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Energy, Economy and Environment Relationship Research Review

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Abstract

There exists a mutually influential and restrictive development relationship between energy, economy and environment. How to achieve coordinated development among the three is a difficult problem that governments and academia need to solve. This paper summarizes existing research findings from aspects of energy and economy, energy and environment, economy and environment, as well as energy-economy-environment, and provides prospects for future research directions.It is found that future research in this field can be expanded in terms of research subjects, scope, and depth.

Keywords

Energy; Economy; Environment; Research Review.

1. Introduction

Energy is an important material foundation for human survival and development. Economic growth relies on adequate energy supply, while effective energy exploitation and utilization prerequisites economic development. Moreover, environmental quality affects the sustainability of economic development and energy use. Since the 21st century, while enjoying economic development achievements, countries worldwide have also been bearing enormous environmental pressure - carbon dioxide emissions mainly from fossil fuel combustion continue to rise, leading to declining air quality, intensifying greenhouse effects and other emerging environmental issues. These environmental pollutions affect human health and the entire natural ecosystem, resulting in persistently high treatment costs that constrain economic development. How to properly coordinate the relationship between energy consumption, economic development and ecological environmental protection has become a difficult problem that governments and academia need to solve.

Since China's reform and opening up, the country has achieved miraculous high-speed economic growth in human economic history, with an average GDP growth rate of 9.1% from 1978 to 2022. However, the rapid GDP growth has brought severe environmental damage and extreme energy waste. As the world's largest energy consumer and second largest economy, China's coordinated development of energy-economy-environment system has become a global focus. President announced at the 75th UN General Assembly that China aims to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. To achieve this goal and promote green low-carbon transformation, China has established and continues to implement the "1+N" policy system, including "Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality", "Action Plan for Carbon Dioxide Peaking Before 2030", as well as carbon peaking implementation plans and supporting policies for energy, industry, transportation and other sectors. These plans and policies play an important role in promoting China's achievement of dual carbon goals. However, China still faces arduous tasks in energy conservation and emission reduction, with pressures from energy and environment severely

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constraining sustainable economic development. This has prompted Chinese scholars to conduct research on energy-economy-environment relationships.

Against this background, this paper reviews domestic and international literature on energy-economy-environment relationships. Through literature review, we organize the content from four aspects: first, research on energy-economy relationship; second, research on energy-environment relationship; third, research on economy-environment relationship; and lastly, research on integrated energy-economy-environment system.

2. Current Research Status at Home and Abroad

2.1. Research on Energy-Economy Relationship

The first oil crisis in the 1970s, when OPEC imposed oil embargo on Western countries leading to soaring oil prices and subsequent global economic recession, made countries worldwide realize the close connection between energy supply security and economic stability. This prompted academia to focus on the relationship between energy and economy. Literature review shows that early foreign scholars mainly analyzed the causal relationship between energy and economic growth through Granger causality test and cointegration theory[1]. For example, Kraft A and Kraft J (1978)[2] first discovered through cointegration analysis a unidirectional causality from US GNP to energy consumption but not vice versa, indicating energy conservation policies would not affect GNP growth. Subsequently, many scholars conducted related research on this conclusion but obtained different results. Among them, Bhartendu (1987)[3], Asafu-Adjaye (2000)[4], Mehrara (2007)[5] supported Kraft A and Kraft J's conclusion through empirical research. However, Akarca and Long(1980)[6], Yu and Hwang(1984)[7], Stern(1993)[8] and others obtained different conclusions through their research, making the relationship between energy consumption and economic growth controversial.

Inspired by foreign research, domestic scholars also conducted studies on this topic. Han Zhiyong et al. (2004)[9] were among the first Chinese scholars to study the cointegration and causality between China's energy and economy, finding bidirectional causality between energy consumption and economic growth but no long-term cointegration. Liu Haiying and Zhao Ying (2011)[10] explored the relationship between energy consumption and China's economic growth using Granger causality test and cointegration analysis, finding energy consumption is an important driver of economic growth but economic growth does not significantly drive energy consumption. Guo Sidai et al. (2012)[11] also used Granger causality test and found unidirectional causality between new energy consumption and economic growth in the short term, but this transforms into bidirectional causality in the long term. Evidently, scholars have not reached consensus on the relationship between China's energy and economic growth.

In recent years, with deepening research, domestic and international methods and models for analyzing energy-economy relationships have become more diverse. Internationally, Namahoro et al. (2021)[12] examined the impact of renewable energy consumption on economic growth in Rwanda during 1990-2015 using NARDL model, showing positive effects of renewable energy consumption on economic growth. Han (2022)[13] used PVAR model to compare and quantitatively describe the relationship between economic growth and energy consumption in developed and developing countries during 1990-2009, finding energy consumption significantly drives economic growth in developing countries but not evidently in developed countries. Shahbaz et al. (2023)[14] examined the roles of energy imports, renewable energy consumption, non-renewable energy consumption, capital, trade openness and other factors in domestic production function for 15 energy-importing countries during 1995-2015. Results showed positive impacts of renewable energy consumption, non-renewable energy

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consumption, trade openness and capital on economic growth, while energy imports negatively affected economic growth.

Domestically, Shao Shuai et al. (2019)[15] established output density model with energy consumption as input factor and CO_2 emissions as undesirable output factor, and examined the relationship between economic agglomeration and carbon emissions using mediation effect model and Dubin model, finding an inverted "N" relationship between economic agglomeration and carbon emissions. Dong Yu (2020) established LSTVAR model and used GIRF generalized impulse response function to explore the dynamic evolution of China's industrial economic growth and energy consumption, finding bidirectional impact effects between energy consumption and industrial economic growth in different periods. She Qunzhi and Wu Liu (2022)[16] used panel data of 99 countries during 1990-2019 to establish dynamic panel model exploring digital economy's impact on carbon emissions, finding digital economy development positively affects carbon reduction at both national and industrial levels. Jiang Kun and Wang Baoling (2023)[17] extended resource-centered DSGE model to analyze impacts of renewable energy substitution rate shock and energy efficiency shock on major macroeconomic variables. Research found strengthening effects on macroeconomy with rising renewable energy substitution rate as energy efficiency improves. Pang Jun et al. (2024)[18] established Tapio decoupling model to analyze decoupling status and spatiotemporal evolution between coal consumption and economic growth across provinces (regions, municipalities), finding most regions in weak decoupling state.

2.2. Research on Energy-Environment Relationship

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After the Industrial Revolution, people ignored ecological environmental carrying capacity for a long time during economic development, gradually forming a "pollute first, treat later" development model. With massive development and utilization of traditional fossil energy, the ecological environment was severely damaged. Under global energy transition background, research interest in energy-environment relationship continues to rise. How to protect our planet while developing and utilizing energy has become an important global issue.

Internationally, Masih et al. (1997)[19] pointed out that technological progress is an important factor affecting development of energy and environmental systems. Syri et al. (2001)[20] linked results from energy model PRIMES with integrated environmental assessment model RAINS to compare three EU energy demand scenarios to 2010 and analyzed their impacts on carbon emissions, acidification and ground-level ozone emissions. Liu Zhao et al. (2016)[21] combined DEA model with window analysis to measure energy-environmental efficiency of road and railway sectors in 30 Chinese provinces, finding both sectors had high environmental efficiency but railway sector had higher probability of improving energy-environmental efficiency. Niu Xiaoyan et al. (2022)[22] investigated influencing factors of renewable energy transition in 21 OECD countries during 1990-2020 using econometric estimation methods. Research showed that except GDP hindering green finance transition, strict environmental policies, environment-related taxes and environment-related technology development all promoted renewable energy transition. Wu Shengwen et al. (2023)[23] studied Pakistan's green energy sector with clean energy as dependent variable and green energy resources, product recycling, CO_2 emissions as independent variables. Using correlation matrix and multiple regression analysis, they determined relationships between green energy, product recycling, CO_2 emissions and clean environment. Results showed significant positive correlations between green energy

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resources, product recycling and clean environment, while significant negative correlation between CO_2 emissions and clean environment.

Domestically, Jiang Wei et al. (2015)[24] established VRS-DEA model with environmental pollution as input variable to measure energy utilization efficiency across Chinese provinces and analyzed influencing factors of energy efficiency under environmental constraints, finding environmental quality significantly impacts energy efficiency performance under environmental constraints. Yin Xiuqing and Zhang Feng (2019)[25] examined impacts of environmental regulation and technological innovation on manufacturing energy consumption structure through two-stage regression model, finding negative shock effect of environmental regulation-induced technological innovation on manufacturing energy consumption structure equilibrium. Tang Ruifeng and Suo Jian (2021)[26] studied impact of energy consumption on atmospheric emissions in Yunnan Province through VAR model from regional perspective, finding increased natural gas and primary electricity consumption helps improve environment in short term, but improvement effect lacks long-term effectiveness due to industrial structure characteristics. Fan Qiufang and Zhang Yuanyuan (2023)[27] established fixed effects model and difference-in-differences model to study impacts of command-and-control and market-incentive environmental policy tools on carbon productivity, finding both types significantly improved carbon productivity. Zheng Yuwen and Zhang Qingfen (2024)[28] quantitatively studied impact of coordinated pollution reduction and carbon reduction promotion on China's textile industry energy and environmental performance using data envelopment analysis, finding coordination helps improve performance but environmental performance improvement faces greater pressure.

2.3. Research on Economy-Environment Relationship

Economic activities, especially production and consumption in industrialization and modernization processes, often put pressure on the environment through pollutant emissions, natural resource consumption, etc. Without control, such negative impacts can lead to environmental degradation, which in turn affects sustainable economic development. Coordinating economic development and environmental protection has reached consensus among scholars worldwide. Grossman and Krueger (1992)[29] first discovered an inverted U-shaped relationship between economic growth and environmental pollution, meaning environmental quality initially deteriorates with economic growth but improves after economic growth reaches a certain level. This became the famous Environmental Kuznets Curve (EKC). Subsequently, research on economy-environment relationships mostly revolved around this curve.

Many domestic and international scholars have verified the existence of EKC curve. For example, internationally, Orubu and Omotor (2011)[30] investigated the relationship between per capita income and environmental degradation in Africa using longitudinal data of suspended particulate matter and organic water pollutants. Empirical results generally showed Environmental Kuznets Curve exists for suspended particulates. He Xiaoping and Yao Xin (2017)[31] analyzed impacts of economic growth and foreign direct investment (FDI) on air pollutant emissions using panel smooth transition regression. Per capita income showed inverted U-shaped relationships with smoke and dust emissions, confirming the Environmental Kuznets Curve (EKC) hypothesis. Nguyen and Doytch (2022)[32] conducted empirical analysis on 95 global economies examining impact of economic complexity on ecological footprint, finding an economic complexity ecological Kuznets curve between economic complexity and ecological footprint. Chen Jinghui et al. (2023)[33] found through numerical fitting that per capita GDP shows typical inverted "U" curve relationships with wastewater and sulfur dioxide emissions respectively.

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Domestically, many scholars support the EKC hypothesis. For example, Fu Jiafeng et al. (2008)[34] conducted EKC numerical simulation of GDP unit and CO_2 emissions from production and consumption perspectives, finding evident EKC curve effects under both perspectives. Wang Fei et al. (2018)[35] explored relationship between CO_2 emissions and economic growth from regional perspective. Panel data regression results showed CO_2 emissions and economic growth in China's eastern, central and western regions all satisfy EKC curve hypothesis. Feng Yan et al. (2022)[36] studied impact of China's urbanization on forest ecological security through fixed effects model, finding inverted U-shaped relationship between urbanization and forest ecological security index in overall sample. Wang Yunhao et al. (2023)[37] added energy consumption and energy structure as control variables when analyzing relationships between carbon emissions, energy consumption and economic growth to verify EKC curve in China, finding evident inverted "U" relationship between per capita carbon emissions and economic growth, thus verifying EKC curve's existence in China.

Many scholars also question EKC curve's existence. For example, internationally, Webber et al. (2010)[38] reviewed empirical literature on Environmental Kuznets Curve and studied relationships between various pollutants and per capita income, finding relationship curves' shapes are not uniformly inverted U-shaped across pollutants but depend on pollutant types. Minlah and Zhang Xibao (2021)[39] used time-varying methods and rolling window Granger causality tests to study causality between economic growth and carbon dioxide emissions, thus testing existence of Ghana's carbon dioxide emission Environmental Kuznets Curve. Research showed empirical results indicate Ghana's carbon dioxide emission Environmental Kuznets Curve slopes upward, contrary to classic inverted U-shape. Xing, Licong et al. (2023)[40] explored economic factors in Asian economies' current environmental degradation and innovation's role in achieving sustainable development using panel autoregressive distributed lag and pooled mean group methods for dynamic panel data. Research showed inverted U-shaped relationship between per capita economic growth and environmental degradation does not hold.

Domestically, Cui Tiening and Wang Lina (2018)[41] analyzed EKC curves of municipal solid waste and economic growth across Chinese provinces. Results showed only some provincial cities' relationships satisfy EKC hypothesis, while others show different shapes. Zhang Xin et al. (2020)[42] studied relationships between major pollutants and CO_2 per capita emissions and per capita deflated GDP to verify ECK curve, finding different emissions and per capita deflated GDP show positive N-shaped, inverted N-shaped, positive U-shaped rather than classic inverted U-shaped relationships. Ye Azhong and Zheng Hang (2022)[43] empirically analyzed economic growth's impact on China's environmental pollution using spatial econometric model, finding provincial economic development level and environmental pollution don't conform to EKC hypothesis but show M-shaped oscillating relationship of "deterioration-improvement-deterioration-improvement". Tian Yun and Cai Yanrong (2023)[44] studied relationship between agricultural carbon emissions and rural per capita net income in Yangtze River Economic Belt, finding significant EKC curve differences across provinces and cities, roughly categorized as inverted N-shaped, inverted U-shaped and positive U-shaped.

2.4. Research on Energy-Economy-Environment Relationship

With deepening research on binary systems, researchers found the world evolves through interactions of multiple systems, and studying binary systems alone cannot explain real world complexity. Moreover, related research work finds it difficult to conduct more comprehensive, in-depth and systematic studies[45]. Thus researchers attempted to incorporate energy, environment and economy into a unified framework for integrated research. Research on Energy-Economy-Environment (3E) system gradually gained academic attention.

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Internationally, scholars focus on constructing 3E system models to clarify interactive relationships through analyzing model operation results. Carla and Henggeler (2011)[46] built a multi-sector economy-energy-environment model for prospective analysis of economic structure and energy system changes while assessing corresponding environmental impacts, providing decision support for policy making. Freire-Gonzalez and Ho Mun S (2021)[47] established dynamic economy-energy-environment computable general equilibrium model to simulate impacts of 75 different behaviors on GDP and net carbon dioxide emissions over 20 years in Catalonia and how carbon tax offsets carbon rebound effects. Research found 2.4-3.6sic/ton carbon tax would completely offset carbon rebound effects for each percentage point reduction in voluntary energy consumption behavior. Lu Chenyu et al. (2023)[48] evaluated energy utilization and economic growth's impacts on ecological environment using pulse response function and generalized method of moments based on spatiotemporal differentiation characteristics of economy, energy and environment factors. Analysis showed overall positive 3E development trend with narrowing regional differences. Raihan and Bari (2024)[49] established autoregressive distributed lag model to explore impacts of economic growth, fossil fuel and renewable energy utilization on China's carbon dioxide emissions, finding 1% increase in fossil fuel utilization and economic growth leads to 4.97% and 0.58% long-term increase in carbon dioxide emissions respectively.

Domestically, Chinese scholars mainly measure and evaluate 3E system coordination degree. For example, Chen Liming et al. (2013, 2015)[50-51] compared accuracy of variable coordination degree model, distance coordination degree model and comprehensive coordination degree model, finding comprehensive model most accurate, followed by distance model and variable model least accurate. Based on comprehensive coordination degree model, they measured 3E system coordination degrees across 30 Chinese provinces, finding large provincial differences but overall rising trend. Cui Lizhi and Jiang Haifeng (2016)[52] proposed establishing PLSPM-GIA model to estimate provincial 3E system coordinated development levels after summarizing key considerations in measuring coordinated development levels. In recent years, as coupling coordination degree model can measure both subsystem interactions and overall system's benign coordination level, researchers widely adopt it to measure 3E system coordinated development status. For example, Cao Chenglong et al. (2020)[53] weighted indicators using principal component analysis then measured Ningbo's 3E system coupling coordination degree using coupling coordination degree model, finding Ningbo's 3E system in overall good, sustainable development state. Liu Lina et al. (2020)[54] measured 3E system coordination degrees of 9 provinces (regions) in Yellow River Basin using comprehensive weighting method and coupling coordination evaluation model. Research found 9 provinces (regions) show temporal evolution trend from barely coordinated to highly coordinated 3E system coupling coordination development. Peng Haofan et al. (2023)[55] established economy-environment-carbon emission evaluation index system and measured coupling coordination relationship between economic development, environmental quality and carbon emission levels in Yichun using entropy method and coupling coordination degree model. Chai Jian et al. (2024)[56] measured and studied 3E system coupling coordination levels and spatial dynamic evolution patterns of 29 Chinese provinces using coupling coordination degree model and spatial panel model. Research found although China's provincial 3E system coupling coordination degrees improved, "bipolar differentiation" intensified with overall spatial positive correlation clustering characteristics.

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3. Conclusion

Literature review shows scholars have conducted extensive research on pairwise relationships between energy, economy, and environment or the overall 3E system, reaching many valuable and meaningful conclusions. The review reveals the following findings.

3.1. Research on Energy-Economy-Environment Relationship

Regarding research objects, studies on energy, economy and environment evolved from binary systems to ternary systems, i.e., from initially studying pairwise relationships to later studying coordinated development of the three-element system as a whole.

Regarding research methods, studies on energy-economy relationships mostly adopt Granger causality test and cointegration analysis. Studies on energy-environment relationships mostly use Data Envelopment Analysis (DEA) and multiple regression analysis. Studies on economy-environment relationships are mostly based on Environmental Kuznets Curve (EKC). For overall 3E system research, international scholars focus on model research while domestic scholars emphasize coordination degree measurement and evaluation.

Regarding research conclusions, except for relatively uniform conclusions on energy-environment relationships showing massive development and utilization of traditional fossil energy severely damages ecological environment, studies on economy-environment, energy-economy and overall 3E system show significant divergence in conclusions due to different scholars' varying indicator selection, data processing and weighting methods.

3.2. Limitations of Past Research

Research objects need expansion. Previous literature has extensively studied binary or ternary systems, but under complex global evolution, more systematic and comprehensive research requires expansion to more diverse systems.

Limited research scope. Previous literature's 3E system research mostly based on national or municipal level, with relatively few studies on individual provinces or urban agglomerations.

Insufficient research depth. Previous literature's 3E system research remains at coordination degree measurement without deeply exploring inter-system action mechanisms. Few studies examine constituent elements' impact degrees on coordination within systems.

Previous literature mostly based on historical data, but in practice we care more about future coordinated development evolution trends, with few literature predicting future 3E system coordination status.

3.3. Future Research Directions

Addressing above limitations, future research directions include:

Research objects can expand to quaternary system coordinated development relationships, such as Energy-Economy-Environment-Technology (3E1T) system, Energy-Economy-Environment-Security (3E1S), Energy-Economy-Environment-Society (3E1S), etc.

Research scope can focus on individual provinces or urban agglomerations.

Research depth can utilize grey correlation analysis or obstacle degree analysis to study inter-system action mechanisms and constituent elements' impact on coordination within systems.

For development trends, prediction models can be used to forecast coordination degrees of 3E or multi-element systems.

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