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Exploration of Energy Transition Paths in Resource-Based Regions Based on the Multi-Energy Coupled New Energy System

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Abstract: Resource-based regions generally face challenges from multiple factors such as a single energy structure, insufficient technological innovation, and backward institutional mechanisms. Their energy transition is a systematic project involving multiple dimensions including technology, industry, and institutions. As a typical resource-based region, Shanxi Province has conducted active explorations in energy transition: its energy consumption structure has been continuously optimized, traditional fossil energy has been utilized in a clean and efficient manner, and the penetration rate of renewable energy has been increasing year by year. Systematically advancing energy transition from multiple dimensions—such as supply-side optimization, consumption-side reform, technological innovation, and policy guarantees—and building a new multi-energy coupled energy system have become a long-term mechanism for promoting resource-based regions to adjust their energy production and consumption structures and achieve sustainable development. The research results provide theoretical reference and practical guidance for resource-based regions to implement the dual-carbon strategic goals and realize green, low-carbon, and high-quality development.

1. Introduction

Against the global backdrop of addressing climate change and advancing the energy revolution, resource-based regions are confronted with severe transformation pressures [1]. As a crucial energy base in China, Shanxi Province holds 27.7% of the country's total coal reserves, and its coal output has long ranked among the top in China. In 2024, the raw coal output of Shanxi Province reached nearly 1.3 billion tons, accounting for 26.66% of China's total raw coal output [2]. However, the ecological and environmental problems as well as carbon emission pressures caused by the long-term economic structure relying on coal resources have become increasingly prominent [3]. Particularly after the Chinese government put forward the "dual-carbon" strategic goals in 2020 [4], Shanxi Province, as a pilot region for comprehensive reform of the energy revolution, is in urgent need of exploring a long-term path for the transformation of resource-based economies.

The new multi-energy coupled energy system, which integrates various energy resources to achieve optimal allocation and efficient utilization of energy, has become a key direction for the energy transformation of resource-based regions [5]. This new system emphasizes the diversification of the energy supply side, the electrification and intelligence of the energy consumption side, as well as the flexibility and resilience of the energy system [6]. In recent years, Shanxi Province has carried out active explorations in the application of multi-energy coupling, such as the "source-grid-load-storage-charging" microgrid project in Datong City and the hydrogen energy industry demonstration base in Xiaoyi City. These practices have not only provided valuable experience for the energy transformation of resource-based regions but also offered references for the transformation and development of similar regions.

Practice has proven that the new multi-energy coupled energy system can effectively improve the consumption capacity of new energy, reduce carbon emissions, while taking into account the stable economic development. It is thus an effective approach for resource-based regions to realize energy transformation and high-quality development [7].

2. Theoretical Framework of the New Multi-Energy Coupled Energy System

2.1. Connotation and Composition of the System

The new multi-energy coupled energy system refers to a new energy supply and consumption model that achieves efficient, low-carbon, and safe operation of the energy system through systematic integration and optimal allocation of different energy types [8]. With renewable energy as the main body, smart grid as the platform, and energy storage technology as the key support, this system realizes the overall optimization of the energy system through means such as multi-energy complementarity and source-grid-load-storage interaction [9]. The core elements of this system cover multiple levels and dimensions, including the coordinated coupling of multi-energy flows, high-proportion integration of renewable energy, intelligent operation and decision-making, support from key energy storage technologies, and coordination of policies and market mechanisms [10].

- The structure of the new multi-energy coupled energy system can be divided into three key levels:
- Foundation Layer: Composed of diversified energy supplies, it includes renewable energy sources such as wind energy, solar energy, hydropower, and biomass energy, as well as traditional energy sources like coal and oil & gas that have undergone clean utilization. The diversification and low-carbonization of the energy structure provide a stable and abundant energy source for green transformation.
- Technology Layer: As the key to supporting energy coupling and system optimization, it mainly includes smart grid, advanced energy storage technology, virtual power plant, and energy digital twin platform. Relying on the smart energy management system, it realizes real-time coordination and optimal scheduling of multi-energy flows, improving the overall efficiency and operational resilience of the system.
- Application Layer: Encompasses application models such as multi-energy complementarity, smart microgrid, integrated energy services, and zero-carbon parks. Relying on the integrated operation of "source-grid-load-storage", it enhances the system’s adaptability to the fluctuations of renewable energy, and ultimately achieves the goal of safe, economical, and low-carbon energy services.

2.2. Multi-Energy Complementation and Coordination Mechanism

Multi-energy complementation is the core mechanism of the new multi-energy coupled energy system. It improves the overall efficiency and reliability of the energy system by leveraging the temporal and spatial complementarity of different energy types. As an extension of traditional distributed energy applications, the multi-energy complementary system embodies the concept of energy system integration, expanding distributed energy applications from "points" to "areas" and forming a regional energy internet [11]. Its core lies not in the simple superposition of multiple energy sources, but in the comprehensive complementary utilization of energy at the system level based on the different grades of energy. It coordinates the matching relationships and conversion processes among various types of energy to achieve more efficient and economical energy utilization. The key core technology is the optimal control of complex multi-energy flow networks under the constraint of safe energy use.

The operation of multi-energy complementation mainly relies on three basic modes: energy source complementation, source-load interaction, and temporal-spatial coupling. Ultimately, unified optimal scheduling is realized through a highly integrated multi-energy complementary comprehensive energy management system. Specifically:

- Energy source complementation utilizes the power generation characteristics of different renewable energy sources to form a complementary mechanism on the time scale;
- Source-load interaction guides loads to actively adapt to the output characteristics of renewable energy through demand-side response measures;
- Temporal-spatial coupling addresses the temporal and spatial mismatch between power generation and electricity load by leveraging the temporal-spatial transfer capability of energy storage.

2.3. Application Value in Resource-Based Regions

For resource-based regions, the new multi-energy coupled energy system holds significant practical value for realizing green and low-carbon transformation, enhancing energy security, and optimizing industrial structure. By systematically integrating various renewable energy sources such as wind, solar, hydropower, and energy storage, and coordinating them with traditional energy sources, the system can effectively improve the overall efficiency and stability of the energy system, helping resource-based regions break free from excessive dependence on traditional high-carbon energy.

On one hand, through multi-energy complementary coordination, scheduling, and control technologies, it solves the intermittency and volatility issues of renewable energy power generation, enhances the power grid’s capacity to accommodate high-proportion new energy, and reduces scheduling risks. On the other hand, relying on the "energy + industry" model, it combines energy transformation with industries such as ecological restoration, modern agriculture, and cultural tourism, forming a sustainable closed loop of industrial complementarity and revenue feedback, and fostering new economic growth drivers. Additionally, the transformation paradigm that achieves the coordinated improvement of economic, ecological, and social benefits through energy system restructuring is of promotional significance for resource-exhausted regions.

3. Current Status and Dilemmas of Energy Transformation in Resource-Based Regions

3.1. Energy Structure Transformation Progress

As an important energy base in China, Shanxi's economic growth has long been highly correlated with the trend of coal consumption, showing significant characteristics of resource dependence. In order to avoid the downward risk of the economy after coal consumption peaks, Shanxi urgently needs to cultivate new pillar industries and promote high-quality development. Since the National Resource-based Economy Transformation Comprehensive Pilot Reform Zone was approved for establishment in 2010, Shanxi's energy transformation has received strong support at the national policy level, giving Shanxi the power to pioneer and test new measures, providing a major opportunity for its industrial upgrading and the optimization of the layout of new quality productive forces.

In recent years, Shanxi has taken a series of effective measures in energy transformation. On the premise of ensuring national energy security, it has resolutely eliminated backward production capacity, cumulatively resolving 157 million tons of excess coal production capacity during the "13th Five-Year Plan" period, and promoting the transformation of the coal industry towards high-quality development. At the same time, taking intelligent construction as a breakthrough, it has taken the lead in applying 5G technology to intelligent coal mines and established the first artificial intelligence computing center in the national coal industry.

In addition, Shanxi has also actively developed renewable energy, and the installed capacity of new energy has grown rapidly, reaching 68GW by 2025. By the end of 2024, the total installed power generation capacity in Shanxi Province was 145.166 million kilowatts, an increase of 9.8% year-on-year. In Figure 1, the installed capacity of hydropower was 2.256 million kilowatts, an increase of 0.2% year-on-year, the installed capacity of thermal power was 81.977 million kilowatts, an increase of 2.3% year-on-year, the installed capacity of wind power was 26.165 million kilowatts, an increase of 4.7% year-on-year, and the installed capacity of solar (photovoltaic) power generation was 34.768 million kilowatts, an increase of 39.6% year-on-year.

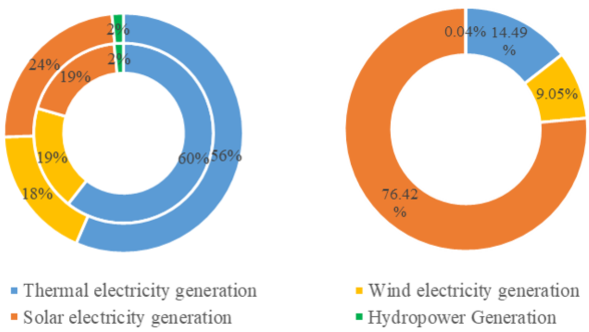

Figure 1: The Composition of Installed Power Capacity and Newly Added Installed Capacity in Shanxi Province.

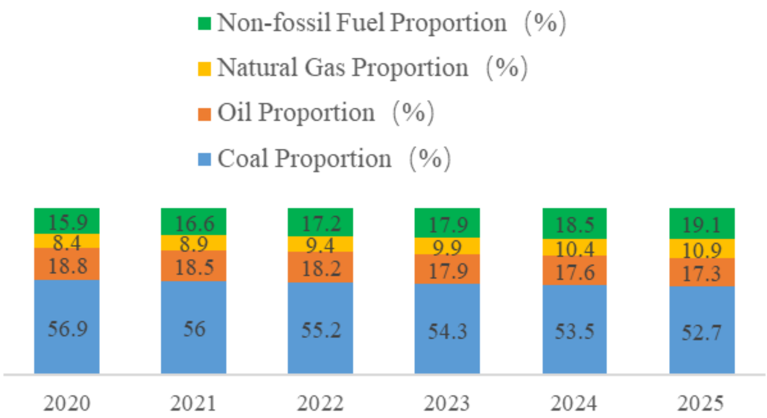

Figure 2: Energy Consumption Structure of Shanxi Province (2020-2025).

Shanxi's energy consumption structure has been continuously optimized as showed in Figure 2, and the proportion of non - fossil energy consumption has been gradually increasing. However, it is still lower than the national average level. From January to December 2024, the total power generation in Shanxi Province was 438.62 billion kWh, with a year - on - year growth of - 1%. In Figure 3, thermal power generation was 367.11 billion kWh, with a year - on - year growth of - 1.1%;

hydropower generation was 4.49 billion kWh, with a year - on - year growth of 31.4%; wind power generation was 47.82 billion kWh, with a year - on - year growth of - 5.8%; and solar power generation was 19.19824 billion kWh, with a year - on - year growth of 6.7%.

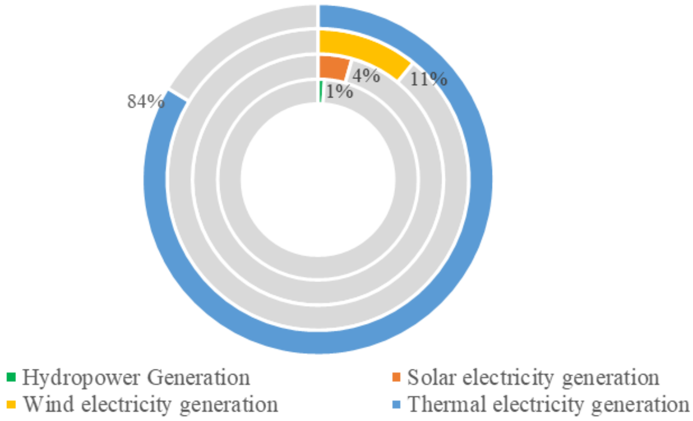

Figure 3: The Proportion Structure of Power Generation in Shanxi Province in 2024.

In 2024, new energy power generation took an absolute leading position in the newly-added installed power capacity of Shanxi Province. The proportion of newly-added installed new energy power generation capacity in the total newly-added installed power capacity of Shanxi Province kept rising [12], which indicates that the power energy structure of Shanxi Province is continuously transforming towards green and low-carbon development. The "green content" in the composition of power energy is constantly increasing, and the scale of new energy installed capacity has continuously achieved new breakthroughs.

3.2. Main Difficulties in the Transformation

In recent years, although Shanxi has made great efforts to improve its energy structure and actively promote the replacement of traditional fossil energy with renewable energy, and has achieved positive results, with the continuous advancement of the "dual carbon" (carbon peaking and carbon neutrality) strategic goals, it still faces a series of practical difficulties, and there is an urgent need to get rid of the high-carbon development path.

First, the industrial structure is rigid, and the economy is highly dependent on the coal industry. For a long time, Shanxi's industrial layout has mainly relied on the traditional coal industry and heavy industry, and the tertiary industry is also largely a service industry developed around the coal industry. As a result, the economy is greatly affected by the coal market. The single industrial structure leads to weak economic resilience of Shanxi, making it vulnerable to various risks, especially in the process of China's energy transformation. At the same time, the per unit area coal consumption in Shanxi Province is about 5 times the national average, resulting in high carbon emission intensity and great difficulty in transformation. Therefore, the withdrawal of high-carbon assets caused by the long-term lock-in of the high-carbon path has also restrained the diversified development of Shanxi's economy.

Second, the pressure of emission reduction and energy supply guarantee coexists, making the low-carbon development path difficult. As an important national energy production and supply base, Shanxi has provided important support for China's energy security. However, long-term coal mining and utilization have also led to Shanxi's dependence on the high-carbon path and serious environmental pollution problems. With the continuous advancement of the "dual carbon" goals, under the pressure of dual control of carbon emissions, Shanxi still needs to undertake the important task of ensuring energy supply. Coupled with practical problems such as high costs and long cycles brought by environmental governance, the multi-faceted pressure poses severe challenges to Shanxi's future transformation and development path.

Third, there is a structural shortage of human resources, and the driving force of technological innovation is insufficient. Shanxi has a weak accumulation of human capital and faces great pressure in stabilizing employment. On the one hand, Shanxi lacks advantages in higher education. There are 2,820 ordinary colleges and universities nationwide, while Shanxi has only 83, accounting for 2.94% of the national total. This leads to relatively weak local talent cultivation capacity and a prominent shortage of high-end talents. On the other hand, the environment and policies for attracting talents need to be further optimized. In particular, the shortage of high-end talents has affected Shanxi's overall scientific and technological innovation capacity, which is not conducive to the development of new-quality productive forces. In 2022, the input intensity of R&D funds in the whole society of Shanxi was only 1.07%, 1.47 percentage points lower than the national average. At the same time, the pains of energy transformation and the rapid expansion of renewable energy have led to fluctuations in the coal industry and instability in the demand for labor in related industries, bringing enormous pressure on stable employment and just transition in the future.

4. Exploration of Energy Transition Paths Guided by Multi-Energy Coupling

Multi-energy coupling, by synergistically optimizing traditional energy and new energy, breaking down barriers between different energy types and systems, and realizing the optimal allocation and efficient utilization of energy resources, has become a crucial path to advance the clean and low-carbon transformation of energy and ensure energy security. It is not limited to technological changes, but also involves in-depth innovations in institutional mechanisms, business models, and system planning.

4.1. Promoting Diversified and Clean Transformation on the Supply Side

The reform of the energy supply side is the key to the energy transition in resource-based regions. Its core strategic framework is to build a "diversified, clean, safe, and efficient" modern energy supply system, increase the proportion of clean energy, and reduce dependence on traditional fossil energy.

4.1.1. Advancing the Diversified Development of Energy Supply

The diversification of energy supply includes three dimensions:

- Diversification of energy structure: Actively develop non-hydro renewable energy sources such as wind energy, solar energy, solar thermal energy, biomass energy, geothermal energy, and ocean energy on a large scale; advance nuclear energy construction in an orderly manner under the premise of ensuring safety; and make forward-looking arrangements for clean secondary energy sources such as hydrogen energy and ammonia energy.
- Diversification of technical routes: Encourage the parallel development and complementarity of technologies such as crystalline silicon and thin-film photovoltaics, onshore and offshore wind power, nuclear power with multiple reactor types, and diversified energy storage technologies, so as to reduce the risk of over-reliance on a single technical path.
- Diversification of development models and entities: Adhere to the simultaneous promotion of centralized and distributed development, create a fair market environment, guide the participation of multiple entities including central enterprises, state-owned enterprises, private enterprises, and foreign-funded enterprises, and promote the diversification of supply chains and energy sources to enhance system resilience and security.

4.1.2. Advancing the Clean Development of Energy Utilization

The clean development of energy utilization involves three processes:

▪ Incremental replacement: Meet the newly added energy demand mainly with renewable energy to realize "green power" replacement.

▪ Stock optimization: Carry out clean and efficient transformation of traditional coal-fired power, and gradually shift it from a main power source to a regulating power source that provides reliable capacity and flexibility.

▪ Whole-process low carbon: Pay attention to carbon emissions throughout the life cycle of energy equipment manufacturing, power station construction, and fuel extraction, and promote the greening of the entire industrial chain.

4.2. Promoting Automated and Intelligent Transformation on the Consumption Side

The reform of the energy consumption side is another important dimension of the energy transition in resource-based regions. Its core lies in deeply integrating advanced information and communication technologies, intelligent control algorithms, and flexible load resources to transform the traditional passive and rigid energy consumption model into an active model that is adjustable, optimizable, and capable of participating in system interaction, thereby improving energy utilization efficiency and reducing carbon emission intensity.

4.2.1. Intelligent and Flexible Load Patterns

On the energy consumption side of building energy use and transportation energy use:

▪ Vigorously develop and deploy smart home energy management systems (HEMS), building automation systems (BAS), and intelligent energy optimization systems for industrial processes, so as to realize automatic perception, coordinated control, and energy efficiency management of end-use energy facilities such as air conditioners, lighting, energy storage, and production equipment.

▪ Promote flexible loads such as electric vehicles (EVs) and electric refrigeration/heat pumps to become mobile energy storage units and flexible regulation resources of the system, and participate in demand-side response through price signals or automated commands to stabilize power grid fluctuations.

▪ Apply big data analysis and artificial intelligence (AI) technologies to achieve accurate profiling of load characteristics, prediction and optimization of energy use behavior, and formulation of automated energy efficiency strategies based on machine learning, so as to maximize the potential of energy conservation and flexibility.

4.2.2. Automated System Interaction and Platformization

On the energy consumption side of automated interaction systems:

▪ Build virtual power plant (VPP) platforms and load aggregator business models, and use digital technologies to aggregate massive and scattered flexible load resources into "virtual units" with observable, measurable, and controllable capabilities, enabling them to automatically participate in electricity market transactions and provide auxiliary services.

▪ Promote automatic demand response (ADR), allowing consumption-side resources to automatically respond to the real-time electricity prices or dispatching instructions of the power grid based on preset strategies or artificial intelligence algorithms, realizing second-level/minute-level rapid and accurate regulation, which greatly improves response efficiency and reliability.

4.3. Promoting the Integration of Energy Storage and Multi-Energy Complementary Technologies

Energy storage technology is a crucial support for the new multi-energy coupling energy system, and a core measure to build a new energy system, enhance the absorption capacity of renewable energy, and improve the flexibility of system operation. Through technological integration and system optimization, it breaks down barriers between energy subsystems, forms an integrated energy supply model featuring synergistic efficiency improvement, spatio-temporal complementarity, and intelligent regulation, and enhances the flexibility and reliability of the energy system.

4.3.1. Technological Integration from "Simple Superposition" to "In-depth Integration"

Energy storage technology is a core means to achieve collaborative optimization of multi-energy complementary systems. Various energy storage technologies (such as electrochemical energy storage, pumped-storage hydroelectricity, compressed air energy storage, and flywheel energy storage) can realize the spatio-temporal transfer of energy and power smoothing, effectively solving the spatio-temporal mismatch between intermittent energy sources (e.g., wind and solar energy) and loads, and enhancing the system's adaptability to uncertain supply and demand.

The "energy storage + multi-energy complementarity" model can build a local microgrid with off-grid operation and black-start capabilities, significantly improving the system's resilience and power supply reliability under extreme operating conditions. At the operation optimization level, relying on the smart energy management system (EMS) for coordinated scheduling of multi-energy flows and energy storage strategies can not only ensure the efficient operation of the system but also achieve economic benefits by participating in peak-valley arbitrage in the electricity market and providing auxiliary services, thereby comprehensively enhancing the economy and comprehensive energy efficiency of the energy system.

4.3.2. Support System from "Traditional Model" to "Innovative Forms"

Promoting the in-depth integration of energy storage and multi-energy complementary systems requires multi-dimensional collaborative innovation:

▪ Technological level: Focus on tackling key technologies such as long-duration energy storage, flow batteries, solid-state batteries, and hydrogen energy storage to continuously reduce system costs; develop multi-energy flow collaborative planning algorithms and digital twin platforms to improve system modeling and optimized operation capabilities.

▪ Mechanism design: Establish market-oriented mechanisms for electricity spot markets, capacity markets, and auxiliary services; confirm the independent market entity status of energy storage and multi-energy complementary systems, ensuring that their flexible resources receive reasonable economic returns.

▪ Policy level: Strengthen standard construction, improve grid connection, safety, and fire protection regulations; include supporting energy storage in the access conditions for new energy projects; and guide technological R&D and demonstration applications through fiscal subsidies and tax incentives.

In addition, it is necessary to actively explore business models such as shared energy storage, leasing, and energy trusteeship to reduce the initial investment cost of users, improve the utilization efficiency of energy storage assets, and form a sustainable development path.

4.4. Promoting Innovation in Market Systems and Mechanisms

Innovation in systems and mechanisms is an important guarantee for the energy transition in resource-based regions. It stimulates the flexible regulation potential of various entities, ensures the clean and low-carbon transformation of energy, and creates a sound institutional environment for the energy transition. Its core lies in building a market system that accurately reflects the spatio-temporal value of energy and economic signals to guide the optimal allocation of resources.

4.4.1. Joint Efforts of Regulatory Systems and Incentive Policies

Promoting innovation in energy systems and mechanisms is a key institutional guarantee for resource-based regions to achieve energy structure transformation. This requires the construction of a unified and efficient market and regulatory system, with a focus on improving the electricity spot market and auxiliary service mechanisms, and establishing a price formation mechanism that reflects resource scarcity and environmental costs. For example, Shanxi has explored the market-oriented reform of new energy grid-connected electricity prices and a sustainable settlement model, providing an institutional foundation for the grid connection and absorption of clean energy and the realization of reasonable returns.

At the same time, it is necessary to implement supporting economic incentive policies, and guide social capital to actively participate in energy transition projects through diversified policy tools such as fiscal subsidies, tax incentives, and green finance. Shanxi encourages private enterprises to participate in the energy sector through models such as energy performance contracting (EPC) and build-operate-transfer (BOT), and connects with the China Certified Emission Reduction (CCER) carbon market mechanism to create a clear profit path for private capital and enhance market-oriented investment momentum.

4.4.2. Strong Support from Technological Innovation and International Cooperation

Technological innovation and international cooperation provide key support for the innovation of systems and mechanisms. The energy transition is essentially driven by technology, which requires strengthening the support of technological innovation to break through the technical bottlenecks of the energy transition. Relying on industry-university-research cooperation platforms, Shanxi promotes the R&D and transformation of core technologies such as hydrogen energy and energy storage. For instance, it has developed the world's first 250kW hydrogen fuel cell system, significantly enhancing the regional independent capability in energy science and technology.

In addition, learning from the advanced international experience of countries such as Germany and Denmark, and participating in the formulation of international standards not only accelerates technological iteration and application but also provides theoretical references and practical paradigms for the innovation of local systems and mechanisms, jointly building a resilient and open energy governance system.

5. Practical Exploration of Shanxi's Energy Transition

Energy transition is a continuous process. Shanxi has actively carried out practical explorations in energy transition since 2017, demonstrating its determination to shift from "dominance of coal and coal-fired power" to "diversified synergy". Positive results have been achieved in structural transformation, systematic efficiency improvement, institutional innovation, and technical support.

5.1. Continuous Optimization of Energy Structure

The core essence of energy transition lies in the continuous optimization of energy production and consumption structures, and the gradual increase in the proportion of renewable energy utilization. In recent years, through multi-dimensional policy intervention and technological innovation, Shanxi has continuously adjusted its energy structure, showing a significant trend of shifting from high-carbon dependence to low-carbon diversification, with renewable energy playing an increasingly important role in the energy structure.

By the end of June 2025, the installed capacity of new energy in the province had reached 75.68 million kilowatts, nearly 40 times that of 2012, representing a substantial increase in new energy installed capacity. In the first half of 2025, the power generation from wind and solar new energy in the province reached 60.274 billion kilowatt-hours, indicating a significant growth in green electricity output. In 2024, the province's new energy power transmission volume reached 16.44 billion kilowatt-hours, including 7.538 billion kilowatt-hours of green power transmission, ranking first in China. It is estimated that by 2030, the proportion of new energy installed capacity in Shanxi Province will exceed 60%.

5.2. Carbon Reduction Transformation of Traditional High-Carbon Industries

The low-carbon utilization of high-carbon energy is also an important path for energy transition, and the clean and efficient utilization of coal resources has become a key focus. In recent years, Shanxi has achieved control over coal consumption and improvement in energy efficiency by phasing out backward production capacity, promoting intelligent and green coal mining, and developing the modern coal chemical industry.

At the same time, the coal-fired power industry has accelerated ultra-low emission transformation and flexibility adjustment to support the absorption of renewable energy. In recent years, a total of over 70 million kilowatts of coal-fired power units have completed the "triple transformation" (energy-saving transformation, flexibility transformation, and ultra-low emission transformation) for energy conservation and carbon reduction, increasing peak-shaving capacity by 6.11 million kilowatts.

Key industries have carried out in-depth emission reduction and circular utilization, and efforts have been made to build cross-enterprise and cross-industry circular economy industrial chains. It is estimated that by the end of 2025, the annual utilization of industrial solid waste will reach more than 200 million tons, and the annual output value of the resource recycling industry will reach 110 billion yuan. Industrial and mining enterprises have implemented electricity substitution, with newly added electricity consumption of 39.1 billion kilowatt-hours, equivalent to replacing 22.42 million tons of scattered coal combustion.

5.3. Synergistic Support from Power Grid Construction and Electricity Market

A stable and efficient power grid and a flexible electricity market are strong supports for energy transition. In recent years, Shanxi has expanded external power transmission channels, promoted flexibility transformation, and innovated grid-connection technologies. It has adopted a new model of "centralized convergence and step-up grid connection" to solve the bottleneck of distributed photovoltaic access, effectively improving power transmission capacity and the absorption level of new energy.

Shanxi took the lead in launching the trial operation of electricity spot market settlement in China, and in December 2023, it became the first province in China to switch to the official operation of the electricity spot market. By the end of July 2025, there were 7 virtual power plants (VPPs) in Shanxi participating in market transactions, with a cumulative aggregated capacity of 2.8807 million kilowatts.

5.4. Sustainable Development of Circular Economy Model

The circular economy model is of systematic and strategic significance for energy transition. It is not only an innovation in technical paths, but also a profound transformation in development paradigms and economic structures, which can provide replicable and promotable practical examples for the green transition of resource-based regions.

The circular economy model, featuring reduction, reuse, and resource recycling, can effectively enhance resource value and reduce carbon emissions and pollution. In recent years, relying on the circular economy model, Shanxi has continuously extended its industrial chain – shifting from single coal mining and primary smelting to high-value-added fields such as new chemical materials, green building materials, and clean energy – creating new economic growth points.

Through the construction of circular economy parks, a closed-loop ecosystem of "coal-chemicals-materials" has been formed. Energy cascade utilization and material recycling technologies have increased resource utilization efficiency to over 98%. In addition, circular economy parks actively participate in power system regulation, enhancing the power grid's capacity to absorb fluctuations in wind and solar power generation, realizing regional energy self-sufficiency and optimization, and promoting energy coupling and efficiency improvement.

6. Conclusions

1) Shanxi's practice shows that the new multi-energy coupling energy system can effectively improve the absorption capacity of new energy, reduce carbon emissions, realize the optimization of energy structure and industrial upgrading, while ensuring economic stability. It provides a replicable transition paradigm for resource-based regions.

2) Through diversification on the supply side, intelligence on the consumption side, integration of energy storage technologies, and innovation in market mechanisms, the multi-energy coupling system has systematically addressed the transition dilemmas of resource-based regions, such as a single energy structure, backward technology, and institutional obstacles. It is an effective path to achieve the "dual carbon" goals.

3) In the future, the energy transition of resource-based regions should continue to strengthen technological innovation and policy synergy, promote breakthroughs in key technologies such as hydrogen energy and long-duration energy storage, improve the mechanisms of the electricity market and carbon market, facilitate the learning of international experience and regional cooperation, and build a resilient, open, and sustainable new energy system.

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