DOI: 10.55643/fcaptp.2.67.2026.5125

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Received: 30/12/2025
Accepted: 21/04/2026
Published: 30/04/2026



# FINANCIAL DEVELOPMENT AND RENEWABLE ENERGY CONSUMPTION: THE MODERATING ROLE OF HUMAN CAPITAL

## ABSTRACT

This study aims to resolve the inconsistency in empirical literature on the nexus between financial development (FD) and renewable energy consumption (REC) by testing the hypothesis that human capital (HC) plays a crucial moderating role. Using an unbalanced panel dataset of 16 developing and emerging Asian economies from 2000 to 2022, we employ the Fixed Effects Model (FEM) with Driscoll-Kraay standard errors and the System Generalized Method of Moments (System GMM) to control for endogeneity and cross-sectional dependence. The empirical results show that, when considered independently, financial development has no significant impact on renewable energy consumption. However, we find strong evidence for the positive moderating role of human capital. Specifically, the impact of financial development on renewable energy is negative in countries with low levels of human capital but becomes positive and statistically significant when human capital surpasses a critical threshold (corresponding to a secondary school enrollment rate of approximately 68.2%). The main conclusion of the study is that human capital is not only an independent driver but also a prerequisite, an "absorptive capacity" that helps transform financial resources into effective renewable energy projects; thereby demonstrating that the effectiveness of financial development in driving the green transition is conditionally dependent on a nation's educational foundation. This finding carries a significant policy implication: strategies focusing solely on financial reform are insufficient and may be counterproductive. To successfully promote the energy transition, policymakers must pursue a dual strategy, synchronously combining the development of the financial system with strategic investment in education and human resource training to maximize the synergy between finance and knowledge.

**Keywords:** Asian economies, financial development, human capital, renewable energy consumption, absorptive capacity, energy transition, threshold effect

**JEL Classification:** Q42, O13, J24, G21

## INTRODUCTION

The transition to renewable energy sources has become an imperative, a central pillar in the efforts to combat climate change, enhance national energy security, and realize the Sustainable Development Goals (SDGs), particularly Goal 7 on affordable and clean energy (United Nations, 2015). In this context, developing and emerging countries in Asia play a particularly crucial role. This region not only has high rates of economic growth and energy demand but also faces increasingly severe environmental challenges and air pollution pressures (Xue et al., 2021). Consequently, accelerating the transition to clean energy is no longer an option but has become an urgent, strategic requirement for the sustainable development of this region.

However, one of the biggest barriers to the large-scale deployment of renewable energy is the requirement for very high initial capital investment. Wind, solar, and hydropower projects demand high costs for technology, construction, and infrastructure. Consequently, a developed financial system capable of mobilizing long-term capital, reducing trans-action costs, and efficiently allocating resources to green projects is considered a prerequisite (Sadorsky, 2010; Pham & Pham, 2025). Theoretically, developed and mature financial markets will provide the necessary capital, promote techno-logical innovation, and reduce risks for investors, thereby creating a strong impetus for renewable energy consumption (Anton & Nucu, 2020).

Despite a theoretical foundation that affirms the undeniable role of finance, a notable paradox emerges in empirical works: the nexus between financial development (FD) and renewable energy consumption (REC) remains ambiguous, with research findings often conflicting. On one hand, many empirical studies have found evidence supporting a positive relationship, arguing that the development of the banking sector and stock markets helps promote renewable energy (Anton & Nucu, 2020; Lahiani et al., 2021; Alsagr & Van Hemmen, 2021; Wang et al., 2022). On the other hand, a significant number of studies find no clear link or even report a negative impact, suggesting that financial channels may prioritize traditional, more carbon-intensive industries over riskier green projects (Charfeddine & Khediri, 2016; Yahya & Rafiq, 2019; Khan et al., 2020; Nguyen et al., 2021).

This lack of consensus in research findings suggests that current models may have overlooked a critical moderating variable, a key factor that could potentially explain why financial policies succeed in one country but fail in another. This study argues that this key factor is human capital (HC). We propose a new hypothesis: the impact of financial development on renewable energy is not a universal constant but depends on the absorptive capacity of an economy, which is determined by the quality of its human resources. Specifically, the availability of capital becomes meaningless without a team of engineers, project managers, and policymakers with sufficient skills and awareness to transform financial opportunities into viable renewable energy projects (Murshed et al., 2022; Benavides-Franco et al., 2023).

Therefore, this study is conducted not only to re-examine a linear relationship but also to investigate the structural role of human capital: whether it is a necessary condition to unlock the potential of financial development in promoting the green transition.

## LITERATURE REVIEW

### Theoretical framework

The theoretical framework of this study is built upon the convergence of three pillar economic theories to explain the complex relationship among financial development, human capital, and renewable energy consumption.

First, the direct relationship between financial development and renewable energy consumption is viewed through the lens of the finance-growth nexus theory. This theory, with its foundations from Schumpeter and systematized by later studies, posits that a developed financial system acts as a key driver of economic growth by improving resource allocation efficiency, mobilizing savings, and reducing transaction costs (Levine, 2005; Mbodj & Laye, 2025). Applied to the renewable energy sector, which requires large initial investments and long payback periods, a mature and efficient financial sector can provide long-term loans, attract private investment, and mitigate risks for green projects. Thus, theoretically, financial development is expected to break down capital barriers and promote the deployment of renewable energy.

Second, the independent role of human capital is reinforced by endogenous growth theory. Unlike traditional growth models, this theory, introduced by Romer (1990) and Lucas (1988), asserts that human capital and technological innovation are intrinsic drivers of sustainable economic growth. In the context of the energy transition, a highly educated and skilled labor force is not only necessary for researching, developing, and operating complex renewable energy technologies but also contributes to raising environmental awareness and creating social pressure, thereby boosting the demand for clean energy.

More importantly, to explain why the impact of financial development is inconsistent and may depend on other socio-economic conditions, this study employs the theory of absorptive capacity as its core foundation (Cohen & Levinthal, 1990). This theory suggests that a nation's ability to recognize, assimilate, and apply new external resources or knowledge depends directly on its existing knowledge base. In our model, capital from the financial system is considered an external resource, and human capital is the nation's absorptive capacity. Accordingly, a country with high human capital will have a better capacity to absorb financial opportunities, transforming them into viable renewable energy projects. Conversely, when human capital is low, abundant capital may not be allocated efficiently to the green sector due to a lack of project management skills, technical expertise, and a favorable institutional environment. Therefore, this theory provides a basis for hypothesizing that human capital plays a moderating role, enhancing the positive impact of financial development on renewable energy consumption.

The convergence of these three theoretical pillars allows us to establish the argument that abundant capital from a developed financial system can only be effectively transformed into the renewable energy sector when the nation possesses a sufficiently robust human capital base. Human capital is not just an independent driver but also acts as an absorptive capacity, determining the success of using financial resources.

**Hypothesis development**

***Financial development and renewable energy consumption***

Theoretically, Sadorsky (2010) identified three main impact mechanisms: a direct effect through efficient capital provision, a wealth effect that increases the general demand for a better environment, and a business effect that promotes economic activities using energy. Empirically, many studies have demonstrated that a developed financial system, including both the banking sector and capital markets, helps reduce financing costs and enhances access to debt and equity for green projects, thereby promoting renewable energy consumption (Alsagr & Almazor, 2021; Lahiani et al., 2021; Wang et al., 2023). This positive impact has been recorded in various contexts, from developed countries (Saygin & İskenderoğlu, 2022) to emerging markets and BRIC nations (Lei et al., 2022; Zhang et al., 2021).

However, this consensus is challenged by a significant number of works with contrary results. Some studies find no statistically significant relationship between financial liberalization and renewable energy consumption (Yahya & Rafiq, 2019). Furthermore, financial development can increase overall energy consumption, potentially nullifying the benefits gained from renewable energy (Nguyen et al., 2021). Moreover, in developing economies, inadequate financial intermediaries can become a serious barrier to the implementation of renewable energy projects (Brunnschweiler, 2010).

This inconsistency in empirical results implies that the impact of financial development on renewable energy consumption is not a universal constant, but rather depends profoundly on the economic context, development level, and institutional framework of each country, especially the heterogeneity across regions (Alinsato et al., 2024).

In the context of developing and emerging Asian countries, we argue that the positive impact is likely to prevail. This region faces dual pressures from soaring energy demand and severe environmental challenges, creating strong policy momentum and an urgent societal need for a clean energy transition. This increases the attractiveness and reduces the policy risk of renewable energy projects, encouraging financial institutions to allocate capital to this sector as a long-term strategic investment opportunity. Based on these arguments, while acknowledging the existence of conflicting results, this study expects that in the specific context of Asia, the benefits from reducing financial barriers will be superior. Therefore, the first hypothesis is stated as follows:

$H_1$: Financial development has a positive impact on renewable energy consumption.

*Human capital and renewable energy consumption*

Human capital, defined as the aggregate of knowledge, skills, and health of the labor force, is identified as a *critical enabler* for the transition to a low-carbon economy (Di Vaio et al., 2024). The positive impact of human capital on renewable energy consumption (REC) is not a singular process but a complex mechanism operating through multifaceted channels, where human capital is not just an independent factor but also a crucial catalyst. First, at the individual and societal levels, human capital accumulated through education and training helps to raise profound awareness of environmental issues and climate change. This not only forms an ecological consciousness but also translates into real demand and a higher willingness to pay for clean energy products and services, creating pressure from the market's demand side (Zafar et al., 2020).

Concurrently, from the supply-side perspective, a labor force with high educational attainment and professional skills is a prerequisite for absorbing, operating, and innovating complex renewable energy technologies (Xu et al., 2023). From engineers designing wind turbines to experts managing smart grids, human capital is the foundation for localizing and developing the green energy value chain (Lin et al., 2021). Furthermore, human capital has a positive correlation with institutional quality. A society with a high level of education often demands transparency, accountability, and a stable legal environment, thereby strengthening the effective implementation of environmental policies and mitigating risks for investors in the renewable energy sector (Sinha et al., 2019). This combined impact is expected to be particularly pronounced in Asian economies. Here, human capital is the key for countries to leapfrog, immediately adopting clean and advanced technologies without having to repeat the traditional industrialization path, which has many negative environmental impacts. Therefore, by simultaneously influencing awareness, technological capacity, and institutional quality, human capital is not just a driver but a necessary condition, creating a solid foundation for promoting renewable energy consumption.

Based on the arguments and empirical evidence presented, we propose the second research hypothesis as follows:


DOI: 10.55643/fcaptp.2.67.2026.5125

$H_2$: Human capital has a positive impact on renewable energy consumption.

*The moderating role of human capital*

Endogenous growth theory suggests that human capital is the core driver of technological progress and long-term economic growth (Romer, 1990). In the context of the energy transition, this technological progress is manifested through the adoption and development of renewable energy.

Our main argument is that the positive impact of financial development on renewable energy consumption is not universal but is amplified by the presence of high-quality human capital. Although financial development provides the necessary capital to finance large-scale renewable energy projects (Sadorsky, 2010), the effective use of this capital depends on the technological and institutional capacity of the recipient country. According to the theory of absorptive capacity (Cohen & Levinthal, 1990), countries with high human capital possess a skilled labor force capable of deploying, operating, and maintaining complex clean energy technologies. Furthermore, human capital also promotes research and development activities that create more efficient energy solutions and attract further investment (Lin et al., 2021). At the same time, a highly qualified human resource base also helps improve institutional quality, building stable and transparent policy frameworks (Hung, 2023; Alinsato et al., 2025), thereby minimizing risks and increasing the attractiveness of renewable energy projects to the financial sector (Ponce et al., 2021).

Based on these arguments, we propose the following research hypothesis:

$H_3$: Human capital positively moderates the relationship between financial development and renewable energy consumption.

## AIMS AND OBJECTIVES

Stemming from the inconsistency in empirical works on the relationship between financial development (FD) and renewable energy consumption (REC), this study's main purpose is to address this contradiction by proposing and testing a new mechanism: the moderating role of human capital (HC). Accordingly, the specific objectives include: (i) to re-examine the impact of FD on REC in the context of Asian economies; and more importantly, (ii) to determine whether HC acts as a moderating factor, an "absorptive capacity" that determines the effectiveness of FD. By doing so, the study aims to provide new empirical evidence, shed light on the complex role of human capital, and propose crucial implications for designing synchronized and effective energy transition strategies.

## METHODS

### Data and sample

This study uses an unbalanced panel dataset of 16 developing and emerging countries in Asia over a 23-year period, from 2000 to 2022. The choice of this period was carefully considered for three main reasons: (i) Data availability: Data for most variables, especially energy and financial indicators, become complete and more consistent for the countries in the sample from the year 2000 onwards. (ii) Historical context: This period begins after the 1997-1998 Asian financial crisis, allowing us to analyze the development process in a new era of economic recovery and global integration. (iii) Timeliness: The period ends in 2022, the most recent year with relatively complete data, allowing us to capture the impacts of recent socio-economic events, including the COVID-19 pandemic.

The initial research sample included all developing and emerging economies in Asia as classified by the International Monetary Fund (IMF). However, we applied exclusion criteria to ensure the homogeneity and suitability of the sample:

- countries with prolonged political conflicts or severe macroeconomic instability;
- 50% of the study period. After the screening process, the final sample includes 16 countries, representing diverse sub-regions of Asia: Vietnam, Indonesia, Malaysia, Philippines, Thailand, Cambodia, India, Pakistan, Bangladesh, Sri Lanka, China, Mongolia, Kazakhstan, Uzbekistan, Kyrgyzstan, and Turkey.

The final unbalanced dataset comprises 352 country-year observations. Secondary data were primarily compiled from two reputable sources: the World Development Indicators (WDI) of the World Bank and the U.S. Energy Information Administration (EIA), to collect data on energy prices.

To mitigate the influence of outliers and measurement errors, all continuous variables in the model were winsorized at the 1st and 99th percentiles.

**Variable definition and measurement**

We selected measures that are widely recognized in previous empirical studies, while also ensuring their suitability for the specific context of Asian countries.

*Dependent variable: Renewable energy consumption (REC)*

We measure REC by the percentage of renewable energy in total final energy consumption (WDI code: EG.FEC.RNEW.ZS). This measure includes energy from modern renewable sources (hydropower, geothermal, solar, wind, biogas) as well as traditional biomass (wood, charcoal, agricultural waste). Although the inclusion of traditional biomass may be a limitation when focusing solely on modern clean energy, we argue that this measure is the most appropriate in the context of this study. First, it is the most consistently and comparably provided indicator by the WDI across developing countries. Second, for many emerging economies in Asia, traditional biomass still accounts for a significant share of the energy mix, especially in rural areas. Therefore, using this measure provides a more comprehensive picture of the overall use of non-fossil fuel energy sources, consistent with the broad definition of Sustainable Development Goal 7. This approach is also similar to influential studies in the field (e.g., Zafar et al., 2020; Murshed et al., 2022).

*Main independent variable: Financial development (FD)*

Following Levine (2005) and recent empirical studies on finance-energy (e.g., Anton & Nucu, 2020; Alsagr & Almazor, 2021), we use the indicator "Domestic credit to private sector as % of GDP" (WDI code: FS.AST.PRVT.GD.ZS) to measure financial development. We acknowledge that this indicator primarily reflects the development of the banking sector and may not fully capture the development of capital markets (stocks, bonds). However, this choice is appropriate given the characteristics of the economies in our sample. In most developing and emerging countries in Asia, the banking system remains the primary and most important channel for investment activities, far surpassing the role of capital markets. Therefore, this measure effectively captures the financial system's ability to mobilize and allocate resources for investment projects, including renewable energy projects.

*Moderating variable: Human capital (HC)*

Human capital is measured by "School enrollment, secondary, gross (% of gross)" (WDI code: SE.SEC.ENRR). This is a flow measure, reflecting investment in secondary education. Although measures based on average years of schooling (e.g., from the Barro & Lee dataset) are a better stock measure, they are often updated with low frequency (every 5 years), which is unsuitable for annual panel data analysis. Secondary school enrollment is a reasonable proxy and is widely used in growth and development studies (e.g., Sinha et al., 2019). We argue that secondary education represents a critical threshold, providing the labor force with the foundational knowledge and skills necessary to adopt new technologies, enhance environmental awareness, and participate in more complex economic activities — all of which are essential for promoting renewable energy.

Table 1 below summarizes all variables used in the study.

**Table 1. Variable definitions and data sources.** *(Source: Authors' compilation from the World Development Indicators (WDI) and the U.S. Energy Information Administration (EIA))*

| Symbol | Variable Name | Measurement and Data Source | Expected Sign |
|---|---|---|---|
| Dependent Variable | | | |
| REC | Renewable Energy Consumption | Renewable energy consumption as a percentage of total final energy consumption (%). Source: WDI (EG.FEC.RNEW.ZS). | (Dependent) |
| Main Independent Variables | | | |
| FD | Financial Development | Domestic credit to the private sector (% of GDP). Source: WDI (FS.AST.PRVT.GD.ZS). | + |
| HC | Human Capital | School enrollment, secondary, gross (%). Source: WDI (SE.SEC.ENRR). | + |
| FD×HC | Interaction Term | The product of Financial Development and Human Capital. | + |

*(continued on next page)*


DOI: 10.55643/fcaptp.2.67.2026.5125

**Table 1.** Continued.

| Symbol | Variable Name | Measurement and Data Source | Expected Sign |
|---|---|---|---|
| Control Variables | | | |
| lnGDP | Log of GDP per capita | Natural logarithm of GDP per capita (constant 2015 USD). Source: WDI (NY.GDP.PCAP.KD). | +/– |
| FDI | Foreign Direct Investment | Foreign direct investment, net inflows (% of GDP). Source: WDI (BX.KLT.DINV.WD.GD.ZS). | + |
| lnEP | Log of Energy Price | Natural logarithm of the annual average Brent crude oil price (USD per barrel). Source: EIA. | + |
| $lnCO_2$ | Log of $CO_2$ Emissions | Natural logarithm of $CO_2$ emissions (metric tons per capita). Source: WDI (EN.ATM.CO2E.PC). | + |

## Empirical model

To test the stated hypotheses, especially the moderating role of human capital ($H_3$), we construct a panel data regression model with an interaction term as follows:

$$REC_{it} = \beta_0 + \beta_1 FD_{it} + \beta_2 HC_{it} + \beta_3 (FD_{it} \times HC_{it}) + \beta_4 lnGDP_{it} + \beta_5 FDI_{it} + \beta_6 lnEP_{it} + \beta_7 lnCO_{2it} + \mu_i + \delta_t + \varepsilon_{it}$$

*where: $i$ and $t$ are indices for country ($i$ = 1, ..., 16) and year ($t$ = 2000, ..., 2022), respectively; $REC_{it}$ is the dependent variable, renewable energy consumption of country i at year t; $FD_{it}$ and $HC_{it}$ are the main independent variable (financial development) and the moderating variable (human capital), respectively; ($FD_{it} \times HC_{it}$) is the interaction term between financial development and human capital; $lnGDP_{it}$, $FDI_{it}$, $lnEP_{it}$, $lnCO_{2it}$ are control variables selected based on theoretical overview and previous empirical studies to minimize omitted variable bias; $\mu_i$ represents country-fixed effects, accounting for unobserved and time-invariant characteristics of each country (e.g., geography, culture, natural resources); $\delta_t$ represents time-fixed effects, controlling for common shocks affecting all countries in a specific year (e.g., the 2008 global financial crisis, energy price fluctuations, the COVID-19 pandemic); $\varepsilon_{it}$ is the random error term.*

## Analytical method

The study's analytical strategy is implemented in several steps. After initial descriptive statistics and multicollinearity checks, the Fixed Effects Model (FEM) is chosen based on the Hausman test. To ensure reliability, the model is estimated using Driscoll-Kraay standard errors to address cross-sectional dependence, heteroskedasticity, and autocorrelation. Subsequently, the System Generalized Method of Moments (System GMM) is applied to control for endogeneity. Finally, robustness checks are performed. All analyses and regression estimations in this study will be conducted using the specialized statistical software Stata version 17.0.

# RESULTS

## Descriptive statistics and correlation analysis

Before proceeding with the regression analysis, we perform descriptive statistics and correlation analysis to provide an overview of the data's characteristics and to preliminarily check for relationships and potential econometric issues such as multicollinearity.

Table 2 presents the descriptive statistics for all variables in the research sample of 352 observations.

**Table 2. Descriptive statistics.** Note: Data are winsorized at the 1st and 99th percentiles. *(Source: Authors' calculation from WDI and EIA)*

| Variable | Symbol | Observations | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|---|
| Renewable Energy Consumption (%) | REC | 352 | 34.82 | 26.15 | 2.41 | 91.56 |
| Financial Development (% GDP) | FD | 352 | 88.65 | 47.23 | 14.88 | 212.40 |
| Human Capital (%) | HC | 352 | 91.74 | 19.08 | 42.33 | 124.61 |
| Log of GDP per capita | lnGDP | 352 | 8.31 | 0.95 | 6.55 | 10.02 |
| Foreign Direct Investment (% GDP) | FDI | 352 | 3.59 | 3.81 | -1.22 | 25.17 |
| Log of Energy Price | lnEP | 352 | 4.15 | 0.40 | 3.12 | 4.73 |
| Log of $CO_2$ Emissions | $lnCO_2$ | 352 | 0.98 | 0.84 | -0.95 | 2.21 |

The results from Table 2 show significant variation across the variables. Specifically, the dependent variable REC has a mean of 34.82% but with a very large standard deviation (26.15), indicating profound differences in the energy structure among the Asian countries in the sample, ranging from a very low level (2.41%) to a primary reliance on renewable energy (91.56%). Similarly, the main variables, financial development (FD) and human capital (HC), also exhibit high heterogeneity, reflecting different stages of economic development and education levels. This heterogeneity suggests the appropriateness of using a panel data model with fixed effects to control for the unique, time-invariant characteristics of each country.

Table 3 presents the Pearson correlation matrix between the variables and the results of the multicollinearity test using the Variance Inflation Factor (VIF).

**Table 3. Correlation matrix and Variance Inflation Factors (VIF).** Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. VIF values are calculated for the full regression model, including the interaction term. The mean VIF is 2.94.

| Variable | REC | FD | HC | lnGDP | FDI | lnEP | $lnCO_2$ | VIF |
|---|---|---|---|---|---|---|---|---|
| REC | 1.000 | | | | | | | 1.78 |
| FD | 0.141** | 1.000 | | | | | | 4.65 |
| HC | 0.235*** | 0.412*** | 1.000 | | | | | 3.82 |
| lnGDP | -0.119** | 0.589*** | 0.691*** | 1.000 | | | | 2.95 |
| FDI | 0.087 | 0.204*** | 0.155** | 0.211*** | 1.000 | | | 1.16 |
| lnEP | -0.045 | 0.102* | 0.098* | 0.134** | 0.063 | 1.000 | | 1.21 |
| $lnCO_2$ | -0.310*** | 0.498*** | 0.652*** | 0.784*** | 0.199*** | 0.071 | 1.000 | 3.51 |

The correlation matrix in Table 3 provides initial indications of the relationships between the variables. Notably, both financial development (FD) and human capital (HC) have a positive and statistically significant correlation with renewable energy consumption (REC), with correlation coefficients of 0.141 and 0.235, respectively. This preliminary result is consistent with our expectation of a positive impact of FD and HC on REC, corresponding to hypotheses $H_1$ and $H_2$.

To ensure that multicollinearity does not distort the regression results, especially after including the interaction term in the model, we calculated the Variance Inflation Factor (VIF). The results show that all individual VIF values are below the common threshold of 10, and the mean VIF is only 2.94. This indicates that multicollinearity is not a serious issue in our analysis, and the obtained regression estimates will be reliable.

### Baseline regression results: The moderating role of human capital

To test the research hypotheses, we use a panel data regression model. First, the choice between the Fixed Effects Model (FEM) and the Random Effects Model (REM) is determined by the Hausman test (1978). The Hausman test result (Chi-sq = 45.72, p-value < 0.001) indicates the existence of correlation between the errors and the explanatory variables, thus the Fixed Effects Model (FEM) is a more appropriate and efficient choice than the Random Effects Model (REM).

Furthermore, to address potential issues of heteroskedasticity, autocorrelation, and cross-sectional dependence, which are common in macroeconomic data of countries in the same region, we estimate the FEM model with robust Driscoll–Kraay (1998) standard errors. Table 4 presents the regression results in progressive columns, allowing us to observe the change in the impact of variables as the model is gradually built.

The results from Table 4 provide important findings. Column (1) shows the impact of the control variables. Notably, $CO_2$ emissions ($lnCO_2$) have a strong positive correlation with renewable energy consumption, suggesting that pressure from environmental pollution is a significant driver for the green transition.

To test hypothesis $H_1$, we add the financial development (FD) variable to the model in Column (2). The coefficient of FD is -0.015 and is not statistically significant. This result does not change much when the human capital (HC) variable is added in Column (3). This provides initial evidence that does not support hypothesis $H_1$, suggesting that, when considered independently, financial development does not automatically promote renewable energy consumption in the Asian countries in our sample.

 DOI: 10.55643/fcaptp.2.67.2026.5125

**Table 4. Fixed Effects Model (FEM) regression results with Driscoll-Kraay standard errors.** Notes: Driscoll-Kraay standard errors are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The dependent variable is REC (Renewable Energy Consumption, %).

| **Variable** | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| | REC | REC | REC | REC |
| FD | | -0.015 | -0.021 | -0.150* |
| | | (0.012) | (0.014) | (0.081) |
| HC | | | 0.183** | 0.152* |
| | | | (0.088) | (0.090) |
| FD × HC | | | | 0.0022*** |
| | | | | (0.0007) |
| lnGDP | -3.154** | -3.189** | -3.401*** | -3.512*** |
| | (1.410) | (1.425) | (1.305) | (1.288) |
| FDI | 0.281* | 0.275* | 0.250 | 0.231 |
| | (0.160) | (0.162) | (0.158) | (0.155) |
| lnEP | 2.553** | 2.510** | 2.418** | 2.350** |
| | (1.120) | (1.131) | (1.095) | (1.076) |
| ln$CO_2$ | 4.120*** | 4.098*** | 3.875*** | 3.654*** |
| | (0.955) | (0.962) | (0.910) | (0.899) |
| Constant | 25.018** | 25.881** | 10.215 | 18.754* |
| | (10.55) | (11.02) | (13.51) | (10.98) |
| Observations | 352 | 352 | 352 | 352 |
| Number of countries | 16 | 16 | 16 | 16 |
| $R^2$ (within) | 0.283 | 0.285 | 0.331 | 0.384 |
| Fixed Effects | Yes | Yes | Yes | Yes |
| Time Effects | Yes | Yes | Yes | Yes |

Hypothesis $H_2$ is tested in Column (3). The coefficient of human capital (HC) is 0.183 and is statistically significant at the 5% level ($p < 0.05$). This finding confirms hypothesis $H_2$, indicating that investing in human capital, specifically improving secondary education levels, has a positive and direct impact on increasing the share of renewable energy. This is consistent with the argument that a more educated labor force will have better environmental awareness and sufficient skills to adopt clean energy technologies.

The central analysis of the study is in Column (4), where we test the moderating role of human capital (hypothesis $H_3$) by including the interaction term (FD × HC). The most important result is presented here. The coefficient of the interaction term (FD × HC) is positive (0.0022) and highly statistically significant at the 1% level ($p < 0.01$). This result provides strong empirical evidence supporting hypothesis $H_3$: Human capital plays a positive moderating role in the relationship between financial development and renewable energy consumption.

More notably, the coefficient of the FD variable now becomes negative (-0.150) and is statistically significant at the 10% level. This finding implies that the impact of financial development on renewable energy is conditionally dependent on the level of human capital. Specifically, when human capital is low, expanding credit to the private sector may even have a negative impact on renewable energy consumption, possibly because capital flows preferentially to traditional, carbon-intensive, and more profitable industries. Only when a country accumulates sufficient human capital can financial resources be effectively transformed into green energy projects. In other words, human capital is not merely a catalyst but also a prerequisite for 'unlocking' the potential of financial development in promoting the energy transition.

To visualize this moderating mechanism, we plot the marginal effect of financial development (FD) on renewable energy consumption (REC) at different levels of human capital (HC), based on the results from Column (4).

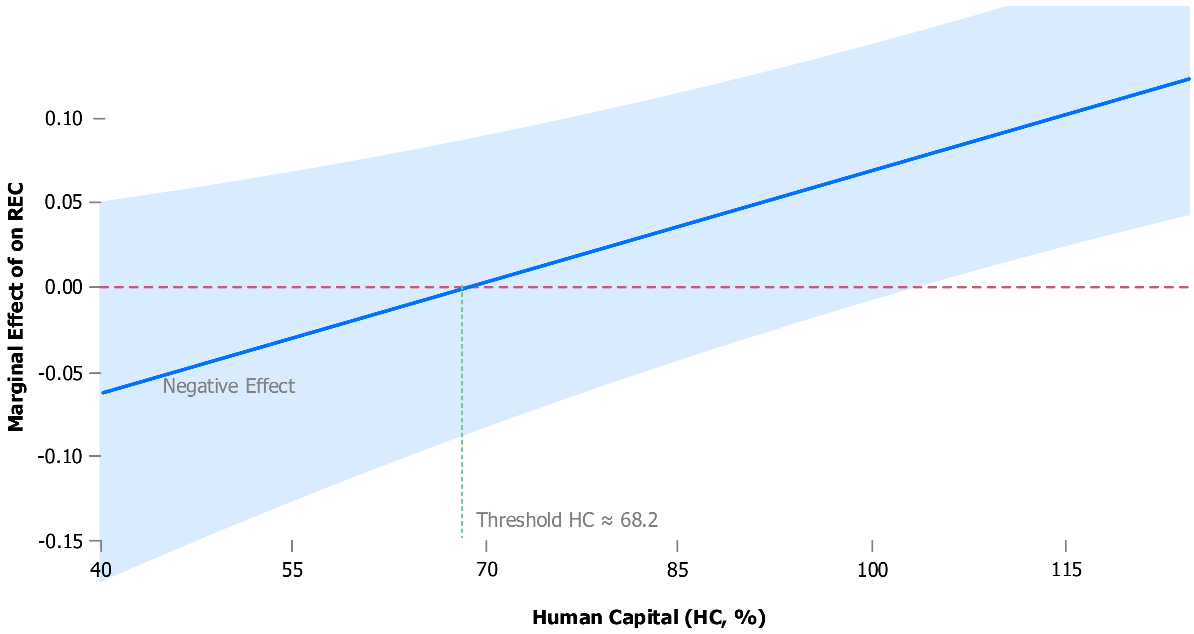


**Figure 1. Marginal effect of financial development on renewable energy consumption with 95% Confidence Intervals at varying levels of Human Capital.**

Figure 1 clearly illustrates the moderating mechanism of human capital. The marginal effect line has a positive slope and crosses the horizontal axis (y=0). This shows that:

- When human capital is at a low level (specifically, below the threshold of about 68.2%), the impact of financial development on renewable energy consumption is negative. The entire 95% confidence interval lies below the zero line, indicating that this negative impact is statistically significant.
- This threshold value is calculated directly from the regression coefficients of model (4) in Table 4. The marginal effect of financial development (FD) on renewable energy consumption (REC) is determined by the equation: ∂(REC)/∂(FD) = β_FD + β_(FD×HC) * HC. Substituting the estimated coefficients, we have: Effect of FD = -0.150 + 0.0022 * HC. The threshold is determined at the point where this effect is zero, i.e., HC = -(-0.150) / 0.0022 ≈ 68.2. This provides a clear quantitative basis for analyzing the moderating effect of human capital.
- When human capital exceeds the 68.2% threshold, the impact of financial development starts to become positive. As human capital increases, this positive impact becomes stronger and more statistically significant (the 95% confidence interval lies entirely above the zero line).

### Controlling for endogeneity

One of the biggest challenges in macroeconomic analysis is the problem of endogeneity, which can arise from three main sources:

1. Reverse causality (increased renewable energy consumption might attract more financial investment and demand higher-quality human resources, not just a one-way relationship).
2. Measurement errors in variables.
3. Omitted variable bias from unobservable factors that change over time.

If not addressed, endogeneity can lead to biased and inconsistent coefficient estimates, undermining the reliability of the conclusions drawn.

To address endogeneity concerns and affirm the robustness of the baseline results from the FEM model, we use the two-step System Generalized Method of Moments (Two-step System GMM) developed by Arellano & Bover (1995) and Blundell & Bond (1998). This method is particularly suitable for panel datasets with a relatively large time series (T) and a small number of cross-sections (N), as in this study. System GMM combines a system of equations in differences (using lagged levels as instruments) and a system of equations in levels (using lagged differences as instruments). This approach not only helps control for unobserved fixed effects but also effectively addresses endogeneity issues by using internal instruments from the dataset itself.


DOI: 10.55643/fcaptp.2.67.2026.5125

Table 5 presents the estimation results from the Two-step System GMM model. To ensure rigor, we use robust standard errors and limit the number of instruments to avoid the "too many instruments" problem, a risk that can weaken the Hansen test.

**Table 5. Two-step system GMM estimation results.** Notes: Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The dependent variable is REC. L.REC is the first-order lagged value of the dependent variable.

| Variable | (5) |
|---|---|
| | REC |
| L.REC | 0.650*** (0.098) |
| FD | -0.125* (0.071) |
| HC | 0.110** (0.054) |
| FD × HC | 0.0019*** (0.0006) |
| lnGDP | -2.850** (1.355) |
| FDI | 0.198 (0.140) |
| lnEP | 1.985** (0.912) |
| $lnCO_2$ | 3.104*** (1.021) |
| Constant | 15.432* (8.995) |
| Number of observations | 336 |
| Number of countries | 16 |
| Number of instruments | 14 |
| Hansen test (p-value) | 0.215 |
| AR(2) test (p-value) | 0.458 |

The results from Table 5 provide robust evidence that reinforces the main findings of the study. First, the suitability of the GMM model is confirmed by important diagnostic tests. The Hansen test of over-identifying restrictions has a p-value of 0.215, which is greater than the 0.1 threshold. This indicates that the null hypothesis that the set of instruments used is valid is not rejected, confirming the validity of the instruments. At the same time, the Arellano-Bond test for second-order autocorrelation in first differences (AR(2)) has a p-value of 0.458 (greater than 0.1), showing no evidence of second-order autocorrelation in the errors. These results together affirm the validity and reliability of the System GMM estimation.

When analyzing the coefficients, we find that the results from the GMM model are very consistent with the previous Driscoll-Kraay FEM model. The coefficient of the lagged dependent variable (L.REC) is positive and highly significant, indicating inertia or path dependence in the energy consumption structure of Asian countries.

Most importantly, the coefficients of the main variables retain their signs and statistical significance. The coefficient of the interaction term FD × HC is 0.0019 and is highly significant at the 1% level. Although the magnitude has changed slightly compared to the FEM estimate, its positive sign and strong statistical significance remain unchanged. This reaffirms our conclusion: human capital indeed plays a positive moderating role, "unlocking" the impact of financial development on renewable energy consumption. Similarly, the coefficient of FD remains negative (-0.125), and that of HC remains positive (0.110), consistent with the analyzed moderating mechanism. This shows that the complex moderating relationship we found is not a random result or seriously affected by endogeneity, but a genuine structural feature in the link between finance, education, and clean energy in developing and emerging Asian economies.

### Sensitivity analysis and robustness checks

To confirm that the main results of the study, particularly the moderating role of human capital, are not specific to the particular choices of variable measures or research sample, we conduct robustness checks. The results of these checks are summarized in Table 6.

**Table 6. Robustness checks.** Notes: Driscoll-Kraay standard errors are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The dependent variable is REC. Column (1) uses an alternative measure for Financial Development (FD_alt): "Commercial bank assets (% of GDP)". Column (2) uses an alternative measure for Human Capital (HC_alt): "School enrollment, tertiary, gross (%)". The number of observations is lower due to less complete data availability for tertiary enrollment. Column (3) presents the regression results for the sub-sample of ASEAN countries (Vietnam, Indonesia, Malaysia, Philippines, Thailand). Column (4) presents the regression results for the sub-sample of the remaining countries in the sample. Column (5) tests for a non-linear relationship by adding the squared term of Financial Development ($FD^2$) to the full model from Column (4) of Table 4.

| Variable | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | REC | REC | REC | REC | REC |
| FD | | -0.141* | -0.165** | -0.129 | 0.051* |
| | | (0.084) | (0.079) | (0.091) | (0.028) |
| $FD^2$ | | | | | -0.0003** |
| | | | | | (0.0001) |
| FD_alt | -0.095 | | | | |
| | (0.062) | | | | |
| HC | 0.148* | | 0.191** | 0.135 | 0.139* |
| | (0.088) | | (0.085) | (0.099) | (0.081) |
| HC_alt | | 0.105** | | | |
| | | (0.049) | | | |
| FD × HC | | | 0.0028*** | 0.0017** | 0.0021*** |
| | | | (0.0008) | (0.0008) | (0.0007) |
| FD_alt × HC | 0.0018** | | | | |
| | (0.0008) | | | | |
| FD × HC_alt | | 0.0020*** | | | |
| | | (0.0006) | | | |
| Controls | Yes | Yes | Yes | Yes | Yes |
| Fixed Effects | Yes | Yes | Yes | Yes | Yes |
| Time Effects | Yes | Yes | Yes | Yes | Yes |
| Observations | 352 | 341 | 115 | 237 | 352 |
| Number of countries | 16 | 16 | 5 | 11 | 16 |
| $R^2$ (within) | 0.365 | 0.371 | 0.412 | 0.359 | 0.401 |

In Column (1) of Table 6, we replace the "Domestic credit to private sector" indicator with "Commercial bank assets (% of GDP)" (FD_alt) as a measure for financial development. In Column (2), we replace "Secondary school enrollment" with "School enrollment, tertiary, gross (%)" (HC_alt) to capture a higher level of human capital. The results show that even when using these alternative measures, our core finding remains unchanged. The coefficients of the interaction terms (FD_alt × HC in Column (1) and FD × HC_alt in Column (2)) are still positive and highly statistically significant (0.0018 at the 5% level and 0.0020 at the 1% level, respectively). This confirms that the positive moderating role of human capital is not a phenomenon dependent on a specific definition, but a structural feature in the relationship between finance, education, and renewable energy.

The Asian countries in the sample are diverse in terms of institutions, level of integration, and policy priorities. To check whether our findings are consistent across different contexts, we split the sample into two groups: member countries of the Association of Southeast Asian Nations (ASEAN) and the remaining countries. Columns (3) and (4) of Table 6 present the regression results for these two groups separately. The results show that the direction of the moderating effect of human capital remains consistent in both groups, reinforcing the generalizability of the finding. However, a noteworthy difference emerged. When we analyze the ASEAN countries separately (Column 3), the moderating effect of human capital appears to be even stronger (interaction coefficient is 0.0028) compared to the group of remaining countries (coefficient is 0.0017). This could be explained by the deeper economic integration, policy coordination, and strong common commitments to sustainable development and energy transition within the ASEAN framework. This regional cooperation environment may create a favorable condition for human capital and financial resources to combine more effectively, promoting renewable energy projects.


DOI: 10.55643/fcaptp.2.67.2026.5125

Finally, we consider the possibility of a more complex non-linear relationship between financial development and renewable energy consumption, rather than a simple linear one. To test this possibility, we included the square of the financial development variable ($FD^2$) in the full model (Column 5, Table 6). The results show that the coefficient of FD is positive (0.051) while the coefficient of $FD^2$ is negative (-0.0003), and both are statistically significant. This suggests the existence of an inverted U-shaped relationship in the direct impact of financial development on renewable energy consumption. Specifically, in the early stages, financial development can promote renewable energy, but after exceeding a certain threshold (around 85% of GDP, calculated by the formula $-\beta\_FD / (2*\beta\_FD^2)$), further financial expansion may prioritize carbon-intensive industries, reducing the share of renewable energy.

However, the most important finding is that even when controlling for this non-linear relationship, the coefficient of the interaction term (FD × HC) remains positive (0.0021) and highly statistically significant at the 1% level. This indicates that the moderating role of human capital is an independent mechanism. Regardless of the shape of the direct impact of financial development, possessing a high-quality human capital base remains the decisive factor in helping to transform financial resources into positive outcomes for the green transition.

## DISCUSSION

### Interpretation of main results and comparison with previous studies

The core and most significant finding of this study is that the role of financial development (FD) on renewable energy consumption (REC) is not a universal constant, but is conditionally dependent on the level of human capital (HC). Specifically, when considered independently, we find no statistical evidence that FD has a positive impact on REC. This result, at first glance, may seem to contradict hypothesis $H_1$ and run counter to a stream of research supporting a positive relationship (e.g., Anton & Nucu, 2020; Wang et al., 2023). However, it aligns with another group of studies that found no clear link or even reported a negative impact (e.g., Charfeddine & Khediri, 2016; Nguyen et al., 2021).

The contradiction in previous studies is the starting point of this research, and our results have shown that simple linear models have overlooked a crucial moderating variable: human capital. Our findings raise a question about the universality of the finance-growth theory's assumptions when applied to the green sector. The results show that the mere provision of capital does not guarantee it will automatically flow to the most effective projects; rather, the effectiveness of this capital flow depends profoundly on other intrinsic factors of the economy, specifically human capital. Our results not only support but also extend the application of the theory of absorptive capacity (Cohen & Levinthal, 1990) within the context of energy and finance. In this context, financial capital is an external resource, and human capital is the economy's "absorptive capacity." Without a sufficiently strong absorptive capacity, manifested through a skilled and educated labor force, abundant capital can be misallocated.

In the practical context of developing and emerging Asian countries, this is particularly true. These nations often face short-term economic growth pressures, causing financial channels to tend to prioritize traditional, carbon-intensive industries that already have established business models and clear profitability. Renewable energy projects, despite their long-term benefits, are still considered riskier due to high technological requirements, long payback periods, and policy dependence. Therefore, without a high-quality workforce capable of developing green projects with sound financial structures and acceptable risk profiles, financial institutions, in their process of risk minimization, will tend to prioritize capital allocation to safer, traditional investment channels. This inadvertently creates a significant financial barrier to the green transition.

### Analysis of marginal effects and the human capital threshold

An interesting finding of this study is the quantification of human capital's moderating role through the analysis of marginal effects (Figure 1). The results reveal a human capital threshold, corresponding to a secondary school enrollment rate of about 68.2%, which is the critical point that alters the impact of financial development.

Below the 68.2% threshold: The impact of FD on REC is negative and statistically significant. This means that in countries with a limited educational foundation, expanding credit to the private sector not only fails to promote but may even reduce the share of renewable energy. For instance, an Asian country has a low secondary enrollment rate (e.g., 50%). When this country's banking system develops and provides more loans, this capital is likely to be channeled into expanding textile factories, cement production, or other industries that use low-skilled labor and old technology, which are fossil-fuel intensive. The reason is that the economy lacks viable renewable energy projects due to an insufficient number of engineers to design, manage, and operate them.

Above the 68.2% threshold: The impact of FD on REC becomes positive and grows stronger as HC increases. This indicates that human capital is the key factor that helps the economy absorb and effectively utilize financial capital, thereby realizing its benefits for the renewable energy sector. For example, a country in the region that has invested heavily in education and has a secondary enrollment rate of 90%. Here, a skilled labor force has formed, along with a middle class with high environmental awareness. As the financial system develops, banks and investors will find many attractive investment opportunities in solar farms, wind power projects, etc., because these projects are developed and managed by competent professionals, reducing risk and increasing feasibility. At this point, finance becomes a true driver for the green transition.

Identifying such a quantitative threshold is not only statistically significant but also carries immense practical value, providing a concrete policy target for countries.

**Heterogeneity in the moderating role: Sub-sample analysis**

When analyzing the ASEAN and non-ASEAN groups separately, we found that the positive moderating role of human capital is a consistent feature, reinforcing the robustness of the results. However, another interesting finding is that this moderating effect appears to be stronger in the ASEAN group (interaction coefficient of 0.0028 versus 0.0017 in the other group).

This difference can be explained by the unique regional cooperation context of ASEAN. ASEAN countries do not just develop individually but are also closely linked through economic and policy cooperation frameworks. Particularly in the energy sector, common commitments such as the ASEAN Plan of Action for Energy Cooperation (APAEC) have created a favorable environment, promoting the sharing of experiences, technology transfer, and policy harmonization. This cooperative environment can create positive spillover effects, helping member countries to more effectively leverage financial and human capital to jointly advance renewable energy goals. This deeper level of integration and policy coordination may be the factor that amplifies the synergy between finance and human capital, something that the group of remaining countries (which is more diverse and less connected) does not have to the same degree.

**The non-linear relationship between financial development and renewable energy**

The robustness check results in Column (5) of Table 6 revealed the non-linear nature of the relationship: the direct impact between FD and REC follows an inverted U-shape. This implies that in the initial stage, as the financial system begins to develop, it helps mobilize capital for renewable energy projects, thus having a positive effect. However, when financial development surpasses a certain threshold (around 85% of GDP), the impact can become negative. This phenomenon can be explained by the tendency of a developed financial system to favor incumbent industries. At this level, financial institutions may become too large and focused on maximizing short-term profits through complex transactions, prioritizing financing for large, established industrial corporations (often carbon-intensive sectors) over newer, riskier renewable energy projects.

However, the most crucial finding is that even when controlling for this non-linear relationship, the positive moderating role of human capital (through the FD × HC interaction term) remains very strong and statistically significant. This indicates that human capital is a foundational mechanism, capable of mitigating the negative tendencies of an overdeveloped financial system by continuously creating attractive green projects and a favorable institutional environment to attract capital.

**Contributions of the study**

This study contributes to the existing body of knowledge in several important ways:

- *Theoretically*, the study resolves one of the major contradictions in the empirical literature on the FD-REC relationship. Instead of simply concluding that the relationship is positive, negative, or unclear, we show that the answer depends on a prerequisite: human capital. By placing absorptive capacity theory at the center, the study has provided a more complete theoretical framework for understanding the complex linkage among finance, education, and energy transition.
- *Empirically:* This is one of the first studies to systematically test and quantify the moderating role of human capital in the context of developing and emerging Asian economies. The identification of a specific threshold value for human capital is a new and groundbreaking contribution, shifting discussions from qualitative to quantitative.
- *Policy-wise:* The study's findings deliver a strong and clear message to policymakers: focusing solely on financial reform is insufficient and can even be counterproductive. To successfully promote the transition to clean energy, countries need to pursue a dual strategy, synchronously combining the development of an effective financial system with strong, strategic investment in high-quality education and human resource training.


DOI: 10.55643/fcaptp.2.67.2026.5125

### Limitations

Although we have achieved the research objectives, we are aware that our study has inherent limitations. First, the macro-level measures, especially the financial development index based mainly on the banking system and the renewable energy index that includes traditional biomass, may not fully capture the complexity of the green capital market and the transition to modern energy. Second, this study focuses on Asian countries, so the generalizability of the results needs to be further tested in other geographical regions.

## CONCLUSIONS

This study affirms that human capital is the decisive moderating factor that reshapes the complex relationship between financial development and renewable energy consumption in developing and emerging Asian countries. We reject the assumption of a simple linear relationship, instead showing that the impact of financial development is conditionally dependent on a nation's educational foundation. Our core finding reveals the existence of a critical point of human capital: below this level, credit expansion can be counterproductive, but once surpassed, finance becomes a driver for the green transition.

By quantifying this role, the study has resolved the existing contradiction in previous empirical works. Our results provide robust evidence that human capital is the 'absorptive capacity'—an indispensable prerequisite for transforming financial resources into viable renewable energy projects. Therefore, this study not only adds a new dimension to current theory but also provides a more complete analytical framework, emphasizing the structural interaction among finance, education, and sustainable energy.

### *Policy implications*

The research findings offer practical policy implications for policymakers in developing and emerging Asian countries.

First, policies focused solely on financial reform are insufficient and potentially harmful. Merely expanding credit without concurrently enhancing the quality of human resources risks misallocating capital to carbon-intensive industries, thereby slowing down the energy transition. Therefore, policymakers must abandon single-sector thinking and recognize that financial development is not a sole and comprehensive solution.

Second, this study recommends a dual, synchronized strategy. Governments need to closely integrate financial development goals with long-term investment strategies for education. Specifically, prioritizing the expansion and quality improvement of education to surpass the absorptive capacity threshold we have identified is a measurable and strategic policy objective.

Finally, inter-ministerial coordination, especially between financial and educational regulatory bodies, is paramount. Designing integrated policy packages, where financial incentives for green energy are linked to skills training and human resource development programs, will create a virtuous cycle, maximizing the effectiveness of both sectors and accelerating the path toward a sustainable energy future.

### *Future research directions*

Future research could expand on this direction by using more multidimensional indicators for the main variables, such as composite indices of financial development (including stock markets and green bonds) and a clear separation between modern and traditional renewable energy. Furthermore, analysis at the industry or firm level would provide deeper insights into the actual capital allocation channels, clarifying how human capital affects green investment decisions at the micro level.

## ADDITIONAL INFORMATION

### AUTHOR CONTRIBUTIONS

*All authors have contributed equally.*

### FUNDING

*This research is funded by University of Finance – Marketing Ho Chi Minh, Vietnam.*

## CONFLICT OF INTEREST

*The Authors declare that there is no conflict of interest.*

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## ФІНАНСОВИЙ РОЗВИТОК І СПОЖИВАННЯ ВІДНОВЛЮВАНОЇ ЕНЕРГІЇ: ПОМ'ЯКШУВАЛЬНА РОЛЬ ЛЮДСЬКОГО КАПІТАЛУ

Це дослідження має на меті розв'язати невідповідність в емпіричній літературі щодо зв'язку між фінансовим розвитком (FD) і споживанням відновлюваної енергії (REC), перевіряючи гіпотезу про те, що людський капітал (HC) відіграє ключову роль у модерації. Використовуючи незбалансований панельний набір даних із 16 економік, що розвиваються, та країн, що розвиваються, в Азії з 2000 по 2022 рік, ми застосовуємо Модель фіксованих ефектів (FEM) зі стандартними помилками Дрісколла-Края та системний узагальнений метод моментів (System GMM) для контролю ендогенності та поперечної залежності. Емпіричні результати показують, що при незалежному розгляді фінансовий розвиток не має суттєвого впливу на споживання відновлюваної енергії. Однак ми знаходимо вагомі докази позитивної пом'якшувальної ролі людського капіталу. Зокрема, вплив фінансового розвитку на відновлювану енергетику є негативним у країнах із низьким рівнем людського капіталу, але стає позитивним і статистично значущим, коли людський капітал перевищує критичний поріг (що відповідає рівневі зарахування до середньої школи приблизно 68,2%). Головний висновок дослідження полягає в тому, що людський капітал є не лише незалежним рушієм, а й передумовою, «поглинальною здатністю», яка допомагає перетворювати фінансові ресурси на ефективні проєкти відновлюваної енергетики; це демонструє, що ефективність фінансового розвитку в спри-янні зеленому переходові умовно залежить від освітньої основи країни. Цей висновок має значний вплив на полі-тику: стратегії, що зосереджені виключно на фінансових реформах, є недостатніми й можуть бути контрпродукти-вними. Для успішного просування енергетичного переходу політики повинні дотримуватися подвійної стратегії, синхронно поєднуючи розвиток фінансової системи зі стратегічними інвестиціями в освіту й навчання кадрів, щоб максимізувати синергію між фінансами та знаннями.

**Ключові слова:** азійські економіки, фінансовий розвиток, людський капітал, споживання відновлюваної енергії, абсорбційна спроможність, енергетичний перехід, пороговий ефект

**JEL Класифікація:** Q42, O13, J24, G21