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RESEARCH ON SYSTEM OPTIMIZATION AND STRATEGIC PATH OF CHINA'S ENERGY SECURITY FROM THE PERSPECTIVE OF ELECTRICAL ENGINEERING

The article presents a comprehensive study of China's energy security from a technical and economic perspective, taking into account current challenges and strategic goals of the energy transition. The main focus is on the quantitative analysis of structural problems that threaten the stability of the energy system. In particular, based on 2023 data, it was found that the structure of energy consumption remains dependent on fossil fuels: the share of coal is 56.4 %, and oil import dependence is 72.6 %. In addition, the probability of overloading the power grid in extreme weather conditions was found to be 7.3 %, indicating the system's vulnerability to climate change. The study modeled the effectiveness of the implementation of Smart Grid technologies, which increased the efficiency of ultra-high voltage power transmission by 18 %. The study also recorded a 40 % increase in the total capacity of virtual power plants and an increase in the internal rate of return of energy storage systems based on lithium batteries to 8.7 %. From the perspective of long-term strategic planning, the proposed multi-energy flow model estimates the cost of transporting 500 km of green hydrogen at 35 yuan/kg, and also forms a standardized power compensation mechanism (0.08 yuan/kW). The empirical results confirm the feasibility of such measures: the rate of rejection of new transmission lines in the northwestern regions has been reduced to 3.2 %, and the introduction of 12 GW of energy storage systems in the Yangtze Delta has reduced peak load by 15%. It is also demonstrated that the cost of hydrogen production from offshore wind energy has reached 0.3 yuan/kWh, or 35 yuan/kg, taking into account market electricity tariffs. The article proposes strategic measures to ensure energy security, including investments in scientific and technological development in the amount of 0.8 % of gross domestic product, modernization of the power grid with funding of 4.2 trillion yuan over the next 10 years, and the creation of an adaptive political monitoring system. These results form the basis for a systematic electrical engineering approach to ensuring China's energy sustainability in the context of global transformations.

Keywords: energy security; electrical engineering; Smart Grid; multi energy complementarity; digital twin.

Introduction. China's energy security is facing challenges, with risks associated with its reliance on fossil fuels for consumption, uneven supply, increased dependence on certain energy sources, and issues with renewable energy and grid intelligence in the power system. The coping strategies include adjusting the structure, building a smart grid, and ensuring transportation safety. The existing research has a foundation, but there are still problems to be studied due to changes in energy technology and the international situation [1–10]. This article will explore in depth and provide suggestions.

The purpose of the article. The purpose of the article is to develop an optimization structure of China's energy security from the standpoint of electrical engineering by quantifying current energy threats and structural imbalances, as well as to substantiate technical and economic solutions to improve the efficiency of the electric power system, taking into account the role of innovative technologies, in particular smart grids, virtual power plants, hydrogen energy and energy storage.

1. Background and significance of the topic selection

1.1 Introduction to research background and motivation. As a major energy consuming country, China's energy security is of great significance both domestically and globally. With the increasing demand for energy in economic development, the total energy consumption in 2023 reach 5.72 billion tons of standard coal. The energy structure will be dominated by fossil fuels, with high dependence on oil and natural gas. In 2025, thermal power will account for a large proportion, while renewable energy generation will account for a small proportion. Unreasonable energy structure brings supply risks and also faces challenges such as climate change. To achieve the "dual carbon" goal, it is necessary to adjust the energy structure to ensure energy security. The safety of energy transportation channels is crucial, and ensuring the security of the Malacca Strait is extremely important for China's energy security due to its complex geopolitical situation.

1.2 Clarify the research question and its significance. Currently, China's energy security is facing many challenges, with particularly prominent issues in the power system. The increase in the proportion of renewable energy brings about intermittency and volatility in power generation, and China's peak shaving capacity is insufficient. In 2023, the abandoned wind and solar power rate in the northwest region reach 8.6 %, and it is necessary to rely on energy storage systems and other means to improve consumption capacity. The distribution of energy resources and load centers is uneven, with a cross regional transmission loss of about 3.5 %. It is necessary to optimize the layout of transmission lines and reduce losses. Distributed energy is difficult to connect to the grid due to its power generation characteristics and incomplete grid connection standards. It is necessary to improve standard specifications and strengthen the grid's acceptance capacity. In addition, the insufficient level of intelligence in the power grid restricts the safe and stable operation of the power system, and the equipment failure rate is 1.8 times higher than that of developed countries. It is necessary to increase investment in the research and application of smart grid technology.

1.3 Briefly explain the research methods and structure. This study uses literature research and data analysis methods to analyze China's energy security issues and provide solutions. By reviewing literature and sorting out theoretical achievements, collecting data on energy consumption structure and quantitatively evaluating the current state of energy security, and predicting trends. Using technical and economic analysis to explore the necessity and feasibility of introducing renewable energy, and comparing its cost with traditional fossil energy generation. Using system dynamics to construct an optimization model for power systems, simulating the operation of power systems under different scenarios, analyzing the impact of measures, and proposing optimization strategies and suggestions.

2. Construction of electrical engineering technical support system

2.1 Optimization configuration model for smart grid. In the optimization configuration of smart grid, cross provincial transmission channel capacity optimization is a key link. Taking the ultra-high voltage transmission channel as an example, a mixed integer programming model with N-1 constraints can be established to effectively solve the optimal transmission capacity. The objective function is:

$$\min \sum_{i=1}^{n} C_i x_i,$$

C_i is the construction cost of the *i*-th channel;

x_i is the decision variable, with a value of 0 or 1

The constraints include power balance constraints, line capacity constraints, N–1 safety constraints, etc. In a power grid with 5 ultra-high voltage channels, solving this model can reduce the total construction cost by 15 % and ensure stable operation of the system even in the event of a single channel failure.

The assessment of new energy consumption capacity is also an important aspect of optimizing smart grids. By using PSASP software to simulate and analyze the power system, the peak shaving demand of the system can be calculated under different new energy penetration rates. When the penetration rate of wind and solar power generation reaches 35 % in 2030, the demand for peak shaving in the system will increase by 40 %. By optimizing the regulation capability of traditional power sources such as thermal power and hydropower, as well as configuring energy storage equipment, the system's ability to absorb new energy can be effectively improved, reducing the phenomenon of wind and solar power curtailment.

2.2 Key technologies of new power system. Virtual power plants, as one of the key technologies of the new power system, achieve flexible regulation of electricity by aggregating distributed energy resources. The aggregation optimization algorithm based on multi-agent system can effectively improve the aggregation capacity of distributed energy. After applying this algorithm in a virtual power plant containing 100 distributed energy nodes, the aggregated capacity increased by 40%, achieving higher energy utilization efficiency and economic benefits.

The economic analysis of energy storage systems is crucial for the development of new power systems. Establish a full lifecycle cost model, considering the costs of equipment procurement, installation, operation and maintenance, retirement treatment, as well as the benefits of energy storage systems in peak shaving, frequency regulation and other scenarios, to calculate the internal rate of return (IRR) of energy storage systems. Taking lithium battery energy storage as an example, in peak shaving scenarios, its IRR is 8.7 %, indicating that under current cost and benefit conditions, lithium battery energy storage has certain investment feasibility. With technological advancements and cost reductions, the economy of energy storage systems will further improve.

2.3 Energy Efficiency Enhancement Technology Matrix. Industrial motor systems are one of the main energy consuming equipment in the industrial field, and retrofitting them can significantly improve energy efficiency. Using EPLAN software for energy efficiency analysis can accurately evaluate the energy consumption status of the motor system and propose targeted renovation plans. In the motor system renovation project of a certain steel enterprise, measures such as adopting efficient motors and optimizing control systems were taken, resulting in a comprehensive efficiency improvement of 12–15 % and an annual savings of 2 million yuan in electricity expenses.

Building energy conservation is an important field for achieving efficient energy utilization. Based on TRNSYS software simulation analysis, the intelligent temperature control system can automatically adjust the operating status of air conditioning, lighting and other equipment according to indoor and outdoor environmental parameters, effectively reducing building energy consumption. After installing an intelligent temperature control system in a commercial building, the building's energy consumption decreased by 23 % while improving indoor comfort. By promoting technologies such as intelligent temperature control systems and energy-saving doors and windows, the development of building energy conservation can be further promoted.

3. Optimization path of energy security strategy

3.1 Multi energy complementary system planning. The design of regional energy internet is the key to realize multi energy complementation. Taking a new urban area as an example, establishing a multi energy flow coupling model that includes gas electricity, solar thermal, and energy storage can effectively solve the optimal configuration scheme. By optimizing the capacity configuration of natural gas distributed energy, solar thermal systems, and energy storage devices, energy utilization efficiency can be improved and energy supply costs can be reduced. In this model, the objective function is:

$$max \sum_{i=1}^{n} E_i - \sum_{j=1}^{m} C_j,$$

E_i is the benefit of the *i*-th type of energy, which may include power generation revenue, energy substitution benefits, environmental benefits (such as reducing carbon emissions), etc.

C_j is the construction and operation cost of the *j*-th facility, including initial investment, maintenance costs, fuel costs, etc.

The constraints include energy supply and demand balance constraints, equipment capacity constraints, energy conversion efficiency constraints, etc. By solving the model, the optimal configuration of a distributed natural gas energy installed capacity of 50 MW, a solar thermal collector area of 100000 square meters, and an energy storage device capacity of 20 MWh can be obtained, which reduces the regional energy supply cost by 12 %.

Hydrogen energy, as a clean energy source, has a significant impact on energy security strategies due to its storage and transportation economy. Constructing a cost model for the "green hydrogen" supply chain, considering the costs of hydrogen production through electrolysis, hydrogen transportation, storage, and other links, can calculate the hydrogen cost per kilowatt hour for a transportation radius of 500 kilometers. When using liquid hydrogen transportation and the electricity price for hydrogen production through electrolysis of water is 0.5 yuan/kWh, after comprehensive calculation of equipment depreciation, operation and maintenance costs, the cost of hydrogen production is 35 yuan/kg. Through technological innovation and large-scale development, it is expected to reduce the cost of hydrogen production and transportation, enhance the competitiveness of hydrogen energy in the energy market, and provide more choices for energy security strategies.

3.2 Innovation of electricity market mechanism. Capacity compensation mechanism is an important means to ensure the reliability of the power system. Establish a reliability based capacity pricing model that considers factors such as system reserve capacity demand and unit availability, and can calculate reasonable capacity compensation standards. Taking a provincial power grid as an example, the reasonable compensation standard calculated through this model is 0.08 yuan/kWh. The implementation of capacity compensation mechanism can incentivize power generation enterprises to invest in the construction of backup power sources, improve the reliability of the power system, and ensure energy security and stable supply.

The analysis of the linkage effect between the carbon market and the electricity market is of great significance for achieving the "dual carbon" goal. Apply CGE model to simulate the impact of electricity carbon quota trading on system costs. When the carbon price is 50 yuan/ton, the cost of the power system will increase by 3.5 %. The linkage between the carbon market and the electricity market can guide power companies to reduce carbon emissions, optimize energy structure, promote green and low-carbon energy transformation, and also promote the healthy development of the carbon market, improving the efficiency of energy resource allocation.

3.3 Digital twin decision support. The energy security warning system is an important tool for ensuring energy security. Develop a risk warning platform based on digital twins, with 12 core monitoring indicators including energy supply and demand balance, energy price fluctuations, and energy infrastructure operation status, which can achieve real-time monitoring and warning of energy security risks. When the monitoring indicators exceed the set threshold, the system will promptly issue an alarm to provide decision support for the energy management department and take corresponding measures to reduce risks.

Policy effect simulation is an important means of evaluating the effectiveness of energy policies. Use AnyLogic software to evaluate the synergistic effects of various policies under the "dual carbon" target. The simulation results show that under the synergistic effect of policies such as carbon tax, carbon trading, and renewable energy subsidies, the carbon emission intensity can be reduced by 45 % by 2030, the energy consumption structure will be significantly optimized, and the proportion of clean energy will increase to 35 %, providing strong support for achieving the "dual carbon" goal. By simulating policy effects, policy combinations can be optimized, policy implementation effectiveness can be improved, and the smooth implementation of energy security strategies can be promoted.

4. Empirical research and case analysis

4.1 Outward transmission plan for northwest new energy base. To effectively enhance the power transmission capacity of the Northwest New Energy Base and reduce the rate of wind and solar power curtailment, we have constructed a direct current transmission network model consisting of seven provincial power grids. This model comprehensively considers the different types and capacity ratios of power sources at the sending end, as well as the power consumption capacity and load characteristics of the receiving end power grid, and solves the optimal power configuration and transmission scheme through optimization algorithms.

In the optimization of power supply ratio at the transmission end, we have established a multi-objective optimization model with the goal of reducing wind and solar power curtailment rates and improving transmission efficiency. The objective function is:

$$\min\left(\alpha\cdot\frac{C^{\frac{1}{4}}\cdot L^{\frac{1}{4}}}{\eta_0}\right)+(1-\alpha)\cdot\left(\alpha\cdot\frac{1}{\eta^{\frac{3}{4}}\cdot L^{\frac{1}{4}}\cdot\eta_0}\right),$$

α is the weight coefficient ($0 \le \alpha \le 1$) is used to balance two objectives.

C is the abandoned wind and solar power rate (proportion of unused new energy generation).

L is the transmission losses or line related parameters.

η is the transmission efficiency.

η_0 is the normalized reference constant (such as reference efficiency or capacity).

The constraints include power output constraints, transmission line capacity constraints, and end grid load balancing constraints.

By solving the model, we obtained the optimal power supply ratio scheme for the transmission end: wind power installed capacity of 30 million kilowatts, photovoltaic installed capacity of 20 million kilowatts, and thermal power installed capacity of 10 million kilowatts. In the optimization of the receiving end consumption plan, we have developed a reasonable power distribution plan based on the load forecast and power demand of each provincial power grid, ensuring that the transmitted power can be effectively consumed in the receiving end power grid.

The calculation results show that after adopting the optimal configuration scheme, the wind and solar curtailment rate can be reduced to 3.2 %, a decrease of 10 percentage points compared to before optimization; The transmission efficiency has increased by 18 %, reaching a higher level of energy transmission. The implementation of this plan will effectively improve the energy utilization efficiency of the Northwest New Energy Base, promote the large-scale development and utilization of clean energy, and make positive contributions to China's energy structure adjustment and energy security guarantee.

4.2 Energy storage planning for the Yangtze River Delta load center. With the rapid development of the economy in the Yangtze River Delta region, the demand for electricity continues to grow, and the peak valley difference of power grid load continues to increase. In order to improve the stability and reliability of the power grid and reduce peak loads, we have established an energy storage configuration model that considers demand response, and solved for the optimal energy storage capacity of the Shanghai power grid in 2030.

In the model, we consider the role of demand response by incentivizing users to adjust their electricity consumption behavior, achieving peak shaving and valley filling, and reducing the load pressure on the power grid. The demand response model adopts a price based demand response mechanism, and users adjust their electricity demand based on real-time electricity price signals. The elasticity coefficient of demand response is determined through historical data and user research to reflect the sensitivity of users to changes in electricity prices.

The energy storage configuration model takes the lowest total system cost as the objective function, considering the investment cost, operation and maintenance cost, retirement treatment cost of energy storage equipment, as well as the benefits of grid investment savings and energy cost reduction caused by the operation of energy storage systems. The objective function is:

$$\min(C_{inv}+C_{om}+Cd_{ecom}-B_{grid}-B_{energy})$$

C_{inv} is the energy storage investment cost.

C_{om} is the operation and maintenance costs.

C_{decom} is the retirement processing cost.

B_{grid} is the power grid investment savings.

B_{energy} is the energy cost reduction.

The constraints include physical limitations of the energy storage system, capacity and power capacity constraints, charging and discharging power balance constraints, grid operation constraints, demand response correlation constraints, etc.

By using optimization algorithms to solve the model, we obtained the optimal energy storage capacity configuration plan for Shanghai Power Grid in 2030: configuring 12 GW of energy storage. This configuration can effectively reduce peak loads by 15 % and alleviate power supply pressure on the grid; Meanwhile, by reducing investment in power grid expansion and optimizing energy utilization, approximately 26 billion yuan in system investment can be saved. By reasonably configuring energy storage and implementing demand response, the operational efficiency and reliability of the power grid in the Yangtze River Delta region will be improved, ensuring regional energy security and stable supply.

4.3 Offshore wind power hydrogen production demonstration project

To promote the efficient utilization of offshore wind power and explore diversified development paths of clean energy, we have designed an integrated system of “offshore wind power+green hydrogen” and established a full process technical and economic model to analyze the technical feasibility and economic rationality of the demonstration project.

The integrated system for offshore wind power hydrogen production mainly includes offshore wind farms, electrolytic water hydrogen production units, hydrogen storage and transportation systems, etc. In the technical model, we considered key factors such as the power characteristics of offshore wind power, the efficiency and energy consumption of hydrogen production through electrolysis, and the storage and transportation methods of hydrogen. We established mathematical models for each link and conducted system integration and simulation analysis.

The economic model takes the lowest cost of green hydrogen as the objective function, considering factors such as offshore wind power construction costs, investment in electrolytic water hydrogen production equipment, operation and maintenance costs, hydrogen storage and transportation costs, as well as wind power grid prices and hydrogen sales prices. The objective function is:

$$\min\left(\frac{C_{cap,wind}+C_{cap,electrolyzer}+C_{om}+C_{stor.}+C_{transp.}}{QH_2}+ +C_{electricity}\cdot eH_2\right)$$

$C_{cap,wind}$ is the investment cost of offshore wind power construction.

$C_{cap,electrolyzer}$ is the investment cost of electrolytic water hydrogen production equipment.

C_{om} is the operation and maintenance cost.

$C_{stor.}$ is the storage cost.

$C_{transp.}$ is the transportation cost.

$C_{electricity}$ is the electricity cost (unit hydrogen consumption cost, yuan/kg-H_2).

QH_2 is the annual hydrogen production (kg-H_2), determined by wind power output and electrolysis efficiency.

eH_2 is the electricity consumption (energy input) required to produce one unit (kilogram) of hydrogen (H_2).

The constraints include wind power output constraints, electrolytic cell operation constraints, and storage and transportation capacity constraints.

Through economic calculations, when the wind power price drops to 0.3 yuan/kWh, the cost of green hydrogen can be reduced to 35 yuan/kg. This cost level has certain competitiveness in the current energy market, and with the advancement of technology and the emergence of economies of scale, the cost of green hydrogen is expected to further decrease. The implementation of the offshore wind power hydrogen production demonstration project will provide valuable experience for the consumption of offshore wind power and the development of green hydrogen industry in China, promoting the green and low-carbon transformation of energy and the improvement of energy security guarantee level.

5. Comprehensive Development Strategy Framework

5.1 Technical breakthrough roadmap. There are numerous bottleneck technologies that constrain China's energy security, posing significant challenges to the independent and controllable development of the energy industry. Table 1 shows 10 key technologies and their research and development paths.

Table 1 – Key technologies and their research and development paths

Technical field	Technical name	Research and Development (R&D) Path
Energy extraction	Efficient deep oil and gas extraction technology	Joint research institutions and enterprises will carry out industry university research cooperation, focusing on researching high-temperature and high-pressure resistant mining materials and equipment. The plan is to achieve key technological breakthroughs within 5 years and large-scale applications within 10 years
	Segmented fracturing technology for shale gas horizontal wells	Establish a special scientific research fund to support joint research and development between universities and enterprises, develop high-precision fracturing design software and advanced fracturing equipment, with the goal of achieving technological breakthroughs within 3 years and promoting their application within 5 years
Energy transmission	Converter valve technology for ultra-high voltage direct current transmission	Increase R&D investment, introduce advanced foreign technology talents, cooperate with international research teams, improve the reliability and capacity of converter valves, and expect to overcome core technologies within 4 years and achieve domestic substitution within 6 years
	Insulation material technology for submarine cables	Organize industry enterprises to establish joint research and development centers to conduct basic and applied research, develop high-performance insulation materials, and strive to complete technical research and development within 3 years and achieve industrial production within 4 years
Energy storage	Solid state battery technology	Encourage enterprises to increase R&D investment, establish R&D laboratories, cooperate with universities and research institutions, and break through key technologies such as solid-state electrolytes. The goal is to achieve technological maturity within 5 years and large-scale application within 8 years
	Large capacity compressed air energy storage technology	Establish national key research and development projects, integrate advantageous scientific research resources, overcome efficient operation control technology and low-cost material technology of energy storage systems, plan to achieve key technological breakthroughs within 4 years, and construct demonstration projects within 6 years
Energy conversion	Efficient solar cell technology	Support research institutions to conduct cutting-edge research, encourage enterprises to establish research and development centers, develop new photovoltaic materials and battery structures, and strive to improve battery conversion efficiency within 3 years and achieve industrialization within 5 years
	Efficient biomass gasification technology	Increase investment in biomass energy research, establish demonstration bases, develop efficient gasifiers and catalysts, with the goal of achieving technological breakthroughs within 4 years and promoting their application within 6 years
Energy monitoring	Energy Internet security protection technology	Strengthen research on network security technology, establish an energy network security laboratory, develop intelligent monitoring and protection systems, form preliminary technological achievements within 2 years, and promote application within 3 years
	Smart meter chip technology	Concentrate the strength of advantageous enterprises, carry out technological breakthroughs, break through key technologies in chip design and manufacturing, achieve chip localization within 3 years, and improve chip performance within 5 years

In order to achieve breakthroughs in the above-mentioned technologies, it is recommended to allocate 0.8 % of gross domestic product (GDP) to energy and power technology research and development. Based on the total GDP of 126.05 trillion yuan in China in 2023, the investment in energy and power technology research and development should reach 1008.4 billion yuan. By continuously and steadily investing funds, attracting outstanding talents, purchasing advanced equipment, and strengthening international cooperation, it is expected to make significant breakthroughs in key technological fields and enhance the technical guarantee level of China's energy security.

5.2 Infrastructure investment planning. The optimization of power grid investment is crucial for improving energy transmission efficiency and ensuring energy security. Applying genetic algorithm to solve the optimal timing of power grid construction from 2025 to 2035, taking a regional power grid as an example, which includes 10 substations and 15 transmission lines, the goal is to minimize the construction and operation costs of the power grid while meeting the growing demand for electricity.

The encoding method of genetic algorithm adopts binary encoding, representing the construction timing of each substation and transmission line as a gene locus. The initial population is randomly generated, and the fitness function is used to evaluate the strengths and weaknesses of each individual. The fitness function considers factors such as power grid construction costs, operating costs, and power supply reliability. The selection operation adopts the roulette wheel selection method, the crossover operation adopts single point crossover, and the mutation operation adopts positional mutation.

After multiple iterations of calculation, the optimal timing scheme for power grid construction has been obtained. Prioritize the construction of key transmission lines in 2025–2027 to meet the recent increase in electricity demand; From 2028 to 2030, construct some substations and optimize the layout of the power grid; From 2031 to 2035, further improve the construction of transmission lines and substations to enhance the power supply capacity and reliability of the power grid. By optimizing the construction schedule, the total cost of power grid construction can be reduced by 18 %, while improving the reliability of power supply.

According to the electricity demand forecast and power grid development plan, China needs to increase its power grid investment by 4.2 trillion yuan in the next decade. Among them, the investment in the ultra-high voltage transmission project is 1.2 trillion yuan, mainly used to construct cross regional transmission channels and improve the ability to optimize the allocation of energy resources. An investment of 2 trillion yuan will be made in the renovation of the distribution network, with a focus on improving the power supply quality and reliability of urban and rural distribution networks; The investment in smart grid construction is 1 trillion yuan, which will be used to promote the application of advanced information technology and automation technology, and improve the intelligence level of the power grid. Through large-scale investment in the power grid, a stronger, smarter, and more reliable power grid will be built, providing a solid infrastructure guarantee for energy security.

5.3 Design of policy guarantee system. Establish a dynamic policy evaluation model and set 15 policy effectiveness evaluation indicators, including energy consumption structure optimization indicators (such as the proportion of clean energy and coal consumption), energy utilization efficiency indicators (such as energy consumption per unit of GDP and energy processing and conversion efficiency), and energy supply security indicators (such as oil and gas dependence on foreign countries and electricity supply reliability). Set reasonable adjustment thresholds for each indicator based on policy objectives and actual situations.

Propose a combination of eight policy tools, including carbon tax and green finance, to promote the implementation of energy security strategies. The carbon tax policy imposes taxes on carbon emissions, increases the cost of using fossil fuels, incentivizes companies and society to reduce carbon emissions, and promotes the transformation of the energy structure towards low-carbon. Green finance policies include green loans, green bonds, green insurance, etc., which guide the flow of funds towards clean energy, energy conservation and consumption reduction through financial means, and support the green development of the energy sector.

The renewable energy subsidy policy continues to provide subsidies for renewable energy generation such as wind power and photovoltaics, reducing the cost of renewable energy generation and improving its market competitiveness; The policy of controlling the total amount of energy consumption sets an upper limit on the total amount of energy consumption, strengthens the control of energy consumption, and promotes energy conservation and efficient utilization; The energy price reform policy gradually improves the mechanism for forming energy prices, reflecting the scarcity of energy and environmental costs, and guiding rational energy consumption; Industrial policies encourage energy enterprises to increase investment in technological innovation, support the development of energy equipment manufacturing industry, and enhance the core competitiveness of the energy industry; Strengthen strategic energy reserves such as oil and natural gas through energy reserve policies, and enhance the ability to cope with energy supply disruptions; The international cooperation policy actively participates in international energy cooperation, strengthens communication and coordination with energy producing and consuming countries, and maintains stability in the international energy market. By comprehensively utilizing these policy tools, a policy synergy is formed to promote the effective implementation of China's energy security strategy.

Conclusions. The article proves that China's modern energy system remains vulnerable due to its overdependence on traditional energy sources, in particular coal (56.4 % of energy consumption) and imported oil (72.6 %), which poses significant threats to energy security in the context of geopolitical instability and climate challenges. The introduction of innovative technologies, such as smart grids, ultra-high voltage lines, virtual power plants and energy storage systems, can improve the efficiency of energy transmission by 18 %, increase the total capacity of virtual stations by 40 % and achieve an internal rate of return (IRR) in lithium batteries of 8.7 %. Economic calculations confirm the feasibility of developing hydrogen energy: the cost of transporting green hydrogen 500 km is 35 yuan/kg, and the compensation tariff is 0.08 yuan/kW. Practical results also confirm the effectiveness of the proposed solutions: the failure rate of new power lines in northwestern China has dropped to 3.2 %, and the use of 12 GW of storage in the Yangtze Delta has reduced peak load by 15 %. In addition, the cost of hydrogen production from offshore wind power decreased to 0.3 yuan/kWh. In order to achieve long-term energy stability, the article proposes to invest 0.8 % of GDP in scientific and technological development, to provide for the modernization of power grids worth 4.2 trillion yuan in the next decade, and to create an adaptive political monitoring system. Overall, the study forms a systematic technical approach to strengthening China's energy security in the context of the global energy transition.

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ДОСЛІДЖЕННЯ СИСТЕМНОЇ ОПТИМІЗАЦІЇ ТА СТРАТЕГІЧНОГО ШЛЯХУ ЕНЕРГЕТИЧНОЇ БЕЗПЕКИ КИТАЮ З ТОЧКИ ЗОРУ НОВИХ ДОСЯГНЕНЬ В ЕЛЕКТРОТЕХНІЦІ

У статті представлено комплексне дослідження енергетичної безпеки Китаю з техніко-економічної точки зору, з урахуванням сучасних викликів і стратегічних цілей енергетичного переходу. Основна увага приділена кількісному аналізу структурних проблем, що загрожують стабільності енергетичної системи. Зокрема, на основі даних 2023 року встановлено, що структура енергоспоживання залишається залежною від викопного палива: частка вугілля становить 56,4 %, а імпортна залежність нафти — 72,6 %. Крім того, виявлено ймовірність перевантаження електричних мереж за екстремальних погодних умов на рівні 7,3 %, що вказує на вразливість системи до кліматичних змін. У дослідженні змодельовано ефективність впровадження технологій Smart Grid, які дозволили підвищити ефективність передавання енергії надвисокою напругою на 18 %. Також зафіксовано приріст сукупної потужності віртуальних електростанцій на 40 % і підвищення внутрішньої норми доходності систем зберігання енергії на базі літієвих акумуляторів до 8,7 %. З погляду довгострокового стратегічного планування, запропонована модель мультиенергетичних потоків оцінює вартість транспортування 500 км зеленого водню на рівні 35 юанів/кг, а також формує стандартизований механізм компенсації потужності (0,08 юанів/кВт). Емпіричні результати підтверджують доцільність таких заходів: рівень відмови від нових ліній електропередавання у північно-західних регіонах знижено до 3,2 %, а впровадження систем зберігання енергії потужністю 12 ГВт у дельті Янцзи дозволило зменшити пікове навантаження на 15 %. Також продемонстровано, що собівартість виробництва водню з офшорної вітроенергетики досягла 0,3 юаня/кВт·год, або 35 юанів/кг з урахуванням ринкових тарифів на електроенергію. У статті запропоновано стратегічні заходи для забезпечення енергетичної безпеки, зокрема інвестиції в науково-технічні розробки у розмірі 0,8 % ВВП, модернізацію електромереж з обсягом фінансування у 4,2 трильйона юанів на найближчі 10 років, а також створення адаптивної системи політичного моніторингу. Надані результати формують основу для системного електротехнічного підходу до забезпечення енергетичної стійкості Китаю в умовах глобальних трансформацій.

Ключові слова: енергетична безпека; електротехніка; Smart grid; мультиенергетична взаємодоповнюваність; цифровий двійник.