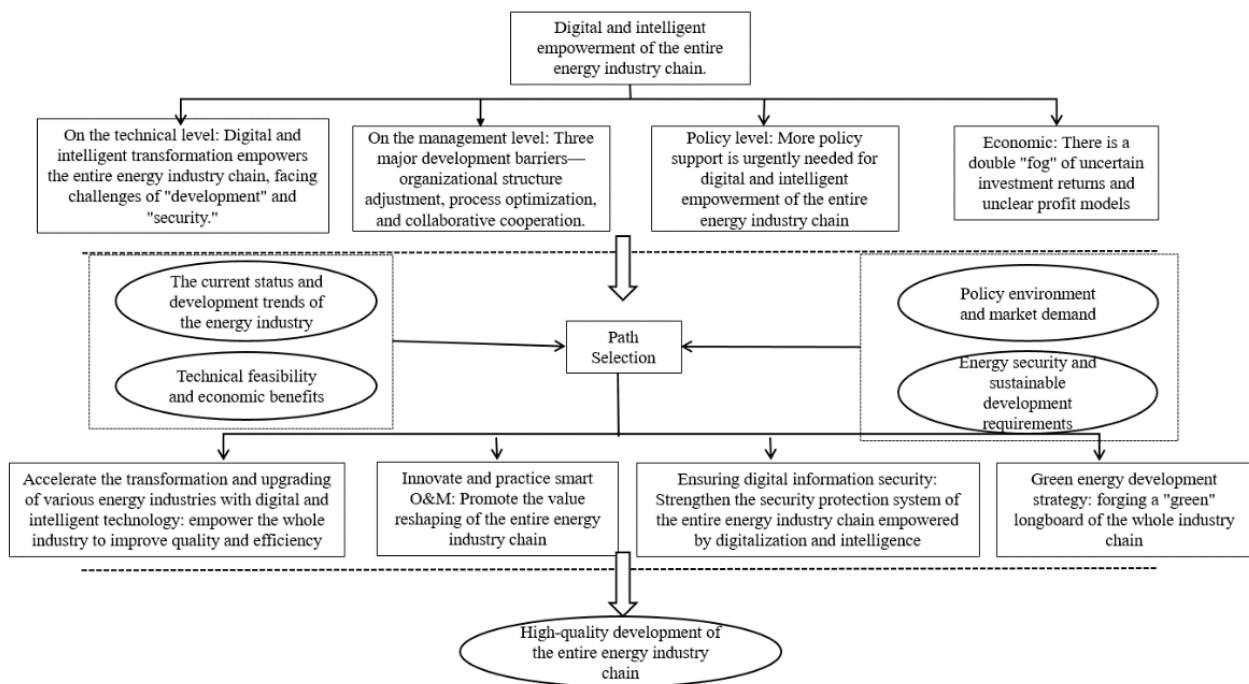


Figure 2. Path Framework Design

4.3. Recommended Path

4.3.1. Accelerating Digital and Intelligent Upgrades Across Energy Sectors: Empowering Industry-Wide Efficiency

Coal Industry: Implement full-process automation systems for coal production, including intelligent excavation equipment, intelligent control platforms, and remote monitoring. Focus on reducing manual involvement to achieve "few-person or even zero-person operations" in underground mining.

Electric Power Sector: Enhance power generation predictability using digital modeling and data analytics to optimize production and supply. Deploy intelligent monitoring systems to improve equipment operational stability while enabling precise profit-cost planning through AI algorithms.

Oil and Gas Sector: Develop specialized software and digital basins for oil and gas exploration. Utilize real-time automation systems for process monitoring, enhancing stability and efficiency in refining and storage operations.

Renewable Energy: Adopt intelligent energy forecasting systems informed by meteorological data to optimize power generation and avoid curtailment, advancing the utilization of distributed energy resources.

4.3.2. Innovative Practices in Smart Operations: Reshaping Energy Industry Chain Value

Develop a robust framework for smart operations across production, transportation, and consumption. By promoting connectivity and collaboration within the energy ecosystem, enhance resource allocation efficiency and stakeholder alignment.

Introduce "strategic & operational co-control" mechanisms incorporating IoT, AI, and big data technologies. Gradually integrate smart production systems into energy node enterprises to achieve smarter workflows and centralized management.

4.3.3. Ensuring Digital Information Security: Strengthening Safety Systems for Digitalization

As digital technologies penetrate all stages of the energy chain, information security becomes increasingly crucial:

Build real-time monitoring and pre-warning systems across the industry chain to identify vulnerabilities.

Enhance algorithmic stability by adopting large-scale historical data processing and predictive analytics tools [8].

Implement cybersecurity policies to safeguard sensitive energy data, focusing on internal security protocols, incident response mechanisms, and integrated risk governance frameworks.

4.3.4. Green Energy Strategy: Cultivating Industry-Wide "Green Edge" Competitiveness

Green Exploration: Promote environmentally friendly technologies for resource extraction, focusing on low-impact coal and petroleum mining techniques.

Green Processing and Transportation: Optimize manufacturing processes using sustainable equipment, improve material efficiency through waste utilization, and adopt green logistics technologies.

Consumer-Focused Green Transition: Develop intelligent energy consumption solutions that encourage behavioral shifts among users towards lower carbon footprints.

5. CONCLUSION

Driven by the wave of digitalization and intelligentization, the entire energy industry chain is experiencing unprecedented changes. Digital transformation is reshaping the value of the entire energy industry chain in ways never seen before, becoming the core driving force behind the high-quality development of the energy sector. This article deeply analyzes the impact mechanisms, real dilemmas, and path choices of digital and intelligent empowerment in the energy industry chain, providing a new perspective for understanding and responding to the challenges of the current digital era. The digital and intelligent transformation of the entire energy industry chain is achieved through the strong drive of technological innovation and the multiplicative effect of data elements. The deep integration of technological innovation and data elements not only profoundly changes the mode of social production but also significantly enhances the efficiency of resource allocation. However, digital and intelligent transformation still faces numerous challenges at multiple levels, including technology, management, policy, and economy. Therefore, governments and enterprises need to collaborate and make concerted efforts through proactive exploration of automated production control, innovative practices in smart operations, strengthening the security protection system for new quality productivity empowered by digital intelligence, and forging a "green" advantage for the entire industry chain, thereby providing solid support for the digital and intelligent development of the entire energy industry chain.

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