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The Nexus Between Hydropower, Nuclear Energy, and Economic Growth in China: Insights from a Simultaneous Equations Model

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Abstract—Amid the global shift toward green development, clean energy is a key driver of sustainable economic growth. Based on China's green transition, the study investigates the dynamic relationships between clean energy generation (hydro and nuclear) and economic development using panel data from 30 provinces (2013–2022). Applying simultaneous equation models to address endogeneity, the analysis reveals a significant bidirectional relationship between nuclear power generation and economic growth, however, hydropower generation and economic development exhibit no statistically significant mutual influence. Research and Development, Foreign Direct Investment and innovation are included as controls to enhance robustness. Findings offer theoretical and practical insights for optimizing China's clean energy strategies and promoting sustainable development.

Keywords: Clean energy generation, Economic Growth, Green Transition, Hydropower, Nuclear power

I. INTRODUCTION

Since the launch of the reform and opening-up policy (1978), China has undergone a profound transformation from a planned economy to a market-oriented system. During this transition, the industrial sector rapidly emerged as the primary engine of economic growth, inevitably leading to a surge in energy demand and a fossil fuel–dominated energy structure. Particularly in coastal regions, the inflow of foreign capital and the concentration of manufacturing industries enabled China to evolve into the "world's factory." In 2022, according to the National Bureau of Statistics, industrial added value accounted for 33.2% of the country's GDP and contributed approximately 36% to national economic growth. As a developing country, China is currently in a stage of moderate economic growth, with its per capita GDP reaching RMB 2,603,145 in 2022.

However, the industrial sector, as a high-emission and energy-intensive domain, has become a major source of pollutants such as carbon dioxide and nitrogen oxides. These environmental concerns have prompted China in recent years to accelerate its transition toward green, low-carbon, and high-quality development (Li et al., 2021). In 2020, the country pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, marking a significant step toward sustainable growth.

Against this backdrop, clean energy—particularly hydropower and nuclear power, as key components of renewable energy—is increasingly emerging as a critical force in achieving the dual goals of both economic growth and environmental sustainability, owing to the low-carbon, efficient, and stable characteristics.

Due to its abundant resource endowment and relatively high operational stability, hydropower plays an indispensable role in the global energy landscape. Beyond electricity generation, its multifunctional benefits—such as supporting irrigation, flood mitigation, and transportation infrastructure—further contribute to reducing the environmental burdens associated with fossil fuel consumption (Li et al., 2018). By 2023, China's hydropower installed capacity had surpassed 300 million kilowatts, accounting for about one-third of the global total installed capacity. In 2022, the hydropower generation in China reached 13521.98 (10^8 kW·h). Sichuan and Yunnan provinces, with the richest water resources, have become the primary areas for hydropower development in China.

Meanwhile, nuclear energy—characterized by high energy density and notable carbon mitigation potential—has become an essential driver of economic development (Ulucak et al.,2022). In the aftermath of nuclear accidents such as the Fukushima disaster, many countries have re-evaluated their nuclear strategies (Wang et al., 2023). Despite global concerns, nuclear power continues to gain prominence in China's energy mix. China's nuclear power installed capacity ranks among the best in the world (Wu et al., 2022), accounting for about 5% by 2024. Meanwhile, several nuclear power plants have been in operation, indicating that China's nuclear power generation capacity is continuously increasing, and the proportion of nuclear energy is growing in the energy structure. Nuclear power generation reached 4075.24 and 4177.76 (10^8kW·h) in 2021 and 2022, respectively, attributed to Guangdong Province, which is the largest producer of nuclear power in China. Thus, emphasizing nuclear energy development aids in realizing the potential for a sustainable energy transition (Gralla et al., 2017).

Therefore, the causal relationship between clean energy and economic development has become a central topic in energy economics (Omri et al., 2015). Despite the considerable academic attention devoted to the energy–growth nexus (Apergis et al., 2010), empirical research focusing specifically on the interactions among hydro, nuclear, and economic growth remains limited—particularly in the context of China, where energy development has progressed rapidly in recent years.

Against this backdrop, this study aims to investigate the causal linkages between hydropower generation and economic performance, as well as between nuclear energy and economic development in China. Unlike previous studies, we employ a simultaneous equations model (SEM) and utilize the most recent panel data covering the period from 2013 to 2022. To address the issue of endogeneity, we adopt the Two-Stage Least Squares (2SLS) estimation method. This allows us to explore the individual and joint contributions of hydropower and nuclear energy to economic growth, and to assess their potential synergistic effects. In addition, key control variables such as Research and Development, Foreign Direct Investment and inflation are included in the model. Our findings are expected to offer theoretical insights and policy implications for optimizing China’s energy structure and advancing green, low-carbon development.

The remainder of this paper is structured as follows. Section 2 introduces the hypotheses and methodological approach. Section 3 presents the data description. Section 4 shows the regression results and discussion. The paper concludes in Section 5, where key policy suggestions are presented.

II. HYPOTHESES AND METHODOLOGY

Early studies based on Classical Growth Theory suggested that economic growth would eventually be constrained by resource limitations, thus highlighting the need to explore more reliable clean energy sources. Meanwhile, proponents of Endogenous Growth Theory regard clean energy as a critical indicator of sustainable economic development.

Some empirical studies have confirmed this perspective. For instance, Mbarek, Nasreen, and Feki (2017) identified a causal relationship between nuclear energy and economic performance in France. Hydropower resources are stable, but development is limited by natural conditions. It neither significantly promotes economic development nor has a strong impact on national economic growth, with weak mutual influence between the two (Ni et al., 2022). Similarly, the link between hydropower generation and economic growth has been established (Michieka et al., 2021). Although economic growth in the early stages may suppress investment in nuclear power, nuclear energy, as an efficient and clean energy source, plays a positive role in promoting long-term economic growth (Çakar et al., 2022).

Thus, the following hypotheses are formulated:

Hypothesis 1 Hydropower generation and economic growth exhibit a mutually negative causal linkage.

Hypothesis 2 Economic growth negatively affects nuclear power generation, whereas nuclear power generation contributes positively to economic growth.

Structural Equation Model：

$$\gamma_{it} = \alpha_0 + \alpha_1\gamma_{it-1} + \beta\gamma_{it} + \delta\chi_{it} + \varepsilon_{it}$$

where γ_{it} are endogenous variables, γ_{it-1} their lagged values, χ_{it} control variables, and ε_{it} error terms.

Specifications of model:

Equation (1): The Hydropower Generation and Economic Growth:

$HYD_{it}=\pi_0+\pi_1 HYD_{it-1}+\pi_2 GDP^{H}{}_{it}+\pi_3 NREG_{it}+\pi_4 RD_{it}+\pi_5 INV_{it}+\pi_6 HC_{it}+\varepsilon_{1it}$

$$GDP^{H}_{it}=\varphi_0+\varphi_1 GDP^{H}_{it-1}+\varphi_2 HYD_{it}+\varphi_3 FDI_{it}+\varphi_4 IR_{it}+\varphi_5 FCI_{it}+\varphi_6 LF_{it}+\varepsilon_{2it}$$

Equation (2): The Nuclear Power Generation and Economic Growth:

$$NUC_{it}=\psi_0+\psi_1 NUC_{it-1}+\psi_2 GDP^{N}_{it}+\psi_3 NREG_{it}+\psi_4 RD_{it}+\psi_5 INV_{it}+\psi_6 HC_{it}+\varepsilon_{3it}$$

$$GDP^{N}_{it}=\omega_0+\omega_1 GDP^{N}_{it-1}+\omega_2 NUC_{it}+\omega_3 FDI_{it}+\omega_4 IR_{it}+\omega_5 FCI_{it}+\omega_6 LF_{it}+\varepsilon_{4it}$$

In the both equations, i, t and ε denotes the Individuals at Time t and the Random Error Terms, respectively. In equation (1), both GDP^{H} and HYD are treated as endogenous variables. NREG, RD, INV, and HC are included as control variables influencing HYD. Meanwhile, FDI, IR, FCI, and LF are incorporated as control variables affecting GDP^{H}. Similarly, for equation (2), GDP^{N} and NUC are endogenous.

III. DATA DESCRIPTION

The data sources taken from the National Bureau of Statistics (NBS) are given below in Table 1. The sample encompasses 30 provinces, with the temporal scope spanning from 2013 to 2022. The core variables included in this study are hydropower generation (HYD) and nuclear power generation (NUC) (10^{8} kW·h) and non-renewable energy generation (NREG) (10^{4} tons), and GDP (CNY), and there are other control variables, they are R&D intensity (RD), innovation level (INV), inflation rate (IR) and fixed capital investment (FCI) (100 million CNY), human capital level (HC), foreign direct investment (FDI) (million CNY), and labor force (LF) (%).

This study begins with a descriptive analysis of the key variables. As shown in Table 1, the mean value of GDP is 10.946, with a minimum of 10.003 and a maximum of 12.155. This indicates that while there are certain regional and temporal differences in economic levels, overall volatility is low and the distribution is relatively concentrated, as reflected by the standard deviation of 0.432.

Table 1. Descriptive statistics and Levin–Lin–Chu unit root test results

Variables	Mean	SD	Min	Max	Adjusted t*	p-value
GDP	10.946	0.432	10.003	12.155	-5.2049	0.0000
FDI	14.635	1.810	7.636	18.622	-3.5091	0.0002
IR	4.625	0.007	4.606	4.643	-13.5923	0.0000
FCI	9.687	0.812	7.767	11.083	-14.6949	0.0000
LF	7.600	0.767	5.545	8.864	-8.0779	0.0000
HYD	4.465	2.201	-3.507	8.265	-8.0144	0.0000
NUC	-0.007	0.178	-1.000	1.778	-6.0858	0.0000
RD	0.017	0.011	0.002	0.065	-7.1302	0.0000
INV	8.807	3.204	0.000	12.399	-3.7823	0.0001
HC	0.022	0.006	0.009	0.044	-9.3113	0.0000
NREG	7.775	2.880	0.000	11.777	-19.0489	0.0000

Source: Author’s own calculations.

To further illustrate the regional disparities in hydropower and nuclear power generation, boxplots were constructed (see Fig. 1). HYD exhibits wide variation across most regions (mean = 4.465; standard deviation = 2.201), with a large interquartile range and the presence of outliers, indicating a dispersed distribution across provinces.

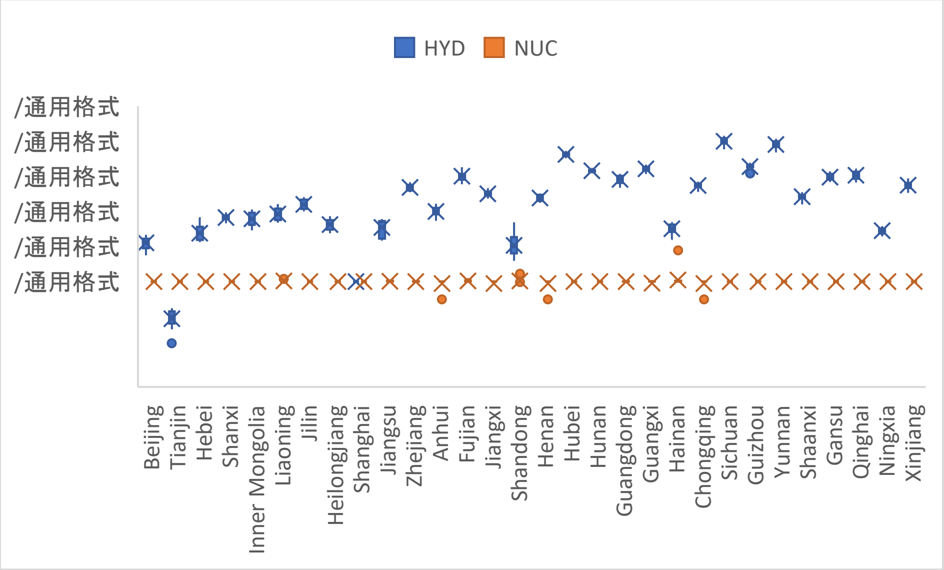

Figure 1. Boxplots for hydropower and nuclear power generation

In contrast, nuclear power generation demonstrates a clearly skewed distribution, with only a few regions recording high levels of output, which aligns with the concentration of nuclear power plants in eastern China. The mean value of NUC is -0.007 (approximately zero), with a standard deviation of 0.178, and maximum and minimum values of 1.778 and -1.000, respectively.

To address the stationarity issue commonly present in panel time series data, the Levin, Lin, and Chu (LLC) test (2002) is conducted firstly. Based on the LLC test results in Table 1, all variables exhibit significantly negative adjusted t-values (e.g., $p = 0.001$), indicating stationarity across 30 panels and 10 periods. Thus, after differencing and log transformation, all variables are stationary (p-values < 0.05) and suitable for regression, avoiding spurious results from non-stationarity.

IV. EMPIRICAL RESULTS AND ANALYSIS

IV.I. ESTIMATION RESULTS OF 2SLS

The objective of this study is to explore the relationship between economic growth and clean energy generation by adopting 2SLS in China from 2013 to 2022, with a particular focus on hydropower and nuclear energy. Each type of energy corresponds to a separate model, and the empirical regression results are presented in Table 2.

Table 2. The nexus between hydro, nuclear and economic growth: results of 2SLS

Variables	HYD	GDP^H	NUC	GDP^N
lagHYD	0.897 (0.023) ***			
lagNUC			0.029 (0.061)	
GDP^H	-0.052 (0.235)			
GDP^N			-0.101(0.061) *	
NREG	-0.061 (0.034) *		0.011 (0.008)	
RD	-10.998 (8.944)		4.666 (2.298) **	
INV	0.052 (0.034)		-0.015 (0.008) *	
HC	-18.993 (8.994) **		2.095 (2.259)	

Variables	HYD	GDP^{H}	NUC	GDP^{N}
lagGDP^{H}		0.708(0.037) ***		
lagGDP^{N}				1.050 (0.128) ***
HYD		-0.002 (0.009)		
NUC				3.177 (0.892) ***
FDI		0.053 (0.014) ***		-0.017 (0.034)
IR		-10.304(1.959) ***		- 10.931 (4.532) **
FCI		0.196 (0.036) ***		-0.044 (0.106)
LF		- 0.271 (0.044) ***		0.085 (0.138)

Source: Author's own calculations.

The values in parentheses represent standard errors.

Asterisks (*, **, ***) denote significance levels of 10%, 5%, and 1%, correspondingly.

Based on the empirical results presented in Table 2, most lagged dependent variables are statistically significant, validating their inclusion in the model. Specifically, while there is no bidirectional causality between hydropower generation and economic growth, a significant two-way causal relationship is observed between nuclear energy generation and economic development.

Columns (1) and (3) of Table 2 further reveal the heterogeneous effects of economic growth on different types of clean energy generation. GDP shows no significant impact on hydropower generation, but has a significantly negative influence on nuclear energy generation, suggesting that rapid economic development may suppress the expansion of nuclear capacity. Specifically, a one-unit increase in GDP is associated with a 0.101% decrease in nuclear energy output. This may reflect two practical realities: firstly, as a conventional form of clean energy, hydropower development in China is geographically constrained (e.g., Sichuan and Yunnan), and most economically viable sites have already been exploited, limiting its responsiveness to changes in GDP. Second, despite its high energy efficiency, nuclear power is characterized by high risk, high cost, and limited public acceptance, which may result in its marginalization during periods of accelerated economic restructuring.

Additionally, Table 2 indicates a significantly negative effect of non-renewable energy generation on hydropower output at the 10% significance level. A 1% increase in non-renewable energy output is associated with a 0.061% decline in hydropower generation. This can be attributed to the intensive water usage of non-renewable energy generation processes—particularly for cooling and industrial operations—which exacerbates water scarcity and limits hydropower capacity. Moreover, human capital, measured by the share of population with higher education, shows a significant negative relationship with hydropower output (significantly 5%). This result reflects a geographic mismatch between water resource endowment and educational attainment. Hydropower resources are primarily located in China's southwestern regions, where higher education levels are relatively low, whereas the eastern coastal regions, rich in educational resources, possess limited exploitable hydropower potential. Therefore, the negative coefficient does not imply that human capital directly constrains hydropower output but rather highlights spatial structural imbalances. The outcome corresponds well with the findings of De Faria et al. (2017).

In contrast, nuclear energy generation is mainly influenced by R&D expenditure and the level of innovation. Column (3) shows that R&D has a significantly positive effect on nuclear output, with a 1% increase in R&D leading to an approximate 4.7% rise in nuclear output. However, the overall level of innovation is significantly negatively correlated with nuclear output (significantly 10%), which may be due to the heavy regulation and policy control in the nuclear sector—limiting the short-term conversion of innovation into practical production gains.

Furthermore, the impacts of hydropower and nuclear energy on economic growth differ considerably. Hydropower shows no statistically significant effect on economic growth, while nuclear energy significantly contributes to economic development at the 1% level, indicating its potential role in driving industrial upgrading and employment creation (Wang et al., 2023). Given the dual constraints of resource availability and environmental impact (Xue et al., 2018), the marginal contribution of hydropower to economic growth may be diminishing (Fan et al., 2022). In 2022, China's hydropower generation was heavily concentrated in the southwestern regions, reaching 815.658 billion kWh—more than three times that of the central region. As such, while hydropower may provide short-term economic stimulation at the local level, its overall contribution to the national economy remains limited and is often accompanied by negative externalities such as population displacement and ecological degradation. This result aligns with the conclusions drawn by Ni et al. (2022).

All the above results corroborate the theoretical expectations formulated in Hypotheses 1 and 2. The analysis also finds that Foreign Direct Investment and Fixed Capital Investment significantly promote economic growth, whereas inflation and labor force exert significant negative effects. These findings are consistent with macroeconomic growth theory and reflect current conditions in China's labor market.

It deserves attention that due to the long investment cycle, high risk, and technological barriers in the nuclear sector, its attractiveness to FDI and FCI is relatively low compared to hydropower. As a result, its economic contribution is not reflected in the baseline model and may even appear negative. However, when applying the MLE model, which accounts for endogeneity and long-term structural relationships, the expected positive economic effect of nuclear energy becomes significant, reaffirming the robustness of the model under refined specifications.

IV.II. ROBUSTNESS CHECK

In this section, we assess the robustness of our results by comparing the outcomes from two different estimation methods. As shown in Table 3, the direction and statistical significance of the key coefficients remain consistent across methods, reinforcing the reliability of the findings.

Table 3. MLE-based robustness test results for key variables

Key Variables	Equation (1)		Equation (2)	
	HYD	GDP^H	NUC	GDP^N
GDP^H	0.032 (0.133)			
GDP^N			-0.327 (0.059)***	
lagHYD	0.899 (0.023) ***			
lagNUC			0.072 (0.069)	
NREG	-0.058 (0.0340 *		0.006 (0.009)	
$lagGDP^H$		0.709 (0.037) ***		
$lagGDP^N$				0.803 (0.036) ***
HYD		-0.001 (0.008)		
NUC				0.874 (0.088) ***
Other Controls	YES	YES	YES	YES
Residual Variance	0.505	0.048	0.043	0.045
SRMR	0.020		0.021	
CFI	0.904		0.861	

Source: Author's own calculations

V. CONCLUSIONS

This paper aims to investigate how economic growth drives the development of clean energy and, in turn, how clean energy feeds back into economic performance. Using panel data from 30 Chinese provinces between 2013 and 2022, and key variables including GDP, hydropower generation, and nuclear power generation, the analysis applies Two-Stage Least Squares and Maximum Likelihood Estimation for robustness testing. The results reveal a complex and asymmetric bidirectional relationship: there is no significant causal link between hydropower generation and economic growth, while nuclear energy appears to unilaterally promote economic development. Given that China is the most populous country globally, the development of nuclear energy represents an essential strategic choice (Zhou et al., 2010). Simultaneously, the development of hydropower should be carefully managed to prevent social problems arising from its rapid expansion (Sovacool et al., 2019).

Although the selection of control variables was grounded in theoretical and practical considerations, certain unobservable factors—such as the quality of energy infrastructure and levels of international support—were excluded due to data limitations. The omission of these variables may introduce bias and limit the model's comprehensiveness and its explanatory power concerning clean energy development.

The findings highlight the need for energy policies tailored to the specific characteristics and development stages of different clean technologies to balance economic growth and sustainability goals. Promoting coordinated development between education and industry in hydropower regions to alleviate the regional mismatch between resource endowments and human capital. Meanwhile, it is crucial to strengthen the policy synergy between nuclear energy and R&D, improve mechanisms for technological transfer, and enhance its economic contribution and public acceptance. In addition, optimizing the spatial layout of clean energy and encouraging foreign investment in long-term energy projects are essential for sustainable energy development.

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