

The Impact Mechanism Research of Integrated Development of Electricity, Computing Power and Energy Storage Based on Mediating Effect Model Inspection

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ABSTRACT

Against the backdrop of the global energy transition and the in-depth advancement of the digital economy, the integrated development of electricity, computing power and energy storage has emerged as a core pathway to achieving energy security, digital transformation, and low-carbon development. This paper presents a theoretical analysis framework to examine the impact of integrating electricity, computing power, and energy storage, focusing on its direct effects on upgrading the regional industrial structure, improving energy efficiency, and constructing a new type of electricity system, as well as its indirect effects mediated by technological innovation, industrial agglomeration, and the intensity of policy support. Using panel data from 30 Chinese provinces from 2016 to 2025, the paper empirically tests the multi-path impact mechanism of electricity, computing power, and energy storage integration. Stepwise regression and bootstrap tests are adopted for the mediating effects model. The results show that: (1) the electricity, computing power and energy storage integration have a significant positive direct impact on regional high-quality development, which is more pronounced in regions with advanced digital infrastructure and superior energy resources. (2) Technological innovation and industrial agglomeration partially mediate the impact path of the electricity, computing power and energy storage integration, whereas the mediating effect of policy support intensity is insignificant. (3) The mediating effects vary across different regions. Specifically, technological innovation plays a stronger mediating role in eastern China, while industrial agglomeration has a more significant impact in central and western China. This paper clarifies the transmission path of electricity, computing power and energy storage integration, providing empirical evidence and policy implications for optimizing the integrated industrial development model and promoting high-quality economic growth.

INTRODUCTION

The dual-carbon target and the digital economy strategy have driven the deep integration of the energy and digital sectors. Electricity forms the basis of the energy supply, computing power is essential for digital development and energy storage is crucial for balancing supply and demand Muñoz et al. (2025). These three elements are interconnected and mutually reinforcing, forming an industrial ecosystem Alam et al. (2024). In recent years, countries around the world have accelerated the deployment of the electricity, computing power and energy storage integration (hereinafter referred to as "ECES" integration) projects. The European Union has incorporated the integration of renewable energy power generation and data center computing power into its Digital Decade Policy Program, while the United States has promoted the construction of "data center + energy storage" micro grids through the Inflation Reduction

Act Covaci et al. (2025). China's 14th Five-Year Plan for Digital Economy Development proposes coordinating the layout of computing power, electricity grids, and energy storage facilities, and promoting the integrated construction of new-type infrastructure Cui et al. (2025).

Current investigations into ECES integration remain at a preliminary theoretical phase, presenting several notable constraints. Initially, while numerous studies examine the technical viability and financial advantages of isolated integration models (such as "solar power + storage systems + computing facilities"), they fail to comprehensively assess the holistic influence dynamics of such integration. Additionally, prevailing empirical research predominantly employs basic statistical descriptions or straightforward regression techniques, overlooking the critical function of intermediary factors like technological advancements and sectoral clustering

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within the causal chain Covaci et al. (2023). Furthermore, minimal attention has been given to examining geographical variations in integration outcomes. Consequently, developing a conceptual model that accounts for both immediate and secondary influences, along with rigorous validation of ECES integration's multifaceted impact pathways through mediation analysis, has become imperative.

MATERIALS AND METHODS

Research Significance

1. Theoretical Significance

Firstly, this paper broadens the research perspective on the integration of the energy and digital industries by constructing a systematic analytical framework for the impact mechanism of the ECES integration. This framework enriches the theoretical system of industrial synergy development. Secondly, by introducing technological innovation, industrial agglomeration and the intensity of policy support as mediating variables, the paper reveals the internal transmission path of the role of integration Sardjono et al. (2024), compensating for the deficiency of existing studies that focus only on direct effects. Thirdly, the paper explores regional heterogeneity in the mediating effect, providing a theoretical basis for the targeted formulation of regional development policies.

2. Practical Significance

For policymakers, the study's findings offer valuable insights for refining the spatial distribution of ECES integration, developing region-specific regulatory frameworks, and enhancing administrative effectiveness. From a corporate perspective, the analysis identifies fundamental approaches to strengthen integration capabilities, including boosting R&D expenditure on critical technological innovations and engaging in industrial cluster development initiatives. Regarding power infrastructure, the research outcomes substantiate the feasibility of establishing advanced electrical networks capable of accommodating substantial renewable energy integration and adaptive demand-side management.

Literature Review

The convergence of electrical infrastructure, computational resources, and energy storage solutions represents a pivotal strategy for facilitating sustainable energy transitions and fostering digital economic expansion. This interdisciplinary field has garnered substantial interest from both scholarly circles and industrial sectors in contemporary times. Our comprehensive analysis methodically organizes existing studies concerning the conceptual framework, underlying influence dynamics, and implementation

trajectories of this synergistic approach, while identifying current research deficiencies and proposing prospective investigation avenues.

The Connotation And Evolution Of Integrated Electricity, Computing Power And Energy Storage Development

1. Connotation Definition

Integrated electricity, computing power and energy storage development is a systematic project involving multiple fields, such as energy, information and the digital economy. Taking the new electricity system as support, it guides the high-quality development of computing infrastructure and the construction of a national integrated computing network Holdyński et al. (2023).

The project aims to optimize computing power and electricity in industrial planning, production, operation, resource scheduling and market systems by promoting technological and institutional innovations such as intelligent scheduling, source-grid-load-storage integration, new power supply and backup, and green power aggregation and supply Kolsi et al. (2022). The core objective is to establish an advanced green computing center cluster that can match supply and demand, is environmentally friendly and low-carbon, and is safe and reliable Stojic et al. (2025). This will support the flexible regulation and digital transformation of the electricity system, while also promoting the high-quality development of the digital and energy economies.

2. Evolution Stage

The integrated development of electricity, computing power and energy storage is a gradual process involving exploration, primary development, coordination and integration. This process can be divided into four main stages. The initial exploration stage is characterized primarily by the independent development of the three fields, with only sporadic cooperation and exploration Baesmat et al. (2025).

During the initial development stage, connections between electricity and computing power begin to emerge, and energy storage is gradually adopted as an auxiliary means Gajdzik et al. (2024). During the deep coordination stage, the three fields establish relatively close cooperative relationships and continuously improve technologies and mechanisms such as source-grid-load-storage integration and computing power load scheduling. The comprehensive integration stage sees the deep integration of electricity, computing power and energy storage, realizing the seamless connection and optimal allocation of resources throughout the entire chain and forming a new development pattern of mutual promotion and coordinated growth Liu et al. (2025).

Impact Mechanism of The Integrated Development of Electricity, Computing Power and Energy Storage

1. Technical Impact Mechanism

Source-Load Interaction Mechanism: The consumption capacity of renewable energy is improved through interaction between electricity sources and computing power loads Wang et al. (2024). As high-energy consumers, computing power centers have flexible load characteristics and can adjust their electricity consumption according to the output of renewable energy, thereby promoting balance and consumption of renewable energy.

Storage-load interaction mechanism: Energy storage systems interact with computing power centers to enhance the reliability and efficiency of power consumption in these centers. On the one hand, energy storage systems can participate in grid peak regulation and obtain economic benefits through market mechanisms, such as price differences between peak and off-peak periods, for computing power enterprises. On the other hand, energy storage systems can be used as emergency electricity sources, improving the reliability of the electricity supply for computing power centers.

Grid-load coordination mechanism: Relying on grid-load coordination improves the safety and reliability of the electricity supply and distribution network, and promotes the digital and intelligent operation of the electricity grid Xiong et al. (2024). Strengthening the coordination between computing power loads and the electricity grid enables the grid to adapt more effectively to changes in computing power loads, improving the efficiency of electricity transmission and distribution and ensuring the grid's safe and stable operation Sapnken et al. (2024).

2. Economic Impact Mechanism

Cost reduction and efficiency increase mechanism: The integrated development of electricity, computing power and energy storage can reduce computing power and energy costs, improving economic efficiency. For instance, locating computing power centers near new energy electricity stations can minimize local clean power consumption and reduce electricity transmission losses Sun et al. (2025). Energy storage systems can help computing power enterprises reduce electricity costs by taking advantage of peak-valley price differences.

Industrial agglomeration and upgrading mechanism: Integrated development can drive the agglomeration and upgrading of related industries, forming a new economic growth point. Building green computing center clusters can stimulate the growth of industries such as information transmission services,

electricity equipment manufacturing, and energy storage technology research and development, promoting the transformation and upgrading of the industrial structure Yang et al. (2025).

Market expansion mechanism: Integrated development can expand the market space of the electricity and computing industries. Developing green electricity and green certificate transactions can increase the proportion of renewable energy used by computing power centers and promote the growth of the green power market Gerlici et al. (2025). Construction of computing power scheduling platforms and trading markets can facilitate the on-demand allocation and sharing of computing power resources and expand the computing power service market Zhu et al. (2025).

3. Environmental Impact Mechanism

Carbon emission reduction mechanism: Integrated development can promote large-scale renewable energy production and consumption, thereby reducing carbon emissions. Data centers consume a large amount of power, and using green energy can effectively reduce their carbon footprint Trinh et al. (2022). Energy storage systems can help the power grid absorb more renewable energy, reducing the need for fossil fuel power generation and thus lowering carbon emissions Cheng et al. (2026), Shao et al. (2025).

Energy conservation and emission reduction mechanism: Integrated development can improve energy utilization efficiency and reduce waste. The application of advanced cooling technologies in computing power centers can reduce cooling energy consumption Iqbal et al. (2025), Yang et al. (2024). Optimal allocation of energy resources through intelligent scheduling and other technologies can also improve efficiency and reduce waste.

Research Gaps

1. Lack Of Systematic Theoretical Research

Although some studies have been conducted on the integrated development of electricity, computing power and energy storage, there is a lack of systematic theoretical research on their connotations, impact mechanisms and development paths. There is also no unified theoretical framework or research paradigm.

2. Insufficient Empirical Research

Most existing studies are qualitative analyses and insufficient empirical research has been conducted to verify the effectiveness of impact mechanisms. The limited availability of data and cases on integrated development affects the accuracy and reliability of the research results.

3. Inadequate Research on Policy and Institutional Support

The integrated development of electricity, computing power and energy storage requires the support of relevant policies and institutions. However, existing research on this topic is insufficient, with a lack of in-depth research on policy formulation, implementation paths and institutional innovation.

In a word, the literature on the electricity, computing power and energy storage integrated development lacks coherence in theory, rigor in empirics, and comprehensiveness in impact assessment. Closing these gaps requires interdisciplinary collaboration across energy economics, computer science, and public policy, with a focus on developing holistic, data-driven, and policy-relevant research agendas Catarino et al. (2025).

Research Content, Framework and Methods

Research Content

The main research content of this paper includes: defining the connotation and measurement index system of the ECES integration; constructing a theoretical framework of the impact mechanism of the ECES integration, and proposing research hypotheses based on the identification of mediating variables; empirically testing the direct impact and mediating effect of the ECES integration by using panel data and mediating effect model; putting forward targeted policy suggestions based on the research results.

Research Framework

This paper adheres to the following logical structure: "theoretical construction → hypothesis formulation → empirical testing → conclusion and policy implications". First, a theoretical analysis framework is constructed for the impact mechanism of the ECES integration, with research hypotheses proposed about direct and mediating effects. Secondly, variables are defined, a mediating effect model is constructed, and panel data are selected for empirical testing. Thirdly, robustness tests and a heterogeneity analysis are conducted to verify the reliability of the conclusions. Finally, it summarizes the research findings and puts forward policy recommendations.

Research Methods

1. Theoretical Analysis Method

This paper uses theories of industrial synergy, technological innovation and resource allocation to analyze the direct and indirect impact paths of the ECES integration.

2. Empirical Analysis Method

This paper uses the stepwise regression method and the

bootstrap test to empirically test the mediating effects of technological innovation, industrial agglomeration and the intensity of policy support.

3. Heterogeneity Analysis Method

The paper divides the research samples into eastern, central and western regions in order to explore regional differences in the mediating effect.

Theoretical Framework and Research Hypotheses

The Core Connotation of the ECES Integration

The ECES integration is a dynamic process involving the sharing of resources, functional complementarity and coordinated development between the electricity industry, the computing power industry and the energy storage industry. This is achieved through technological coupling, institutional coordination and market interaction. Its core connotation includes three aspects:

Technological Coupling

This involves integrating electricity generation, transmission, and distribution technologies with computing power, scheduling, data processing, and energy storage conversion technologies. Examples include the application of artificial intelligence to coordinate the scheduling of electricity and computing, and combining electrochemical energy storage with data center peak shaving.

Industrial Synergy

An industrial chain ecosystem is being formed that covers electricity generation, energy storage, data center construction, computing power operation and demand response. This ecosystem will promote the development of both the upstream and downstream industries.

Policy Coordination

Supporting policies should be formulated in areas such as market access, price mechanisms and subsidy policies. This will help to break down institutional barriers between industries and promote the flow of factors such as capital, technology and talent between them.

The Direct Impact Mechanism of The ECES Integration

The ECES integration directly affects regional high-quality development through three channels:

Optimizing The Industrial Structure

The integration promotes the development of high-end industries, such as new energy power generation, energy storage equipment manufacturing and cloud computing. This drives the transformation of the industrial structure

from labour-intensive and capital-intensive to technology-intensive.

Improving Energy Efficiency

The coordinated scheduling of electricity and computing power realizes peak shaving and valley filling of energy demand, while energy storage facilities reduce waste from renewable energy generation, thereby improving the region's overall energy utilization efficiency.

Promoting The Construction of a New-Type Electricity System

The integration enhances the flexibility and stability of the electricity system, supports high levels of renewable energy penetration, and promotes the transformation of the electricity system from traditional supply-led to demand-responsive Vandevenne et al. (2023).

Based on the above analysis, this paper proposes the following hypothesis:

Hypothesis H1: The ECES integration has a significant positive direct effect on regional high-quality development.

The Mediating Impact Mechanism of The ECES Integration

The ECES integration has a direct effect and an indirect impact on regional high-quality development, mediated by variables such as technological innovation, industrial agglomeration and the intensity of policy support.

The Mediating Role of Technological Innovation

The ECES integration process encourages enterprises to engage in technological innovation in the following ways:

Firstly, the integration of cross-industry technologies creates a greater demand for key technologies such as energy storage conversion efficiency, electricity and computing power coordination, which motivates enterprises to increase their R&D investment.

Secondly, market demand stimulated by the integration process encourages technological innovation, enabling enterprises to achieve higher market returns by developing innovative technologies.

Hypothesis H2: Technological innovation mediates the impact of the ECES integration on regional high-quality development; that is, the ECES integration promotes regional high-quality development by improving the level of technological innovation.

The Mediating Role of Industrial Agglomeration

The ECES integration significantly promotes the agglomeration of related industries. Firstly, integrated development requires the coordinated layout of electricity plants, energy storage stations and data centers, promoting

the spatial agglomeration of related enterprises. Secondly, enterprise agglomeration reduces transaction and transportation costs, promoting the sharing of infrastructure and public services. Thirdly, industrial agglomeration accelerates the flow of factors such as capital, technology and talent, forming a positive cycle of industrial development. Industrial agglomeration further promotes the economies of scale and synergy of the industry, thus promoting regional high-quality development.

Hypothesis H3: Industrial agglomeration plays a mediating role in the impact of the ECES integration on regional high-quality development; in other words, the ECES integration promotes regional high-quality development by accelerating industrial agglomeration.

The Mediating Role Of Policy Support Intensity

Government policy support is crucial for ensuring the success of the ECES integration. The government can promote integration by providing fiscal subsidies, tax incentives and land support policies. However, the impact of the intensity of policy support on the integration effect may be affected by factors such as the efficiency of policy implementation and the regional institutional environment. In regions with a sound institutional environment Rashidi et al. (2025), policy support can effectively guide the flow of resources to the integrated industry. In regions with

an imperfect institutional environment, however, policy support may crowd out market resources, resulting in an insignificant mediating effect.

Hypothesis H4: Policy support intensity may play a mediating role in the impact of the ECES integration on regional high-quality development. However, the mediating effect may be affected by the regional institutional environment and be insignificant.

Research Design

Variable Definition

Explained Variable: Regional High-Quality Development (HQD)

Based on existing research, this paper proposes a system of evaluation indices for regional high-quality development, covering five areas: economic development; innovation; green development; improvement in people's livelihoods; and coordinated development Zhou et al. (2025). The entropy weight method is then used to calculate the overall HQD score.

Core Explanatory Variable: Eces Integration Level (Ice)

This paper proposes a comprehensive evaluation index system for the ECES integration level, considering three dimensions: electricity industry development, computing

power industry development, and energy storage industry development.

1. Electricity Industry Development

Indicators include installed renewable energy electricity generation capacity per capita, electricity transmission and distribution network density, and electricity consumption per unit of GDP.

2. Computing Power Industry Development

The indicators are the number of data center racks per 10,000 people, the size of the cloud computing market, and the broadband penetration rate.

3. Energy Storage Industry Development

Indicators include the installed energy storage capacity per capita, the energy storage equipment output value and the energy storage conversion efficiency.

The entropy weight method is used to calculate the comprehensive score of the ECES integration level.

Mediating Variables

1. Technological Innovation (TI)

It can be measured by the number of invention patents granted per 10,000 people in the region, as well as the R&D investment intensity of industrial enterprises.

2. Industrial Agglomeration (IA):

It can be measured by the location entropy of integrated industries (including electricity, computing power and energy storage).

3. Policy Support Intensity (Psi):

It can be measured by the number of policy documents related to the ECES integration issued by local governments, as well as the proportion of fiscal expenditure on energy and digital infrastructure within the total public budget.

Control Variables

In order to control for the impact of other factors on regional high-quality development, this paper selects the following control variables: per capita GDP (PGDP), urbanization rate (UR), level of openness (OL) and level of human capital (HC).

Model Construction

This paper constructs the following stepwise regression model based on the mediating effect test procedure Rizki et al. (2025):

1. Direct effect model: Testing the impact of the ECES

integration level on regional high-quality development.

$$HQD_{it} = a_0 + a_1 ICE_{it} + \sum a_k Control_{kit} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where: i represents the region, t represents the year; μ_i represents the regional fixed effect; λ_t represents the time fixed effect; ε_{it} represents the random error term.

2. Mediator regression model: The aim is to test the impact of the ECES integration level on the mediating variables.

$$M_{it} = \beta_0 + \beta_1 ICE_{it} + \sum \beta_k Control_{kit} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where: M_{it} represents the mediating variables (TI, IA, PS).

3. Mediating effect model: This model is used to test the impact of the ECES integration level and mediating variables on regional high-quality development.

$$HQD_{it} = \gamma_0 + \gamma_1 ICE_{it} + \gamma_2 M_{it} + \sum \gamma_k Control_{kit} + \mu_i + \lambda_t + \varepsilon_{it}$$

The steps for testing the mediating effect are as follows:

First, test the significance of a_1 in model (1). If a_1 is significant, proceed to the next step.

Second, test the significance of β_1 in model (2).

Third, test the significance of γ_2 in model (3). If both β_1 and γ_2 are significant, the mediating effect exists. If γ_1 is not significant, the effect is complete. If γ_1 is significant, it is a partial mediating effect.

Finally, the bootstrap test is used to verify the significance of the mediating effect.

Data Sources and Descriptive Statistics

This paper uses panel data from 30 Chinese provinces (excluding Tibet, Hong Kong, Macau and Taiwan) from 2016 to 2025 for its research. Data sources include the China Statistical Yearbook, the China Energy Statistical Yearbook, the China Information and Communication Statistical Yearbook, local statistical yearbooks and the database of the State Intellectual Property Office. Descriptive statistics were conducted on all variables to check for outliers and data normality.

RESULTS

Empirical Results and Analysis

Benchmark Regression Results

Direct Effect Regression Results

The regression results for model (1) show that the ICEit coefficient is significantly positive at the 1% level. This indicates that ECES integration has a positive direct effect on regional high-quality development, thus verifying Hypothesis H1. This is likely because the ECES integration optimizes the allocation of energy and digital

resources, promotes industrial restructuring, and improves energy utilization efficiency, thereby enhancing regional high-quality development.

Mediating Effect Regression Results

1. Mediating Effect of Technological Innovation

The regression results for model (2) show that the ICEit coefficient on Tlit is significantly positive at the 1% level. The regression results for model (3) show that both the ICEit and Tlit coefficients are significantly positive at the 1% level. This indicates that technological innovation plays a partial mediating role in the impact of the ECES integration on regional high-quality development. This verifies Hypothesis H2.

2. Mediating Effect of Industrial Agglomeration

The regression results for model (2) show that the ICEit coefficient on Iait is significantly positive at the 5% level. The regression results for model (3) show that both the ICEit and Iait coefficients are significantly positive at the 5% level. This indicates that industrial agglomeration plays a partial mediating role in the impact of the ECES integration on regional high-quality development. This verifies Hypothesis H3.

3. Mediating Effect of Policy Support Intensity

The regression results for model (2) show that the ICEit coefficient on PSit is not significant. Similarly, the regression results for model (3) show that the PSit coefficient is not significant. This indicates that the mediating effect of policy support intensity is insignificant, thus verifying Hypothesis H4. This may be because the current policy support for the ECES integration is not targeted enough and the efficiency of policy implementation in some regions is low.

Bootstrap Test Results

To avoid the issue of low statistical power in stepwise regression, this paper employs the bootstrap method with 5,000 repetitions to test the mediating effects. The results show that the 95% confidence interval for the mediation effect of technological innovation and industrial agglomeration does not include zero, indicating a significant mediation effect. In contrast, the 95% confidence interval for the mediation effect of policy support intensity does include zero, suggesting an insignificant mediation effect. These results are consistent with those of the stepwise regression analysis, which further verifies the reliability of the conclusions.

Heterogeneity Analysis

Regional Heterogeneity Analysis

This paper categorizes the research samples by eastern, central and western regions for regression analysis.

The results show that: In the eastern region, the mediating effect of technological innovation is significant, whereas the mediating effect of industrial agglomeration is not. This may be because the eastern region has a high level of technological innovation and the ECES integration primarily promotes regional high-quality development through technological innovation.

In the central and western regions, industrial agglomeration has a more significant mediating effect, whereas technological innovation does not. The possible reason is that the central and western regions have a low level of technological innovation, and the ECES integration primarily promotes regional high-quality development through industrial agglomeration.

Development Stage Heterogeneity Analysis

This paper categorizes the research samples according to the median of the ECES integration level, dividing them into regions with high and low integration levels. The results show that the mediating effect of technological innovation and industrial agglomeration is more significant in regions with a high integration level than in regions with a low integration level. This may be because regions with a high integration level have established a robust industrial ecosystem in which the mediating effects of technological innovation and industrial agglomeration can be fully realized.

Robustness Test

This paper adopts the following robustness test methods to verify the reliability of the empirical results:

1. Variable Replacement

The explained variable (regional high-quality development) is replaced by the per capita GDP growth rate, and the core explanatory variable (the three-in-one integration level) is replaced by the number of ECES integration projects in the region. The regression results are consistent with the benchmark regression results.

2. Sample adjustment

Exclude data from municipalities directly under the central government (Beijing, Tianjin, Shanghai and Chongqing) from the regression analysis. The regression results are consistent with the benchmark regression results.

Fixed effect replacement: Replace the two-way fixed effects model with a random effects model in the regression analysis. The Hausman test results indicate that the two-way fixed effects model is more appropriate, and the regression results are consistent with those of the benchmark regression Alecos et al. (2023).

Robustness tests show that the conclusions of this paper are reliable and stable.

CONCLUSIONS

Conclusions And Policy Implications

Research Conclusions

This paper presents a theoretical analysis framework for the impact mechanism of the ECES integration and empirically tests its direct and indirect effects on regional

high-quality development. Panel data from 30 Chinese provinces between 2016 and 2025 were used for this analysis. The main conclusions are as follows:

1. The ECES integration has a significant positive direct effect on regional high-quality development, which is more pronounced in regions with a high level of digital infrastructure and energy endowment.
2. Technological innovation and industrial agglomeration play a partial mediating role in the impact path of the ECES integration, whereas the mediating effect of policy support intensity is insignificant.
3. The mediating effect varies across different regions. Technological innovation plays a stronger mediating role in eastern regions, while industrial agglomeration has a more significant impact in central and western regions.
4. The mediating effect of technological innovation and industrial agglomeration is more significant in regions with a high integration level, and less significant in regions with a low integration level.

Policy Recommendations

Core Principles for Policy Optimization

Guided by the "four revolutions and one cooperation" energy security strategy, policy optimization should adhere to three core principles. The first is systematic coordination, which involves breaking down administrative silos between the energy and digital sectors to enable overall planning and unified deployment from top-level design to local implementation. Secondly, it should be market-driven and policy-supported. This means giving full play to the decisive role of the market in resource allocation and using targeted policy tools to make up for market failures and reduce the cost of collaborative development. Thirdly, pilot first and gradually promote: focus on key areas such as national computing hubs and renewable energy bases, summarize replicable experiences through pilot demonstrations and avoid one-size-fits-all promotion.

Key Directions and Specific Measures for Policy Optimization

1. Improving Top-Level Coordination Mechanisms to Break Down Cross-Sectoral Barriers

The fragmented management of the electricity, computing power and energy storage sectors is the main obstacle to

integrated development Mahnitko et al. (2025). Strengthening top-level design and improving cross-departmental coordination mechanisms is necessary. Firstly, an inter-ministerial joint conference system should be established, led by the National Development and Reform Commission and the National Energy Administration. This system should include the National Data Administration and other relevant departments. The aim is to formulate a special development plan for ECES integration. This plan should clarify development goals, key tasks, and the division of responsibilities. It should also ensure the alignment of policies in planning, approval, and supervision. Secondly, ECES integration should be promoted in national and local development plans to realize the ECES coordinated planning of electricity grids, computing clusters, and energy storage facilities. For example, when planning national computing hub nodes, supporting green power supply and energy storage configuration plans must be prepared simultaneously and linked to the computing power project approval process.

At the local level, encourage the establishment of regional coordination platforms. In regions with plentiful renewable energy, such as Qinghai and Inner Mongolia, consider merging energy and digital management departments to achieve unified scheduling and management of electricity and computing resources, and encourage the local consumption of locally generated green power for computing projects.

2. Innovating Market Mechanisms to Enhance Economic Viability

The lack of effective market incentives and unreasonable price signals are important factors that restrict the participation of market entities in ECES integration. In order to improve the economic viability of integrated projects, it is necessary to innovate market mechanisms Bae et al. (2025).

Firstly, the green power trading system for computing power should be improved. The scope of direct green power trading should be expanded to allow data centers and other computing power entities to participate directly in green power transactions. A "green power certification – computing power consumption" linkage mechanism should also be established. For example, a pilot scheme could be introduced to issue "green computing certificates" for computing power projects that use green power, supporting their use for carbon emission accounting and policy incentives.

Simultaneously, optimize cross-provincial green power transaction costs by reducing or exempting additional fees, such as cross-provincial transmission and distribution fees, for green power used by computing power projects. Narrow the price gap between green and thermal power. Secondly, improve the price incentive mechanism for energy storage and flexible load. Implement differentiated

time-of-use electricity prices for computing power facilities and increase the peak-valley price difference to encourage the shifting of computing power loads to off-peak times. Incorporate energy storage supporting computing power projects into auxiliary service markets, such as peak shaving and frequency modulation. Clarify the compensation mechanism for energy storage participation in market transactions. For data centers with flexible load regulation capabilities, explore implementing "demand response incentive prices" and provide financial subsidies or electricity price discounts based on their contribution to grid stability.

3. Strengthening Technological Innovation and Standard System Construction

Technological bottlenecks and inconsistent standards hinder the efficient integration of ECES. Therefore, it is necessary to strengthen policy support for technological innovation and accelerate the development of a unified standard system.

Firstly, increase financial support for key technological research and development. Special funds should be allocated to support the research and development of core technologies, such as AI-driven joint forecasting of computing power load and renewable energy output, flexible load control systems for intelligent computing centers, and long-duration energy storage technologies (such as compressed air and flow batteries). Encourage enterprises, universities and research institutes to establish innovation consortia to drive collaborative innovation and accelerate the industrialization of technological achievements. For example, support the establishment of a national ECES integration technology innovation center to address key technologies such as intelligent scheduling and efficient energy storage.

Secondly, establish a unified technical standard system. Accelerate the development of standards for the grid connection of ECES integrated systems and the technical requirements for the energy storage configuration of computing power projects. Also, develop green power traceability for computing services. Clarify the technical specifications for integrating electricity systems and computing power networks, unify data formats and transmission protocols, and reduce the cost of cross-system data interaction. One example would be to formulate the "Technical Specifications for Source-Grid-Load-Storage Integrated Operation of Data Centers" to standardize the energy storage configuration ratio, the technical requirements for demand response participation, and the operational safety standards. Thirdly, promote pilot demonstrations of integrated technologies. Focus on national computing hub nodes and renewable energy bases, launching a number of ECES integration demonstration projects based on the "distributed new energy + energy storage + intelligent computing center" and "virtual electricity plant + computing power cluster" models.

Summarize successful experiences and promote technological iteration and model replication.

4. Optimizing Regional Layout Policies to Promote Coordinated Development

Taking advantage of the "East Data, West Computing" project, optimize regional layout policies to promote the coordinated development of ECES integration between the east and west Yang et al. (2025).

Firstly, strengthen policy incentives for western regions. Offer preferential policies regarding land use, taxation and electricity prices to computing power projects in western green electricity bases, in order to attract computing power resources to the west. For instance, in Ningxia and Inner Mongolia, implement preferential electricity prices for green power used by computing power projects and streamline the approval process for integrated projects. At the same time, accelerate the construction of supporting infrastructure, such as electricity grids and communication networks, in the west to improve the capacity of computing power projects.

Secondly, guide the eastern regions in carrying out incremental optimization. For computing power projects in the eastern regions where the electricity supply is limited, encourage the development of new distributed energy sources and energy storage facilities, and promote the "local green power supply" model. In the Yangtze River Delta and Pearl River Delta regions, for example, support the construction of 'green computing parks' integrating distributed photovoltaic electricity generation, energy storage and data centers to improve local green power absorption capacity.

Thirdly, strengthen cross-regional resource allocation. Accelerate the construction of ultra-high-voltage transmission channels connecting western green power bases and eastern computing power demand centers. Improve cross-regional electricity transmission capacity and scheduling flexibility to realize the optimal allocation of green power resources and computing power demand across regions.

5.Improving Safety Supervision Policies to Guard Against Development Risks

ECES integration involves electricity security, data security and multiple other fields. It is therefore necessary to improve safety supervision policies to ensure stable development. Firstly, the safety of the electricity supply for computing power projects must be strengthened. Mandatory standards for energy storage configuration should be formulated for large and extra-large data centers, requiring the energy storage capacity to meet emergency electricity supply needs for a certain period (such as two hours). The operation safety of energy storage facilities should also be inspected and supervised more closely. Secondly, guide computing power projects to participate

in the construction of virtual electricity plants to improve the electricity system's resilience against extreme weather and other risks.

Secondly, improve data and cyber security supervision. This should involve establishing security supervision standards for ECES integration, clarifying the security requirements for data transmission and storage between electricity systems and computing power networks, and strengthening real-time monitoring of energy flow and computing power load. Promote the use of encryption and block chain technology for green power traceability and data interaction, ensuring data security and privacy.

Thirdly, establish a risk early warning and control mechanism. This should involve strengthening the monitoring and analysis of the ECES integration industry and establishing an early warning indicator system for overcapacity in computing power and energy storage. This will help to avoid blind investment and redundant construction by ensuring strict capacity assessment and project approval.

Policy Guarantee Measures

To ensure the effective implementation of optimized policies, policy guarantees must be strengthened in three areas. Firstly, increase financial support. Expand the scale of special funds for the new energy and digital economies, providing key support for the ECES integration and technological innovation projects. Financial institutions should be encouraged to launch green financial products, such as special loans for ECES integration, and enterprises should be supported in raising funds through green bonds and other channels. Secondly, talent training and introduction must be strengthened. Support universities and vocational colleges in setting up interdisciplinary majors such as "energy-digital integration" to cultivate professionals who are proficient in both energy and digital technologies. Attract high-end talent in related fields through policies such as talent subsidies and project incentives. Thirdly, strengthen supervision and assessment. Establish a mechanism to assess the effectiveness of policy implementation, taking the green power utilization rate of computing power projects, the scale of energy storage configuration and the contribution to grid stability as key indicators. Link the assessment results to policy incentives to ensure that various policies are implemented.

Research Limitations and Prospects

Research Limitations

1. The measurement of the ECES integration level is only based on macro-level indicators, and micro-level indicators (such as the degree of integration enterprises)

are not considered, which may affect the accuracy of the research results.

2. This paper only considers the mediating variables of technological innovation, industrial agglomeration and policy support intensity. Other mediating variables, such as market demand and the institutional environment, are not taken into account, which could result in important impact paths being overlooked.

3. As this paper only conducts empirical research on the domestic situation in China and does not make comparisons with other countries, the conclusions drawn are limited in their universality.

Research Prospects

The following research directions can be carried out in the future:

1. Expand the research sample to include more regions and industries to improve the universality of the conclusions.

2. Explore other mediating and moderating variables (such as policy intensity and marketization level) to enrich the research framework of the impact mechanism.

3. Combine enterprise-level micro data to research the impact mechanism of integrated development at a micro level.

4. Conduct comparative research on integrated development models in different countries and regions to provide more references for China's integrated development practices.

DECLARATIONS

Competing Interests

The authors declare that they have no competing interests.

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Data Availability

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent For Publication

Informed consent was obtained from all individual participants included in the study.

Author Contributions

All authors contributed equally to this work.

Methodology, H.X.; Formal analysis, Y.X.; Data curation, Y.X.; Writing—original draft, H.X. and Y.X.; writing—review and editing, H. X. and Y.X.; All authors have read and agreed to the published version of the manuscript.

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