The Moderating Role of Human Capital on the Relationship Between Globalization and Green Technology Adoption in Emerging Economies

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Abstract

Shifting to clean or green energy technologies is important for emerging economies that aim to separate economic growth from environmental harm. Existing research has already proved that globalization channels—such as economic, social, trade, and financial globalization—have promoted the adoption of green technology. However, a significant gap remains in understanding how a country's internal human capital influences this international spillover. We used 22 years of yearly data from 25 emerging economies from 2000 to 2021. This paper explores whether local human capital influences the way dimensions of globalization impact the adoption of green technology across emerging economies using a two-step System GMM methodology . The empirical evidence suggests that in the case of economic, social, and trade globalization, they cannot solely impact the adoption of green technology across emerging economies. Conversely, their interaction with local human capital has a robust and significant impact on technology adoption. Among all the dimensions, only financial globalization independently facilitates the adoption of clean energy. Simultaneously, leveraging human capital significantly enhances the link between globalization and green technology, nearly doubling the adoption rate. These findings imply that, without skilled technicians and engineers, imported technologies may be underused or remain unused in warehouses. This highlights that the advantages of green technology transfer heavily rely on having a skilled workforce to implement the transition. To this finding, we propose some policy recommendations for governments in emerging economies: They should step away from the idea of trade liberalization and invest more in bringing in advanced technology, dedicated STEM education, compulsory green training contracts for their corporate employees , and upskilling of labor to overcome the mismatch in skill sets.

Keywords: Green Technology Adoption, Globalization, Human Capital, Absorptive Capacity, System GMM, Emerging Economies.

1 Introduction

Emerging market economies are facing a difficult situation in the global development landscape right now. On the one hand, they face internal pressure to maintain higher economic growth to address socio-ecological problems such as poverty, inequality, and infrastructure development, and to enhance the standard of living for the growing population. On the other hand, this economic growth has negative side effects that transcend local borders and will have an impact at the global level: global environmental issues such as rising temperatures, rising sea levels, forced climate migration, and the loss of millions of species (Abbass et al., 2022). Even a major emerging economy like China, which has experienced rapid growth in manufacturing and global trade over recent decades, has suffered significant negative impacts from this development due to its heavy reliance on fossil fuels to fulfill rising energy needs. (Economy, 2013). This encompasses rising CO2 emissions, deteriorating air and water quality, and excessive use of natural resources (Erumban et al., 2019). Thus, rapidly growing environmental issues require an urgent move towards cleaner production methods and sustainable development.

The rise of global environmental challenges is linked to twin pressures on the economy in emerging economies over the past few decades, namely structural transformation (industrialization) and rising global integration. However, industrialization is an important part of economic growth in emerging economies (Lewis, 2013; Ranis & Fei, 1961). The existing literature confirms that as industrialization increases in emerging economies, there is a structural shift from agriculture to industry. Because the industry relies on heavy machinery and plants, energy demand increases. This increase in energy demand is largely met by non-renewable sources such as fossil fuels (Sadorsky, 2014), and non-renewable energy is the primary driver of environmental degradation. (Khan et al., 2023). Furthermore, the rapid pace of global integration has been responsible for the rise in global demand for products and services, creating a parallel need for more power. Global integration is highly dependent on energy demand, largely met by non-renewable sources, which worsens environmental degradation (Shahbaz et al., 2017a). Furthermore, trade liberalization often leads to increased pollution in emerging economies by shifting pollution-intensive production to regions with lax environmental laws. (Onwachukwu et al., 2021).

To address these worldwide environmental risks, member countries made a legally binding international treaty at the Paris UN Climate Conference (COP21). The treaty made it mandatory to limit the global temperature increase to below 2°C above the pre-industrial era, with an aspirational goal of keeping it under 1.5°C. To meet these targets, countries must create national strategies to tackle these environmental challenges. (UNFCCC, 2015). In this context, shifting toward clean energy has emerged as a key solution to decouple economic growth from environmental degradation. Existing research shows that advanced economies, such as the OECD, the USA, and the EU, have reduced environmental degradation through the use of clean energy (Özkan et al., 2023; Hou et al., 2023). However, for emerging economies, transformation is challenging due to carbon lock-in and high technology costs.

On the other hand, globalization offers a pathway for emerging economies to overcome these domestic challenges. Through multidimensional pathways of globalization, such as global value chains, FDI, trade openness, and cultural exchanges, developing countries gain the vital ability to import advanced clean technologies from wealthier nations (Elfaki & Ahmed, 2024; Bilal et al., 2022). However, simply having environmental technologies available is not enough to guarantee their domestic adoption. As Cohen & Levinthal (1990) highlight, a country's internal absorptive capacity—determined by the depth and scale of its human capital—is a critical piece of the puzzle. If the nation lacks the necessary human resources to install, repair, and maintain the technology and adapt it to local needs, the technology will either be underused or left idle in government-funded warehouses.

This study has added to the existing research in two important ways: (1) it focuses on Green Technology. Adoption at the national level, while earlier works have touched on the diffusion or infusion of green technology, is one of the key results of globalization.(2) It presents econometric evidence that human capital acts as a buffer between globalization and the adoption of green technology

The remaining sections of this paper are organized as follows. Section 2 provides a review of the pertinent theoretical literature. Section 3 introduces existing theoretical literature. Section 4 details the data sources and the econometric methodology employed. Section 5 presents and elucidates the empirical results. Finally, Section 6 concludes with an overview of policy implications.

2 Literature Review

Globalization is a multidimensional phenomenon encompassing the expansion of trade, the liberalization of financial markets, the sharing of knowledge and technology, and the signing of international treaties to address both global and local issues (Gygli et al., 2019). It affects people's lives in many ways and is difficult to define narrowly because it spans economic, social, political, and cultural domains (Bodisla et al., 2017). The process has become increasingly important in emerging economies due to rising trade, foreign direct investment (FDI), and cultural and knowledge sharing. Globalization involves the dissemination of knowledge and the expansion of advanced technologies and ideas. technologies and manufacturing processes, thereby encouraging the adoption of cleaner, greener technologies (Verma et al., 2025). It also promotes better trade policies that lower trade barriers and supports green technologies (Bilal et al., 2021). Scholars such as Fu et al. (2025) and Xu (2024) have emphasized that globalization accelerates the adoption of green technologies. The current literature indicates that the policy goal should be to increase globalization to promote knowledge transfer and encourage environmentally friendly innovation (Verma et al., 2025).

2.1 The Multi-dimensional Impact of Globalization on Green Technology

2.1.1 Impact of Economic Globalization

Economic Globalization of the economy involves the increasing integration of global markets through the removal of trade and investment barriers. This promotes more trade and foreign investment (Chang & Lee, 2010). In the end, it makes countries more attractive to international investors. The literature holds two contrasting viewpoints regarding the impact of economic globalization on green technology uptake. First, they believe that economic globalization encourages the adoption of environmentally friendly technologies through three main channels. First, greater integration offers access to areas where advanced technologies are developed. This access reduces costs because these technologies can be imported via international trade (Garsous & Worack, 2022). Secondly, foreign direct investment (FDI) is a crucial element of economic development globalization. They are a means of transferring clean technology. Multinational companies in host countries tend to introduce eco-friendly technologies and processes, a phenomenon known as the 'Pollution Halo Hypothesis'. Third, countries with less trade restrictions or more trade liberalization tend to adopt environmental technologies earlier (Aydin et al., 2024). Likewise, it is clear that integrating digital technology, closely linked to economic globalization, supports faster and more sustainable economic growth in the Asia-Pacific region (Elfaki & Ahmed, 2024).

The second perspective suggests that foreign investors in the Philippines are more likely to introduce fewer clean technologies, which reduces the dissemination of green innovations (Abbass et al., 2022). Additionally, outward FDI in China (Luo et al., 2021) and long-term FDI in OECD countries (Behera & Sethi, 2022) have negatively affected green technology innovation.

2.1.2 Impact of Social Globalization

This part examines how global social change affects the adoption of green technology. Social globalization, defined as the worldwide exchange of culture, societal values, ideas, and knowledge, also increases demand for green innovations. Whereas economic globalization is largely market-driven, social globalization focuses on global consumer preferences and drives the adoption of sustainable technologies by individuals and companies (Fu et al., 2025). Researchers highlight those social interactions, such as peer influence, social trust, and societal pressures, play a crucial role in promoting technology adoption (Lio et al., 2025). Evidence shows that the social dimension of globalization has a greater influence on the uptake of renewable energy than the economic dimension (Nan et al., 2023). Furthermore, social globalization promotes eco-innovation, as demonstrated by the Driscoll-Kraay estimator model fitting analysis of G20 countries' data (Li et al., 2025). It also indirectly reduces energy intensity by disseminating environmental knowledge, technological skills, and sustainability principles globally (Maneejuk et al., 2026). Social globalization spreads eco-friendly ideas and attitudes through social media and the internet, thereby creating ecological awareness (Kirikkaleli & Adebayo, 2024). Therefore, sharing information and experiences through global social networks helps promote sustainable production and consumption practices (Kasap, 2026).

2.1.3 Impact of Trade Globalization

An Important part of Economic Globalization is the Trade Globalization which focus on free flow of product and services across globe through reduction in tariff and non-tariff barriers . It is a important for emerging economies to import clean advanced technologies. Scholars generally hold two perspectives regarding its influence on the adoption of green technology. From a first-person view, research tracking Bangladesh, India, Pakistan, Sri Lanka, and Nepal confirms that trade openness directly enhanced their capacity to import solar panels, wind turbines, and related infrastructure (Murshed, 2018; Oh, 2024). Ultimately, trade globalization drives economic growth and introduces advanced technologies, which lead to the implementation of more rigorous environmental regulations (Onwachukwu et al., 2021).

However, under the second view, scholars such as Guo (2021) and Amankwah (2016) argue that trade liberalization can lead to the flow of old, unused technologies from advanced economies to emerging economies. This can worsen environmental damage in those countries. Moreover, G7 research indicates that higher trade liberalization correlates with reduced production costs as a result of greater competition from around the world, ultimately possibly causing a decrease in sustainable practices (Qi, 2024).

2.1.4 Impact of Financial Globalization

Financial globalization involves connecting domestic financial markets with worldwide capital markets. It enhances cross-border investment, banking and financialization. The section provides an overview of existing studies related to the effect of financial globalization on green technology adoption. The costs of clean-energy projects, including large-scale solar and wind, smart-grid systems, and energy-storage technologies, are significant. These costs are typically higher than the budgets of many emerging-economy governments or private sectors. International financial markets like green bonds, impact investing, and development finance institutions can help bridge this funding gap by attracting foreign investment into clean energy initiatives (Majeed et al., 2022; Adebayo et al., 2025). Financial globalization can foster clean energy innovation and spread, as it can overcome financing constraints that may prevent emerging economies from investing in green infrastructure on a large scale (Fatima and Safdar, 2025). Based on Asian economies, Xu et al. (2024) offer evidence that the combination of financial development, innovation and good governance is essential for a successful energy transition. In contrast to other aspects of globalization which tend to contribute to access to technology or to norms, financial globalization provides a direct supply of economic resources to convert this access into investment. This is a unique situation in which adoption would be possible without relying too much on other factors.

2.2 Human capital plays a crucial role in driving technological diffusion.

Human capital includes the knowledge, skills, and practices that allow individuals to earn income and profits for themselves, their employers, and society. The components of human capital also encompass basic literacy and arithmetic skills, as well as knowledge and skills that a person has acquired and in which they have special expertise (Kuzminov et al., 2019). Education and training contribute to human capital by making people more productive. This results in higher lifetime earnings, fewer days of unemployment, and better working conditions (Saiti & Chletsos, 2024). Existing panel data studies on human capital, especially green human capital in China's manufacturing sector, show that a knowledgeable and skilled workforce understands sustainable development principles. This understanding significantly enhances innovation in clean energy technologies and environmentally friendly practices. (Abbas & Najam, 2025). Similarly, Khan et al. (2026) and Mubarik & Naghavi (2022) demonstrate that human capital alone enhances environmental awareness and the demand for green energy, leading to increased innovation and adoption of green energy while supporting ecological mitigation (Khan et al., 2025).. Economies aiming for sustainable development should encourage policymakers to focus on developing green human capital skills (Ni et al., 2025). Thus, a country's human capital plays a critical role in boosting clean energy adoption. Within the current research framework, multi-dimensional globalization and human capital are regarded as crucial factors influencing the adoption of green technology in both emerging and advanced economies. However, a significant gap exists in understanding how a country's domestic human capital affects the link between multidimensional globalization and green technology adoption. Specifically, current research has not explored how human capital interacts with globalization regarding green technology adoption. This suggests the need to explore how human capital influences the relationship between globalization and green technology adoption. Recognizing the importance of human capital, this research aims to determine whether it moderates the relationship between the dimensions of globalization and green technology adoption in emerging economies. The literature suggests that various forms of globalization have significantly increased the adoption of green technology. We expect that a country's human capital can enhance the connection between multidimensional globalization and green technology adoption.

This study, therefore, aims to explore the following hypothesis based upon different dimensions of globalization:

H1: The interaction between a country's human capital and economic globalization has a significantly positive effect on green technology adoption.

H2: Higher levels of national human capital positively condition the relationship between social globalization and the integration of clean technologies.

H3: Trade globalization requires a strong threshold of domestic human capital to optimally drive green technology adoption.

H4: The direct positive impact of financial integration on green technology adoption is further accelerated by domestic human capital assets.

3. Theoretical Model

3.1 Introduction

This chapter applies well-regarded theoretical perspectives to demonstrate that without an adequate level of local human capital, emerging nations cannot effectively adopt imported eco-friendly technologies. Although many economists view globalization as a primary driver of the spread of innovation and technology, this research shows that mere exposure to global markets is not enough. We contend that moving toward cleaner, greener technology heavily depends on the quality of domestic human resources. To substantiate this, we rely on three core frameworks: the Schumpeterian Frontier Opportunity (Aghion & Howitt, 1992, 1998), the Open-Economy Channels of Transmission (Grossman & Helpman, 1991), and the Augmented Theory of Absorptive Capacity (Nelson & Phelps, 1966; Benhabib & Spiegel, 1994). Using these theories, we support the development of the interaction term, which is the primary predicted outcome of this study interaction term ($GLOB_{it} \times HC_{it}$) which is the main predicted result from this study.

3.2 The Technological frontier and catch-up opportunities and Open Economy

This section employs the Schumpeterian Frontier Opportunity (Aghion & Howitt, 1992, 1998) and the Open-Economy Channels of Transmission (Grossman & Helpman, 1991) to examine how emerging economies reduce the existing technological gap via global integration.

According to Schumpeterian Frontier Opportunity theory, the worldwide technological level is represented by the Global Technological Frontier, while domestic technology lags behind it. Using Aghion and Howitt (199), represent the global technological frontier at time t as growing at a constant exogenous rate g, and let a_i denotes the technology frontier of an emerging economy *i*. The technological gap in an economy can be expressed as:

$$a_{it} = \frac{a_i}{A_t}$$

Where $a_{it} \in (0,1)$. As,a_{it} depicts the technological gap; a lower value signifies a wider technological gap, whereas a higher value indicates a narrower technological gap in the case of an emerging economy.

According to the convergence literature initiated by Gerschenkron (1962) and later formalized in modern Schumpeterian theory, this technological gap is actually described as a unique “advantage of backwardness." For economies at the frontier, achieving productivity growth requires genuine, resource-intensive innovation through R&D. In contrast, emerging economies with a low level of technological development mainly grow by imitating and adapting existing frontier technologies. Since copying or importing technology is much cheaper than developing new inventions, a larger technological gap theoretically offers greater potential for rapid catch-up growth through deeper integration with the world.

According to the Schumpeterian frontier model, catching up is not certain. The rate at which emerging economies catch up relies on their domestic conditions. There is a lot of non-rival knowledge at the global frontier, but the tacit and uncodified aspects of technology require a certain level of domestic capacity, often measured by institutions and human capital, for adoption. If the country is unable to adopt new technologies, the technology gap might create a vicious circle of lagging behind rather than moving forward. This reflects the value of human capital, which is discussed in the next section.

3.3 The Macroeconomic Level: Absorption Capacity Perspective and Human Capital's Moderating Role

Globalization is important in narrowing the technology gap for emerging economies, but the effectiveness of technology depends on local structural constraints such as human capital. This study confirms this relationship by drawing on Endogenous Growth and Technology Diffusion Theory (Nelson & Phelps, 1966; Benhabib & Spiegel, 1994) to account for countries' ability to absorb technology. Nelson and Phelps (1966) state that the concept of human capital is not only regarded as a production factor but also plays a significant role in the rate at which a country can adopt and utilize new technologies. Benhabib and Spiegel (1994) used this idea to develop an empirical model for comparing countries. They showed that the speed at which a country adopts a new technology depends on two main factors: local human capital and global integration. Clean technologies are advanced technologies that will not simply function if a country imports them. They also need skilled human capital with sufficient knowledge to perform installation, operation, and repair.

This can be further explained through two scenarios :

(1) Low Human Capital: If a country opens its border, then the imported advanced clean technology, like solar panels and other green equipment, will start flooding into the country. However, if the domestic human capital lacks trained engineers, technicians, or project managers, then no one knows how to set up machinery, operate it optimally, or repair it when needed. Then, this expensive green technology will end up in the storerooms as a total waste. Globalization brought green technology to the adoption stage, but insufficient human capital resulted in little to no adoption.

(2) High Human Capital: If a country opens its border, then the imported advanced clean technology will start flooding into the country again, but if the domestic human capital is highly skilled and has STEM education, then they can easily not install it but repair it locally, and make some modifications in the technology according to the requirements of the country.

3.4: Theoretical Rationale for Control Variables

To ensure that the moderating impact of human capital on the relationship between globalization and green technology adoption is isolated and unbiased , a theoretical framework to justify control variable is provided . Each control variable is chosen based on established economic theories:

(1) GDP per Capita: This measure captures the macroeconomic development level within emerging nations. Grounded in the EKC framework, its inclusion assumes that rising income levels afford countries the financial flexibility to invest heavily in clean technologies. We therefore hypothesize a positive correlation between GDP per capita and the integration of green technology.

(2) CO2 per Capita: This acts as a proxy of the pollution due to the existing energy infrastructure. Therefore, high carbon emissions signal a carbon lock-in scenario. Economies highly dependent on fossil fuels for energy production find it difficult to shift because of huge sunk costs and political/institutional constraints. Thus, a negative relationship is anticipated.

(3) Urbanization: This describes the migration of people from rural regions to urban areas seeking a better quality of life. However, this shift worsens energy consumption patterns. Evidence shows that urbanization in developing countries raises electricity demand. This leads these countries to rely more on non-renewable sources, such as fossil fuels, to meet that demand. As a result, urbanization can hinder the growth of green energy infrastructure and harm clean energy adoption

(4) Institutional Quality: This factor considers the effectiveness, reliability, and equity of a country's laws, governance, and regulations. Better Institutional Quality means less corruption and the effective use of funds for sustainable projects, rather than their waste. Therefore, we can expect a positive relationship.

4:Data, Variables, and Estimation Framework

The conceptual definition and data channels used in the empirical study are mapped out in this section. Furthermore, it clarifies the reasons why the specific econometric techniques were the most appropriate to address the main study objectives.

4.1 Data Description

This analysis is based on an annual panel data set on 25 emerging market countries between 2000 and 2021 and classifies countries according to the categories of the International Monetary Fund (IMF) and its World Economic Outlook. This country-year matrix was the only one which was dependent on the data accessibility across multiple prominent repositories. In the context of the extreme acceleration of industrialization, the increasing global interdependence, the growing ecological strain and human capital reserves, it is more important than ever to study these emerging countries. The dependent variable used in this research is Green Technology Adoption, which is measured by the ratio of renewable energy consumption from World Bank's World Development Indicators (WDI) to total energy consumption. This measure can reflect a state's transition to renewable energy. Explanatory factors are four main aspects of globalization: economic, trade, financial and social. Both are assessed using separate model specifications of the KOF Globalization Index de facto measures. Local skills of the workforce are taken into account by considering the Human Capital Index from the Penn World Table database. This model uses a set of control variables from the WDI such as per capita GDP, urbanization and carbon dioxide (CO2) emissions. It also incorporates the V-Dem Liberal Democracy Index for institutional quality and finally, it guarantees strong empirical estimates. In Table 1 you can find the detailed descriptions and setups of all of these indicators.

Table 1

Definition and sources of variables

Variable Name	Measurement	Data Source
Dependent Variable Green Technology Adoption	Renewable energy consumption (% of total final energy consumption)	WDI , World Bank
Key variables:		
Human Capital	Human Capital Index	Penn World Table
Economic globalization	KOF Economic Globalization Index, De Facto	KOF Globalization Index
Trade Globalization	KOF Trade Globalization Index, De Facto	KOF Globalization Index
Financial Globalization	KOF Financial Globalization, De Facto	KOF Globalization Index
Social Globalization	KOF Globalization, Facto Social De	KOF Globalization Index
Control Variables:		
Urbanization	Urban population as a share of the total Population	WDI, World Bank
GDP per capita	GDP per capita (constant 2015 US$)	WDI, World Bank
Institutional Quality	Liberal Index Democracy	V-Dem Dataset
CO2 per capita	Carbon dioxide emissions (CO2) excluding LULUCF per capita (t CO2e/capita)	WDI, World Bank

4.2 Model

This study aims to evaluate the individual impacts of four globalization types—economic, trade, social, and financial—on the adoption of green technology. Furthermore, we seek to understand how the interaction of each of these forms of globalization with a country's human capital index influences green technology adoption in emerging economies (which shows the moderating impact of human capital in the globalization-green technology adoption nexus). As green technology adoption is a dynamic process, it tends to be persistent, meaning last period's adoption often influences this period's decision regarding clean energy adoption. Ignoring this phenomenon would lead to misleading interpretations and results. Thus, we specify a dynamic panel model for each dimension of globalization as:

$$\log(GTA_{it}) = \alpha + \beta_1 \log(GTA_{i,t-1}) + \beta_2 GLOB_{it} + \beta_3 (GLOB_{it} \times HC_{it}) \\ + \gamma X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

Where,

$\log(GTA_{it})$ = natural logarithm of green technology adoption for the country i in year t (dependent variable)

$\log(GTA_{i,t-1})$ = one-period lag of the dependent variable (captures persistence)

$GLOB_{it}$ = each form of globalization (economic, trade, social, or financial), estimated in separate models

$GLOB_{it} \times HC_{it}$ = interaction term between globalization and human capital, whose β_3 captures the moderating role of human capital

X_{it} = vector of control variables comprising urbanization, GDP per capita, CO_2 per capita, and institutional quality

μ_i = country-specific fixed effects

τ_t = time-specific fixed effects

ε_{it} = idiosyncratic error term

Using the equation specified above, four separate models, one for each form of globalization, are estimated. To address nonessential multicollinearity arising from interactions between globalization dimensions and the human capital variable, we mean-centered the individual variables before forming the interaction term, following the methodology of Aiken and West (1991) and Brambor et al. (2006). This approach could help minimize the risk of multicollinearity within the interaction terms and the individual terms themselves, and retain the meaning of the model's controlling mechanisms.

4.3 Dynamic Panel estimation and use of System GMM

This section uses System GMM to implement a dynamic panel estimation.In this section a dynamic panel estimation is implemented via System GMM. The above model is not estimable by traditional panel methods. In this section, we state the reasons behind our use of System GMM in our research and explain the technical details of the mathematical formulation of the System GMM, namely the moment requirements for the differenced and level equations.

4.3.1 Why System GMM is used: Justification

The challenge that we have to face in our methodology is the management of a dependent variable describing the continuous adoption of the green technology over time. This is a delayed variable which is not consistent with the typical assumption of strict exogeneity which is required to apply typical estimators for the panel.

Because of the significant econometric differences involved in estimating a dynamic panel model with endogenous lagged dependent variable, the traditional estimators are not appropriate. Conventional Pooled OLS without considering unobserved country-specific heterogeneity results in an upward bias of the coefficient of the lagged dependent variable. The problem of endogeneity comes into play, however, if these "fixed" characteristics of the country are filtered out through a Fixed Effects (FE) within-transformation. In particular, there is a negative correlation between the converted lagged dependent variable and the idiosyncratic error factor. This results in the notorious Nickell (1981) bias which is downward and is problematic when T is not infinity.

To overcome these difficulties, Arellano and Bond (1991) developed the first-difference GMM estimator which is based on differencing the fixed effects. The pace of change in macroeconomic indicators, such as measures of human capital or institutional quality, however, is not particularly great and is relatively constant. If such a near-unit-root behaviour is observed, then the differences in levels are not that useful to look at for determining the initial differences after. A significant decrease in estimating efficiency and a strong finite-sample bias are symptoms of the weak-instrument issue.

In order to deal with these estimator biases and weak-instrument restrictions together, this research relies on the two-step System GMM approach of Arellano and Bover (1995) and Blundell and Bond (1998). This method greatly enhances the instrument's strength by estimating a system of equations in both levels (instrumented with lagged differences) and first differences (instrumented with lagged levels) simultaneously.

The two-step System GMM is preferable than the one-step version in our opinion. This two-step version has greater asymptotic efficiency than the one-step version which requires a weighting matrix with homoscedastic residuals. Thus this weighting matrix is robust to any heteroscedasticity. Finally, we always rely on the finite-sample adjustment of Windmeijer (2005) as the two-step GMM standard errors may be biased downward in small cross-sectional samples, as is the case here ($N = 25$). To make sure that the reported standard errors are strong against serial correlation and heteroscedasticity, they are all clustered at the national level.

4.3.2 Methodology

It is the simultaneous use of the initial differences and the level equations that are employed in the System GMM architecture. This is the baseline dynamic panel model with levels:

$$y_{it} = \gamma y_{i,t-1} + \beta_1 X_{it} + \beta_2 Z_{it} + \eta_i + \varepsilon_{it}$$

Some countries (*i*) have a time period (*t*) which is linked to them. The lag variable $y_{i,t-1}$ represents a lagged one year, and the dependent variabley_{it} is Green Technology Adoption. The endogenous or predetermined variables X_{it} are measured by the former, while the vector of all the variables that are not endogenous or predetermined Z_{it} is measured by the latter. The error structure is composed of η_i, which accounts for unobserved country-specific fixed effects, and ε_{it}, which represents the idiosyncratic white-noise error term.

To eliminate the time-invariant fixed effects (μ_i), we apply a first-difference transformation to the baseline model:

$$\Delta y_{it} = \gamma \Delta y_{i,t-1} + \beta_1 \Delta X_{it} + \beta_2 \Delta Z_{it} + \Delta \varepsilon_{it}$$

While $\text{first} - \text{differencing successfully removes}\ \eta_i$, but it introduces a correlation between the transformed lagged dependent variable $\Delta y_{i,t-1} = (y_{i,t-1} - y_{i,t-2})$and the transformed error term $\Delta \varepsilon_{it} = (\varepsilon_{it} - \varepsilon_{i,t-1})$through the $y_{i,t-1}$ component. Assuming that the idiosyncratic error ε_{it} exhibits no serial uncorrelated, lagged levels of the dependent and endogenous variables from the period $t-2$ become deeper, serve as valid instruments for our analysis.

The resulting population moment conditions for the first-differenced equation are defined as :

$$E(y_{i,t-s} \Delta \varepsilon_{it}) = 0 \quad \text{for } t \geq 3 \text{ and } s \geq 2$$

Similarly, if a regressor in $X_{it}$is endogenous, its lagged levels are instrumented following the same timing structure:

$$E(X_{i,t-s} \Delta \varepsilon_{it}) = 0 \quad \text{for } t \geq 3 \text{ and } s \geq 2$$

When the independent variables are highly persistent over time, their lagged levels act as weak predictors of the subsequent first differences, leading to considerable finite-sample bias in the standard Difference GMM estimator. System GMM resolves this issue by merging the original level equation with the differenced equation into a unified system.

For the equation in levels, the unobserved individual effect η_i remains in the composite error term $u_{it} = \eta_i + \varepsilon_{it}$ .Therefore, the instruments chosen for this equation must be orthogonal to η_i.Blundell and Bond (1998) introduce a crucial initial condition assumption: though the variables' levels may be related to η_i The initial differences of these variables are uncorrelated with the fixed effects, indicating that the data-generating process is in a steady state.

Formally, the initial condition is expressed as:

$$E(\Delta y_{i2} \eta_i) = 0 \quad \text{for all } i = 1, \dots, N$$

This assumption provides additional, non-redundant moment conditions for the level equation, thereby making lagged first differences valid instruments for it.

$$E\left(\Delta y_{i,t-1}(\eta_i + \varepsilon_{it})\right) = 0 \quad \text{for } t \geq 3$$

For any endogenous regressors in X_{it}, The corresponding moment conditions for the level equation are similarly specified as:

$$E\left(\Delta X_{i,t-1}(\eta_i + \varepsilon_{it})\right) = 0 \quad \text{for } t \geq 3$$

4.5 Diagnostic testing

For each specification, we run three important post-estimation diagnostic tests for each of these four specifications to ensure that our two-step System GMM estimates are reliable and valid:

(1) Arellano-Bond test for serial correlation, assessing both AR(1) and AR(2) in the first differenced and second differences residuals. We expect AR(1) to be statistically significant, indicating first-order serial correlation, while a sufficiently high p-value in AR(2) suggests no second-order serial correlation (Arellano & Bond, 1991).

(2) The Hansen Test of Overidentifying limitations can be used to see if the group of instruments and the exclusion limitations are together valid. The model specification is correct, with the p-value of the instruments not being significant (Sargan, 1958; Hansen, , 1982).

(3) Instrument Count Verification: An excessive number of instruments can severely weaken the diagnostic power of the System GMM estimator, particularly when the instrument count expands alongside the time dimension (T) and surpasses the cross-sectional sample size (N). Instrument proliferation risks overfitting the endogenous regressors and can artificially inflate the Hansen test p-value toward 1.00, masking instrument invalidity (Roodman, 2009a, 2009b). We actively monitor and restrict the instrument count to preserve test reliability.

5. Results & Discussion

This section presents the empirical findings obtained from the two-step System GMM estimations

5.1 System GMM results for models

Table 2-5 shows the System GMM results for economic, social, trade, and financial globalization.

Table 2 presents the results of Model 1, the economic globalization model, which explores how human capital influences the relationship between economic globalization and green technology adoption in emerging economies. Notably, the one-period lag of log (GTA_{it})has a positive and significant effect on its current-year value at the 1% significance level. This shows that a 1%change in the previous year's period value leads to a change in the current value of log $(GTA_{it})$by a 0.695% increase, all else being equal, confirming the strong historical persistence of clean energy paths. Evidence indicates that economic globalization alone has no significant effect on green technology adoption ($\beta = 0.002$, $p > 0.10$). The interaction between economic globalization and human capital has a positive and highly significant impact. ($\beta = 0.009$, $p < 0.05$), supporting H1. The reasoning behind these results is that simply opening up the economy through FDI and trade cannot automatically lead to the adoption of clean energy in emerging economies. According to the Augmented Theory of Absorption Capacity (Nelson & Phelps, 1966; Benhabib & Spiegel, 1994), imported advanced clean technologies require complex and advanced knowledge. The country's economic integration alone is insufficient to help in the operation of these technologies. Thus, a country's human capital acts as a critical filter because a highly educated, STEM-educated workforce lowers the local cost of adoption, modification, and installation, allowing the domestic economy to close the technological gap more rapidly than economic globalization alone.

Table 2.

Results of Model 1: Baseline system GMM estimates (Economic Globalization)

Variables	log (GTA_{it})
log $(GTA_{i,t-1})$	0.695***
	(0.111)
Economic_Glob	0.002
	(0.002)

Economic_Glob_x_Human_capital	0.009**
	(0.004)
GDP_per_capita	0.000***
	(0.000)
Urbanization	-0.006**
	(0.002)
CO2_per_Capita	-0.132***
	(0.038)
Institutional_quality	0.460*
	(0.246)
Constant	1.284***
	(0.435)

*Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.*

Thus, in reality, if an emerging economy opens up its borders for trade and foreign capital without having a strong domestic technical expertise, the advanced technologies would end up underutilized or completely idle in the government's warehouses. Thus, greater economic integration with a domestic workforce having specialized skills to operate, repair, and manage imported technology is required for greater adoption of green energy. The practical implication of this is that governments in emerging economies should stop assuming that bringing in foreign technology or firms into their region will stop the environmental degradation; rather, they should make it compulsory for foreign firms setting up green projects to actively involve the skill-building of the domestic labor force.

Our results support the framework of Cohen & Levinthal (1990) absorption capacity, which talks about the need for internal spillover to maximize the environmental returns. Whereas, our findings contradict those of Aydin et al. (2024) and Elfaki & Ahmed (2024) that only global integration doesn't automatically increase green technology adoption. The contradiction arises because the existing research failed to take the interaction effect into account. Treating globalization as an ultimate driver makes the earlier model suffer from omitted variable bias by vanishing the structural impact of human capital as a moderator.

The GDP per capita ($\beta = 0.000$, $p < 0.01$) and institutional quality ($\beta = 0.460$, $p < 0.10$) have significant positive impacts on the adoption of green technology. On the other hand, CO2 emissions per capita ($\beta = -0.132$, $p < 0.01$) and urbanization ($\beta = -0.006$, $p < 0.05$) both have significant negative impacts. The results corroborate what was expected: a correlation between GDP per capita and the adoption of green technology is stronger. This is in line with the Environmental Kuznets Curve Hypothesis, which states that richer countries are more likely to invest in renewable energy sources (Grossman & Krueger, 1995). Ofoeda et al. (2024) revealed that there was a positive relationship between the quality of institutions and the adoption of clean technology. This is because stable governments are better able to implement environmental rules. As per capita CO2 emissions increase, however, adoption of green tech becomes more difficult due to carbon lock-in, high costs, and challenges of transitioning to green energy for fossil fuel-dependent countries. The result is consistent with carbon lock-in theory (Unruh, 2000) and the energy economic research (Sadorsky, 2014; Khan et al., 2023), a higher carbon footprint acts as a barrier to clean energy adoption. This is consistent with Sadorsky (2014) and Shahbaz et al. (2017), who have pointed out that increasing urban consumption also drives up energy and infrastructure requirements, which then creates fewer funds for green measures, further limiting the impact of urbanization on uptake.

Table 3

Results for Model 2: Baseline system GMM estimates (Social Globalization)

Variables	$\log(GTA_{it})$
$\log(GTA_{i,t-1})$	0.746***
	(0.097)
Social_Glob	0.002
	(0.003)
Social_Glob_x_Human_capital	0.006**
	(0.003)
GDP_per_capita	0.000***
	(0.000)
Urbanization	-0.004*
	(0.002)

CO2_per_Capita	-0.082**
	(0.034)
Institutional_quality	0.328
	(0.253)
Constant	0.993**
	(0.386)

*Significance levels are indicated by * for p < 0.10, ** for p < 0.05, and *** for p < 0.01*.

Table 3 displays the outcomes of the social globalization model, emphasizing how human capital influences the connection between social globalization and green technology adoption in emerging economies. The one-year lag significantly affects its current value at the 1% significance level. Specifically, a 1% rise in the previous year's value results in a 0.746% increase in the current value, ceteris paribus. The evidence indicates that social globalization has a positive but not significant relationship with green technology adoption ($\beta = 0.002$, $p > 0.10$). Nonetheless, the model's moderating influence is both positive and highly significant ($p < 0.05$). This confirms H2 and indicates that social globalization involving the cross-border exchange of information, cultures, people, and ideas across borders is alone insufficient to promote the adoption of green technology in these economies . Thus, with the global interaction, specialized local skills are required to transform technology into clean energy solutions. In reality, social media or internet connection cannot alone reduce the carbon-based dependencies if we don't have skilled local human capital who can build and modify the renewable energy source . The government should take money away from social marketing and awareness programs and spend it on skill-building of domestic human capital

This outcome aligns with Kirikkaleli & Adebayo (2024) and Kasap (2026), who highlighted that global social connections increase demand for sustainability, but contradicts Nan et al. (2023), who identified that social globalization can alone impact renewable energy consumption. It contradicts the authors because of their being highly done in the context of social globalization's impact on advanced economies, whereas we have studies 25 emerging economies proving that social awareness is ineffective without domestic capacity for adoption of clean energy. Regarding the control variables, their signs and significance levels are consistent with the economic globalization model, except for institutional quality, which remains insignificant.

Table 4

Model 3 Results: Baseline System GMM Estimates (Trade Globalization)

Variables	log (GTA_{it})
log $(GTA_{i,t-1})$	0.858***
	(0.093)
Trade_Glob	0.000
	(0.001)
Trade_Glob_x_Human_capital	0.006**
	(0.003)
GDP_per_capita	0.000**
	(0.000)
Urbanization	-0.00
	(0.003)
CO2_per_Capita	-0.065*
	(0.034)
Institutional_quality	0.236
	(0.237)
Constant	0.545
	(0.387)

*Significance levels are indicated as * for p < 0.10, ** for p < 0.05, and *** for p < 0.01.*

The trade globalization model, presented in Table 4, investigates how trade globalization influences the adoption of green technology in emerging economies. Notably, it considers the impact of the log of trade globalization with a one-period lag of log (GTA_{it})has a positive and there is a significant effect on its current value at the 1% level, meaning that a 1% increase in the previous year's value results in approximately a 0.858% rise in the current period, all else being equal. The data show that trade globalization has a positive but statistically insignificant relationship with green technology adoption. ($\beta = 0.000$, $p > 0.10$). In contrast, the interaction between trade globalization and human capital is both positive and statistically significant ($\beta = 0.006$, $p < 0.05$) in its influence on green technology adoption, thereby supporting H3. This indicates that trade globalization removes trade barriers, which helps in the import of clean energy and encourages the adoption of green technology, but without a domestic skilled workforce, open trade leads to the import of old, unused technologies into emerging economies(Guo ,2021 ; Amankwah ,2016). Whereas a highly skilled domestic capital can filter out the polluting technologies and help in the import of the cleanest available technologies. In reality, opening a country to global trade without investing in labor is ineffective for long-term development. Imported advanced technologies remain useless until local laborers have the specific skills to adopt and modify technology as per the nation's demand. The government can't achieve sustainability through tariff and non-tariff barrier reduction; rather, it is a need of the hour for the foreign ministry to collaborate with the education ministry and train the domestic human capital for the technology they are planning to import beforehand

These findings strongly support Murshed (2018) and Oh (2024), who argue that trade openness leads to the import of renewable infrastructure only when internal constraints are resolved. The result contradicts Qi (2024), who claimed that trade liberalization alone leads to greener domestic industries. This contradiction exists because emerging economies face high-sunk-cost domestic barriers that simple tariff reductions cannot break unless paired with localized engineering and adaptation skills. Among the control variables, their signs and significance are consistent with the economic globalization model, except that institutional quality and urbanization are insignificant in this context.

Table 5

Results for Model 4: Baseline system GMM estimates (Financial Globalization)

Variables	log (GTA_{it})
log $(GTA_{i,t-1})$	0.673***
	(0.080)
Financial _Glob	0.005***
	(0.002)
Financial _Glob_x_Human_capital	0.010***
	(0.003)
GDP_per_capita	0.000**
	(0.000)

Urbanization	-0.007***
	(0.002)
CO2_per_Capita	-0.120***
	(0.025)
Institutional_quality	0.531***
	(0.135)
Constant	1.376***
	(0.336)

*Significance levels are shown as * for $p < 0.10$, ** for $p < 0.05$, and *** for $p < 0.01$.*

Once the three outcomes of globalization are established, financial aspects of this phenomenon can be discussed. The System GMM estimations (Table 5) examine the importance of human capital in the relationship between financial globalization and the introduction of green technology in developing countries. Most importantly, at the 1% significance level, the present value is positively and significantly affected by the lag of the log of (GTA_{it}) from the previous year. With constant everything else, it means that the current value of the log is approximately 0.673% higher than the previous year's value for every 1% increase in the value from the previous year. The positive effect of financial globalization on the adoption of green technology is significant and positive ($\beta = 0.005$, $p < 0.01$), unlike the three models that have been previously discussed. In addition, the interaction effect between human capital and financial globalization is positive and highly significant ($p < 0.01$). This is proof that FDI and international capital flows directly address the financial gap faced by emerging economies by providing them with access to international capital flows needed for the adoption of green energy. But when this sole effect interacts with skilled domestic human capital, it creates a multiplier effect by increasing the pace of clean energy adoption. This implies that global financial integration alone is a powerful mechanism for clean energy adoption, but its effect is maximized with skilled managers, engineers, and the labor force. Government should support Green bond and inflow of financial capital to buy clean technologies, but it can twice the impact when human capital is skilled, for that bank should provide necessary financial help for the adoption of the company to have clauses for the inclusion of local workers and engineers in their projects.

These results match with Majeed et al. (2022) and Fatima & Safdar (2025) findings that opening the financial market is a good way to bridge the financial gap. But it contrasts with Behera & Sethi's (2022) results, which highlighted that financial investment can distort green innovation in the study area. The difference in the result can be due to global financial changes in finance market during 2000-2021, our study period.

suggests that financial globalization has a larger effect when human capital is highly skilled. The values of the control variables are the same as those of the economic globalization model.

5.2 Diagnostic tests

Table 6 summarizes the critical diagnostic statistics for each of the four empirical specifications so that the System GMM estimates are internally valid and consistent. There are three simple criteria which are used to test the structural integrity of our identification strategy: instrument proliferation thresholds, the Arellano-Bond tests for residual autocorrelation, and the Hansen test for overidentifying restrictions. One important issue that concerns the System GMM is the proliferation of instruments which diminishes the effectiveness of the overidentification test and causes endogenous regressors to be seriously overfitted. Roodman (2009a) requires that the number of the instruments utilized in the study be much smaller than the number of the cross-sectional units (N). The number of instruments in our study is well below 25 nations used for study in all four models. This conservative footprint on the instrument ensures that instruments does not change the finite-sample standard errors, and does not inflate the statistics of the diagnostic tests.

The Hansen J-test is used to check the validity of our internal instruments, as well as the exclusion limits, to which they are connected. The very high p-values in all four models fail to reject the null hypothesis of joint instrument exogeneity significantly over the conventional p-value of 0.10 significance level. The confirms that lagged level and difference used as instruments, are

orthogonal to the idiosyncratic error factor and moment condition. Without accepting this null hypothesis, our central identification technique would have been of no use, but this a clear non rejection across all the models show that the validity of model used in our study.

First-Order Autocorrelation [AR(1)]: As predicted, the Arellano-Bond test statistically rejects the null hypothesis that none of the four models have first-order serial correlation. The first differencing transformation was not imposing a misspecification of the model but gives rise to the on-the-spot correlation of neighboring differenced errors. It is important to note that for all four specifications the p-value for the AR(2) test is significantly larger than the significance level, which is 0.05 confirming that the second-order autocorrelation is absent in the differenced residuals indicating that the level errors are randomly varying. This is the most crucial criterion that underpins the legitimacy of using t-2 variables as valid internal instruments.

Table 6: Results from the Diagnostic Tests

Tests	Economic Globalization Model	Social Globalization Model	Trade Globalization Model	Financial Globalization Model
AR(1)	0.010**	0.005***	0.003***	0.010**
AR(2)	0.396	0.138	0.193	0.514
Hansen Test	0.553	0.597	0.237	0.976
Number of Instruments	14	24	24	14

*Significance levels: * for $p < 0.10$, ** for $p < 0.05$, *** for $p < 0.01$.*

6: Conclusion and implications

This study demonstrates that globalization alone isn't sufficient to bring ecological modernization to poor countries. Considering the relationships between a number of elements of global integration and the introduction of green technology, the empirical findings confirm that domestic human capital is the key link. It indicates that skilled human capital amplifies the positive effects of these dimensions of globalization on green technology adoption, as measured by renewable energy consumption. To test this hypothesis and obtain reliable results, the research employs a two-step system GMM panel-data approach, which effectively addresses issues such as endogeneity and unobserved heterogeneity. The findings suggest that, among four globalization models, skilled domestic human capital significantly boosts green technology adoption when combined with global integration. Therefore, domestic skilled human capital is crucial for realizing environmental advantages in emerging economies. This indicates that cross–border green technology transfer is unlikely to be effective without the necessary skilled workforce to reduce external costs and maximize the technology's benefits. The most effective way to absorb, preserve, and maximize the green ideas from other countries is to merge them with the relevant local knowledge.

Based on this empirical evidence, achieving sustainable development is not possible through globalization alone. Governments in emerging economies must develop a multidimensional policy framework that reduces external costs and maximizes domestic human capital. Based on these results, the study recommends the following policies: First, the government should not focus solely on trade liberalization, increasing FDI, the movement of cross-border ideas, and importing high-tech technology; it should collaborate with the education ministries to ensure that whenever a green technology policy is implemented, the domestic workforce is trained simultaneously to reduce skill-mismatch situations.

Second, when a country adopts green technology from foreign multinational firms, it should not only purchase the technology but also enter into contracts to train local workers for its construction, maintenance, and operation. Third, the government can offer tax incentives to companies that project costs. be placed on STEM education and green job certification, with a focus on practical skills such as installing solar panels and manufacturing green technologies. Developing a highly skilled local invest in upgrading their employees' skills in green technology. Finally, greater emphasis should workforce reduces reliance on foreign experts for high-tech projects and helps lower overall

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