Article

Impact of Renewable Energy and Human Capital on the Lao PDR's Economic Growth

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Abstract:

This study aimes to investigate the impact of renewable energy and human capital on the Lao PDR's economic growth using time-series data from 1990 to 2019. Applying the augmented Solow Growth framework and the autoregressive distributed lag (ARDL) model techniques to find the clue impacts in the long-run propensity, the empirical results reveal that renewable energy and human capital significantly affect economic growth. These potentials reflect their crucial long-term impacts on economic growth. The significant coefficient of the error correction in the short-run dynamics is towards long-run equilibrium, demonstrating cointegration. The findings imply that hydropower capacity in renewable energy and dynamic effectiveness in human capital may efficiently drive economic growth. Consequently, these crucial factors might play a central role in the Lao PDR's clean energy transition, while supporting the country's economic growth in sustainability. Comprehensive policies related to energy mix, skills, knowledge, and clean-energy technology should be promoted to enhance investments in energy efficiency towards sustainable industrialization.

Keywords: *Renewable Energy, Human Capital, Economic Growth, the Lao PDR.*

1. Introduction

Since the New Economic Mechanism (NEM) was established in 1986, the Lao People's Democratic Republic (Lao PDR) has reformed to pursue a centrally planned market economy to promote industrialization and modernization. Consequently, the country has experienced rapid economic growth driven by industries in recent decades. However, economic

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challenges remain in energy development and emerging power policy. Undeveloped transmission networks from hydropower remain, while there have been limited job creation spillovers in the energy sphere (World Bank, 2022). These constraints reflect the depressed policies on the Lao PDR's sustainable development in the clean energy transition.

While finite resources vary in economies, renewable energy is a crucial component of the energy transition and sustainable development. The rise in regional energy demand by 80% between 2000 and 2019 has increased fossil fuel use in ASEAN (Energy Transition in ASEAN, 2023). Meanwhile, renewable energy has remained at 20% contribution to regional primary energy and is expected to be 25% in 2025 and 65% in the final energy by 2050 (IEA, 2022). The growth in renewable energy to replace fossil fuels can help to curb carbon dioxide (CO_2) and greenhouse gas (GHG) emissions (60% unconditional target for Lao PDR). Based on the ASEAN decarbonization goals, the Lao PDR has set targets for 30% renewable energy in the national energy demand and 98% electrification by 2025 to achieve its net-zero target by 2050 (Milattanapheng et al., 2010; Vakulchuk et al., 2020). In 2022, renewable production was 44.984 million kWh, while 34.903 million kWh were exported, and only 9.162 million kWh was consumed domestically (1.272 million kWh imported). Almost 80% of renewable energy is produced for the power trade, and energy growth in Lao PDR is relatively increasing with 7.5% in energy supply, 4.4% installed capacity energy, and 0.9% in renewable energy share of supply in 2022 (Economic Research Institute for ASEAN and East Asia-ERIA. 2023). As the Lao PDR has experienced a stable supply in power trading while its pioneered hydropower industry in Asia for exports is being developed, renewable energy has grown significantly. It has experienced a fourfold increase in electricity exports over 15 years from 2000 to 2015 (Lao PDR. MEM and ERIA, 2018). Renewable energy has helped the power sector to drive economic development toward sustainable industrialization. Clean energy investment in export-oriented hydropower industries bring the Lao PDR more integrated and connected energy to Southeast Asia in the future. For transportation, the clean energy strategy (Utama et al., 2023; Safrina and Utama, 2023) has been developed to promote electric vehicles (EV), the transportation industry and technology transfer, infrastructure development for clean-energy transportation, and renewable energy penetration from other sources. Thus, renewable energy interdependently affirms the sustainable development of energy resources and economic growth (Todaro et al., 2012; Weil, 2016). Indeed, sustainability should be an integral part of policy in the transition of energy-industry infrastructure (Ahmad et al., 2021).

In Lao PDR, the power sector and natural resources have been crucial drivers of economic development. Economic growth continued at 5.8% on average over five years (2016–2020). Kyophilavong et al. (2017) indicate that a rapid growth rate of 6–8% on average (2000–2013) has enhanced manufacturing and industry development. Since 1991, per capita income has increased sevenfold, from approximately USD 235 to USD 1,824 in the present.

Meanwhile, the country's economy has faced critical challenges in the power generation sector due to the economic rents and conventional pressure of resource and mining booms (Kyophilavong et al., 2013; 2014; 2016) such as the Dutch disease of the resource curse and the lack of human capital development inducing the limit of labor force deployed in the economy (Manolom and Promphakping, 2016; Daovisan and Chamaratana, 2020). Nonetheless, power (mining and energy) industries have played sufficient roles in generating employment required for inclusive growth (ERIA, 2016); engaging in renewable energy can offer initial conditions and lucrative opportunities.

There are various empirical arguments regarding the impact of energy resources (renewable and non-renewable energy) and human capital on economic growth. The findings are mostly inconclusive regarding the causality effects from being critical energy resources to competing natural resource theories (Tietenberg et al., 2012; Jović et al., 2016; Ampofo et al., 2020; Asif et al., 2020), and the effectiveness of human capital allocated in countries with different incomes, (in the form of education; Weil, 2016). Human development is crucial for leveraging the resource-related economy's activities to boost economic growth and social development in the long-run. While energy resources are intertwined with the economy's rapid production and consumption processes, industrialization plays a transitional role in developing renewable energy to encompass economic growth and energy demand (Topcu et al., 2020). Hence, renewable energy has different comparative advantages (Tietenberg et al., 2012).

For the Lao PDR's circumstance, the previous studies have not solely specified the impact of renewable energy and failed to include human capital in concisely operating the long-standing economic growth since 1990. Amidst limited research on renewable energy and human development in shaping the economy, the negative result of human capital (absorption in foreign direct investment-FDI) has shown inconclusive evidence. Therefore, this study aims to provide empirical evidence on the impacts of renewable energy and human capital on the Lao PDR's economic growth. The following research questions are proposed: (1) what is the contribution of renewable energy incorporation to the economic growth in Lao PDR? Is this, contribution not associated with the resource course? (2) How does human capital interact with the resource-growth nexus in Lao PDR?

This study intends to investigate these questions by applying the extended Solow Growth model and autoregressive distributed lag (ARDL) technique. The ARDL's advantage is its flexibility in implementing cointegration inference in the case of the integration order among variables and in solving the problems of autocorrelation and endogeneity. Moreover, the ARDL is efficient for a small finite sample in time-series data (baseline in 30 years) of the Lao PDR to determine the evidence of fit estimations integrated with short-run dynamics and long-run equilibrium under the long-run propensity (LRP), also called the long-run multiplier based on the notation of cointegration.

The remaining paper is organized as follows: Section 2 reviews the background of the Lao PDR's economy and previous research. Section 3 presents the model specifications, data, and analytical methodology. Section 4 discusses the empirical results and relevant evidence. The final section presents the conclusion and policy implications of this study.

2. Background of the Lao PDR's Economy and Literature Review

(1) The Lao PDR's Economy

Economically, the Lao PDR counts as a least developed country (LDC), has a 78% mountainous area of 238,600 km^2 and a population of 7.5 million. The Mekong River flows through the country from north to south with its branches (13 principal tributaries; Sadettanh and Kumar, 2004). With an estimated 260,000 MW (megawatt) of technical hydropower potential, energy production capacity in the power industry is surging to become a gradually developing industry shared in GDP 30-34% during 2010-2021. Thus, the Lao economy has experienced rapid economic growth continuing at 5-6% per annum with GDP per capita of 1,824 USD (2023). Moreover, the power sector substantially contributes 16% to GDP (equivalent to half of industry), and hydropower-based electricity export is 15% of total export revenues (2020). Table 1 shows that renewable energy accounts for a relatively large share of the Lao PDR's economy. The total energy supply is 7.20 Mtoe (Million tons of oil equivalent) with 45% from renewable energy, and the remaining from coal and oil. Meanwhile, energy consumption is 3.92 Mtoe (renewable energy at 52%) with only 0.47 Mtoe coal consumed domestically. 83% of renewable energy produced in Lao PDR is from its substantial hydropower capacity (IEA, 2021); 3.04 Mtoe of electricity is mainly exported to Thailand and Cambodia, while 2.33 Mtoe of oil is imported.

Table 1. Energy summary of the Lao PDR in 2021.

Energy	Coal	Oil	Hydro	Bio	T-Bio	Elec.	Total	% RE
Primary supply (Mtoe)	3.48	2.33	2.83	0.45	1.15	−3.04	7.20	45.5%
Final consumption (Mtoe)	0.47	1.41	—	0.27	1.08	0.69	3.92	52.1%
Installed power capacity (GWh)	—	—	—	—	—	—	10.89	—
Electricity generation (TWh)	—	—	—	—	—	—	44.91	—
Installed renewable capacity (GWh)	—	—	—	—	—	—	8.90	82.8%

*Note: T-Bio = traditional biomass, Elec. = electricity, RE = renewable energy share.
Source: ASEAN Energy Statistics Leaflet 2023.

While the Laotian economy currently has an unsecured energy supply and unprecedented externalities from oil shocks and inflation, renewable energy is urgently needed for economic development and power for export electricity markets. Increasing energy demand in the industry by 8% and transportation by 5% has led to the need for renewable energy to ensure an adequate baseline for economic activities. From the perspective of opportunities for power trade, transport decarbonization pathways are new avenues for harnessing renewable energy. The expansion of electrification and transport are significant linkages in fostering e-mobility and renewable energy integration in Lao PDR to support low-carbon growth in the ASEAN region (Dixon et al., 2023). Therefore, the 9th Five-Year National Socio-Economic Development Plan (NSEDP) 2021-2025 takes bolder steps in energy and human capital to stimulate economic growth toward sustainable and inclusive development. The Lao PDR has explored the diversity and mechanisms of energy development beyond its resource-based economy. Renewable energy policies should be integrated into socio-economic development plans for self-sufficiency, secure energy supply, and sustainability.

Few studies have focused on renewable energy and human resources. Most studies have focused on electricity consumption and exports as the main sources of revenue and resource-led growth (Menon and Warr, 2013; Lamphayphan et al., 2015; Kyophilavong et al., 2017). Nantharath et al. (2019) focus on the effect of absorptive human capital in foreign direct investment (FDI) on economic growth. Related studies have indicated sustainable hydropower's social and environmental impacts (Jusi, 2011), and Laos' hydropower development and cross-border power trade in the Lower Mekong Basin (Tran and Suhardiman, 2020). As shown by Jusi (2010), sustainable hydropower development requires the integration of socio-economic development and environmental protection along with water resources and energy-industry management. These key roles in the sustainable power industry and economic development are prospective directions for Laotian power policy.

(2) Renewable Energy and Economic Growth

Energy is critical for economic development. Many countries and regions have empirically validated the ambiguous effects of energy on economic growth. Previous studies have shown that economic activities and industrialization have increased the growing energy demand. For non-renewable energy, excessive dependence on conventional resources, entirely such as fossil fuels (oil, gas, coal, etc.), has affected the environment and economy, and its consequence is related to the resource curse hypothesis (Asif et al., 2020). However, other studies argue that resource blessings in middle and low-income countries using abundant natural resources can efficiently achieve high growth in the long run. To emphasize the impact of energy, a key pillar of sustainable development on economic growth, contributes to energy efficiency policies (Topcu et al., 2020). As unconventional energy sources with their regeneration and use repeatedly, renewable energy sources exist in different forms (hydropower, wind, biomass, geothermal, solar photovoltaic, biofuels, tidal power, and so forth). Renewable energy resources will have different comparative advantages in economic impact and potential development (Tietenberg et al., 2012).

In Asian economies, energy resources derived from renewable capacity significantly influence economic growth without concerns for environmental issues. Renewable energy resources enable countries to have sustainable industries and economic development (Jain et al., 2022). Globally, energy resources from hydropower and other renewable sources have considerably lower environmental impact than counterparts of conventional energy sources. Renewable energy resources validate the importance of modern energy technologies in supporting sustainable development across the global economy (Stecula, 2017). Increasing the production of energy resources benefits employment (9.8 million people in 2016) and investments in competitive technology in infrastructure plants for renewable energy compared to fossil fuel energy activities.

Renewable energy resources (RERs) play a critical role in economic growth. Previous evidence focuses on the nexus between energy resources and economic growth, based on Sebri (2015), and the empirical clusters of causality support to the theoretical hypotheses (growth, conservation, feedback, and neutrality). As evidenced by Kahia et al. (2016), Erdoğan et al. (2019), Zafar et al. (2019), and Khan et al. (2021), the empirical results are found in different contexts of economies and dimensions of energy resources (non-renewable and renewable resources) and sustainable economic growth. Alper and Oguz (2016) show that growth, conventional, and neutrality hypotheses have occurred among European Union (EU) members to study the causality between renewable energy consumption and economic growth. Renewable energy is the milestone of the future energy. Thus, empirical evidence suggests that economic development depends on potential energy investments and energy industry development. Opportunities in renewable energy technology with natural resource-based economies are viable for transitional roles in economic growth and sustainable development.

Ivanovski et al. (2021) provide evidence from the Organization for Economic Cooperation and Development (OECD) and non-OECD countries on the time-varying impact of energy consumption (renewable and non-renewable) with the energy transition on sustainable growth, stress investment, and transitional development in renewable energy. Zafar et al. (2019) examine disaggregated energy consumption (renewable and non-renewable) in the Asia-Pacific Economic Cooperation countries (APEC). The long-run output elasticities of energy consumption stimulate economic growth, while renewable energy positively affects economic growth for individual countries. Heterogeneous causality reveals a feedback effect (bidirectional) between economic growth and energy consumption.

Ahmad et al. (2021) validate energy industry investments as a potential driver of economic performance in China. The results confirm the feedback of causality effects. Importantly, Ma et al. (2023) examine how renewable energy, driven by spatial factors, can lead to technological spillovers that enhance productivity across the entire economy. Their evidence of innovation shows that the adopted technologies and development of renewable energy can significantly contribute to the improvement of overall productivity (total factor productivity, TFP) through technological spillovers and stimulate structural transformation. The latter is pivotal for TFP growth, as it involves both the reallocation of resources and the accumulation of human capital tailored to the pressing needs of a greener economy.

Natural resources are crucial for stimulating economic growth; however, they also impede production in other sectors of the economy. As one of the three critical theories (dynamic industrialization) focuses on this phenomenon, the industrial process explains the distortion of the structural economy. Abundant natural resources spur economic growth with long-term effects that impede the economy, which is also called the resource curse (Weil, 2016). A country that exports natural resources will import other manufactured goods for domestic consumption. While contracts in manufacturing sectors will undergo efficient adjustment in the short run, even if manufacturing industries maintain rapid technological progress, the importing country will miss progress and be worse off than a country with a lack of natural resources. Prominent historical evidence comes from the Dutch disease, Holland with natural gas in the 1960s, and Spain with gold and silver inflows from the Americas during Europe's discovery of the new world, in the 16th century (Nafziger, 2006; Weil, 2016). Implicitly, unsustainable growth varied in most mineral-exporting countries in the 1980s-1990s. While their experienced performance has specifically reflected the visible resource curse, there is no inherent to explaining the economic phenomenon of slow growth and non-sustainability by resource endowment (Mikesell, 1997), etc. However, the theory of dynamic industrialization implies that the effect of a country's economic growth depends on the level at which natural resources stimulate or impede production in other sectors (trade and non-trade) of the economy through backward linkages (the capacity of resources to provide sufficient demand for the creation of industries) and forward linkages (natural resources are industrially processed to produce other goods). When backward and forward linkages are represented as demand mechanisms for creating manufacturing industries and processing natural resources, natural resources can drive economic development in the whole economy in the long run. The industry development brought by backward and forward linkages can stimulate growth in other economic sectors sequentially, as reflected by resources driven to maximize social benefits and profitability.

With the co-existence of the resource curse and resource blessing, natural resource dependence and human capital accumulation affect the economic circle. Shao and Yang (2014) highlight that human capital plays a critical role in the relationship between resource activities and economic growth. Although human capital is an element that functions in resource activities in economic growth, a resource boom may have adverse effects on economic growth with the trap of insufficient human capital and the resource curse of crowding out human capital. Resource prosperity may exert positive effects on human capital accumulation and economic growth through resource blessings under sufficient conditions and through efficient resource allocation. Similarly, Asif et al. (2020) indicate that natural resources promote economic and financial activities to attain economic growth through both the resource curse and resource blessing. In contrast, Olufemi（2012）finds that the resource curse is in line with the Dutch disease in the case of Nigeria's energy-abundant resources, which directly and indirectly affects economic growth. Furthermore, technological progress, thanks to the absorptive capacity provided by human capital in the context of low-income countries where research and development（R&D）does not almost existent, is crucial in preventing the outcomes of the resource curse（Maswana and Farooki, 2013）.

As crucial drivers, renewable and non-renewable resources play significant roles in the energy demand in both developed and transitional emerging economies. The empirical evidence（Kahia et at., 2016; Erdoğan et al., 2019; Ahmad et al., 2021; and Khan et al., 2021）provides great insights that transitioning energy infrastructure to the renewable energy industry offers a potentiality for sustainable economic development. However, the resource curse and resource blessing exist in countries with energy-abundant resources in driving economic growth and development.

⑶ Human Capital and Economic Growth

Human capital is a critical element of economic growth and sustainable development. Human capital contributes to economic growth in production functions associated with its mechanism of productivity and technology. From exogenous to endogenous role functions, human capital has affected economic growth in different ways, even in different-income countries. A low level of human capital has been found as related to low total factor productivity growth（Cervellati et al., 2023）. Countries with a better-educated workforce tend to adopt more advanced technology, which reflects income distribution across countries. Thus, human capital policies are a critical factor in technology diffusion and income convergence. As adopted technology, human capital is a crucial factor in scaling up renewable energy consumption in the economy and a significant means of transitioning to sustainable development（Zhongwei and Liu, 2022）. Human capital, as an accumulation factor（educational attainment and human capital stock）contributes to economic growth in the long run（Lee and Lee, 2016; Cunha, 2021）.

Previous studies have examined the fundamental role of human capital in different ways. Theoretically, human capital contributes to economic growth in different roles exogenously（Solow, 1956; Mankiw et al, 1992）and endogenously（Romer, 1990）. Human capital affects economic growth across countries with different income levels. According to endogenous growth theory, which links long-run economic growth to human capital, human capital is an important determinant of socioeconomic outcomes（Cunha, 2021）. A lower growth rate in the supply of skilled labor may reduce productivity growth, while fostering the formation of skilled labor may affect economic growth and productivity in the long term. Human capital has multiple effects on economic growth through productivity. As evidenced by

Cervellati et al. (2023), different types of human capital have different outcomes by the degree of productivity and technology diffusion. Human capital, by capturing more advanced education, enables faster adoption and higher intensity in technology affects the productivity of economic growth in terms of income convergence. A low level of human capital has been associated with low total factor productivity growth, whereas a higher-skilled workforce adopts technology more intensively. Moreover, as evidenced by human capital externalities, even one worker directly influences the increased productivity of other workers (Acemoglu, 2012).

Based on human capital in the form of education, human input into production describes how labor supplies vary enormously, and how labor quality contributes to different incomes. Weil (2016) shows that human capital experience affects income. Like physical ability, the educational form determines wages as intellectual ability. Education for improving intellect and high skills has become the most important factor in investing in human capital. Qualified workers who receive higher education based on their average years of schooling can earn higher wages. Thus, human capital in the form of education reflects changes in wages and income levels in the economy. Consequently, people with a better labor supply are more productive and produce higher-quality goods and services.

Regarding human capital stock, Kim (2013) finds the effect of human capital on economic growth in endogenous theory. To explain the effective role of human capital, labor allocation is defined in the economic growth model. Along with the amount of human capital, its composition (shape of human capital) is important for explaining income levels and economic growth. When human capital is allocated intensively to the technology sector, its effective role helps explain the high average income and growth rate. Similarly, Lemoine and Munoz (2021) indicate that initial education is at the heart of growth models based on the interaction between human capital accumulation and the technological frontier. The human capital puzzle has a significant effect on growth in countries with low educational attainment, whereas, in countries with high educational attainment, the level of human capital has a relatively negative effect. Even with cross-country differences in technology, the effects increase in countries with more advanced technological progress.

This study specifies the condition of transitional industries for economic development using the augmented Solow Growth model. The ARDL model technique is applied to examine the roles of renewable energy and human capital in the short-run dynamics and long-run equilibrium. New data are comprehensively collected from multi-international sources to grasp ex-ante empirics of the Lao PDR.

3. Methodology and Data

(1) Model Specification

This study investigates the impact of renewable energy and human capital on the Lao PDR's economic growth. Even if we assume that technology is an essential function of primary renewable energy, we can modify the production function to reflect this relationship. Here's how we could incorporate it into the augmented Solow Growth model and end up with an econometric specification:

Starting with the augmented Solow Growth model's production function (Mankiw et al., 1992)[1]:

$$Y_t = K_t^{\alpha} H_t^{\beta} (A_t L_t)^{1-\alpha-\beta} \tag{1}$$

Where, Y_t is the total output at time t, K_t represents the physical capital stock (broadly defined as aggregate investment), H_t denotes the human capital stock (where the alternative level of human capital is embedded in labor applying the Mincerian approach), while L_t is total labor force and A_t is the level of technology. The parameters α and β indicate the output elasticities of physical and human capital, with the constraint $\alpha + \beta \leq 1$ ensuring diminishing returns to each input.

To incorporate renewable energy (RE_t) into the technological progress component A_t, in line with the literature (e.g., Ma et al., 2023) arguing that the endowment of renewable energy is a significant driver of TFP growth in developing countries, primarily through pathways that enhance efficiency, technology spillovers, and structure transformation. For the context of Lao PDR, we postulate the extended model from Mankiw, Romer, and Weil (1992) that the initial technology is a function of the existing stock of technology, which is relatively enhanced or influenced by emerging renewable energy investment as follows:

$$A_t = A_0 \cdot (RE_t) \tag{2}$$

Notably, to be consistent with the constant exogenous nature of the MRW (1992) framework, the functional form and the parameters are determined outside the model, while not influenced by the endogenous variables within the model. Arguably, since A_0 is specified exogenously, the resulting (A_t) is determined by factors outside the main economic variables in the model (like capital and labor). This could maintain the neutral exogeneity in technology emerging renewable energy in the model.

Amending the original MRW production function Eq. (1) to include this relationship, we have:

$$Y_t=K_t^{\alpha}H_t^{\beta}(A_0\cdot(RE_t)L_t)^{1-\alpha-\beta} \tag{3}$$

To express the function in per capita terms, we divide both sides by labor force L_t this yields:

$$y_t=k_t^{\alpha}h_t^{\beta}(A_0\cdot(RE_t))^{1-\alpha-\beta},\ \text{where } y_t=\frac{Y_t}{L_t},\ k_t=\frac{K_t}{L_t},\ \text{and } h_t=\frac{H_t}{L_t} \tag{4}$$

Applying a natural logarithm transformation to linearize the model for empirical analysis as:

$$\ln(y_t)=\alpha\ln(k_t)+\beta\ln(h_t)+(1-\alpha-\beta)\ln(A_0)+(1-\alpha-\beta)\ln(RE_t) \tag{5}$$

In Equation (5), the term $(1-\alpha-\beta)\ln(A_0)$ is constant because A_0 is the initial stock of the technology which does not change over time. Thus, we can define β_{0t} as $\beta_{0t}=(1-\alpha-\beta)\ln(A_0)$. Also, the effects of technology are reflected at the reference level of renewable energy investment. β_{1t} and β_{2t} represent the output elasticities of capital per capita and human capital per capita, henceforth $\beta_{3t}=(1-\alpha-\beta)$ captures the strengthened effect of renewable energy on technology and output, ε_t is the stochastic error term.

$$\ln(y_t)=\beta_{0t}+\beta_{1t}\ln(k_t)+\beta_{2t}\ln(h_t)+\beta_{3t}\ln(RE_t)+\varepsilon_t \tag{6}$$

(2) Data Description

Applying a unit of labor, the labor force (L_t) is the total number of labor employed in economic activities (age ranged from 15 to 64). Given the case of Lao PDR, the annual change in GDP per capita (constant-2015 USD) is a proxy for economic growth (y_t). Per capita share of gross capital formation represents the capital per effective worker (k_t), (under the expectation of i.e., $\beta_1>0$). Human capital per capita (h_t) in the form of education is measured by the average number of years of schooling (4–8 years) based on the Barro and Lee method (Barro and Lee, 2013; Lee and Lee, 2016; Kraay, 2018). Human capital creates incubation conditions for a country to shift its economic development. Educational attainment, experience, skills, competencies, and training help in utilizing human capital in productive sectors over time (Romer, 2012). Unlikely, the form of knowledge capital is more approached to innovation intensively, where human capital allocation is more entirely defined in the technological progress of the endogenous growth model. Shao and Yang (2014) find evidence of the efficient allocation of production factors in a resource-based economy, revealing that sufficient human capital is an essential mechanism for economic growth by leveraging the resource blessing. Thus, the effect of human capital (h_t) is expected to be positive i.e., $\beta_2>0$.

Meanwhile, renewable energy (RE_t) is a core explanatory variable measured by primary resources of production in renewable energy based on the previous works (Kahia et at., 2016; Stecula, 2017; Jain et al., 2022). Lao PDR is the 68th rank of primary energy production in the world (EIA, 2021), while renewable energy produced from hydropower has the highest share of production capacity at approximately 83% or 0.251 quadrillion Btu (British thermal unit). Energy from production is 0.301 in total energy 0.552 quadrillion Btu in 2021. Energy resources are heavily driven by hydropower across the country (88 of 140 hydropower sites installed in 2019). Thus, renewable energy (RE_t) is expected to influence economic growth positively, i.e., $\beta_3 > 0$.

The annual data is collected from the World Bank-WDI, Energy Information Administration (EIA), and Penn World Table. The given data available for Lao PDR is the period from 1990 to 2019. The measurements and data sources are listed in Table 2. After log transformation, the dependent variable (y_t) is GDP per capita in constant 2015 USD, independent variables are per capita share of gross capital formation (k_t), human capital per capita (h_t), and renewable energy (RE_t).

Table 2. Sources and indicators of key variables (1990-2019).

Variables	Acronym	Measurements	Data Sources
Economic Growth	y_t	Gross Domestic Product per Capita (Constant -2015 USD)	WDI
Capital	k_t	Share of gross capital formation per capita at PPPs, representing capital per effective worker	Penn World Table
Human Capital	h_t	Human capital index per person, average years of schooling, and returns to education	Penn World Table
Renewable Energy	RE_t	Total renewable energy production (Quadrillion Btu)	EIA

*Note: Btu = British thermal unit. One quadrillion = 10^{15} Btu or equivalent to about 293 Terawatt-hours (TWh).

(3) Estimation Process

From Equation (6), the ARDL technique is applied to obtain an efficient inference (estimations are asymptotically valid). Regardless of whether the variables are stationary or have different orders of integration, both $I(1)$ and $I(0)$, the ARDL is explicitly applied for the combination orders to test cointegration. Thus, the ARDL can be extended to examine long-run evidence from the augmented Solow Growth framework and can be re-parameterized in the error-correction (EC) mechanism corresponding to the cointegration with the bounds testing approach developed by Pesaran et al., (2001), and Kripfganz and Schneider (2022). The estimation techniques are described as follows:

First, the ARDL model is explicitly expressed to estimate the bounds test approach.

$$\Delta logy_t = \beta_1 + \beta_y logy_{t-1} + \beta_k logk_{t-1} + \beta_{hc} logh_{t-1} + \beta_{re} logRE_{t-1} + \sum_{i=1}^{p} \theta_{yi} \Delta logy_{t-i} + \sum_{i=0}^{q} \theta_{ki} \Delta logk_{t-i} + \sum_{i=0}^{r} \theta_{hci} \Delta logh_{t-i} + \sum_{i=0}^{s} \theta_{rei} \Delta logRE_{t-i} + \mu_t \qquad (7)$$

In Equation (7), the model presents the bounds test of the ARDL technique, where Δ is the first difference operator, p-q-r-s are the lag length with i the number of optimal lags,

θ is denoted as dynamics for error correction in short-run and μ_t is a serially uncorrelated error term. As β represents the long-run links, the null hypothesis of no long-run relationship is ($\beta_y=\beta_{re}=\beta_{hc}=\beta_k=0$) and the alternative hypothesis of long-run cointegration is ($\beta_y \neq \beta_{re} \neq \beta_{hc} \neq \beta_k \neq 0$). The bounds test is used to estimate the value of conventional F-and t-statistics for pairs of critical values based on Pesaran et al. (2001) and Kripfganz and Schneider (2020; 2022). If values of the F-test and t-test are outside the bounds (Lower Critical Bound-LCB and Upper Critical Bound-UCB), the null hypothesis is either rejected or not rejected. While the value is greater than UCB, long-run cointegration exists; if the value is lower than LCB, cointegration does not exist. Meanwhile, if the values are within the bounds test (LCB and UCB), the result is relatively inconclusive cointegration in the long run.

Second, the ARDL model optimally selects the lag length for the estimation criteria.

To avoid biased results and error term problems, the optimal lag length for each variable in the ARDL model must be determined. The Akaike information criterion (AIC) and Schwarz/Bayesian information criterion (SBIC or BIC) are data-driven approaches that select the optimal lag to fit the regression for the ARDL model. The lag in higher values of the log-likelihood function is suitable for fitting the model with an effective sample size. The BIC is larger than the AIC when selecting more parsimonious models (Kripfganz and Schneider, 2022). Thus, the optimal lag orders are determined by estimating and choosing the model that enables to yield of the smaller value of the AIC or BIC.

Third, the ARDL model is expressed solely in the error correction (EC) to estimate the effects.

As the bound test criteria in Equation (7) and the optimal lag selection for the ADRL model, if the values (F-and t-statistics) specify the existent cointegration, the null hypothesis is rejected. We can apply both short-and long-run models of the ARDL in EC form. As inferred from the potential specification of the ARDL model, the coefficient of the EC term (e_{t-1}) is a parameter of error correction that measures the relationship between the short- and long-run. We assume that the values of the estimation vary between zero to one, with a negative sign indicating statistical significance. The best-performing dynamic ARDL model is extended to include the EC term as follows:

$$\Delta logy_t=\beta_1+\beta_y logy_{t-1}+\beta_k logk_{t-1}+\beta_{hc} logh_{t-1}+\beta_{re} logRE_{t-1}+\sum_{i=1}^{p}\theta_{yi}\Delta logy_{t-i}+\sum_{i=0}^{q}\theta_{ki}\Delta logk_{t-i}+\sum_{i=0}^{r}\theta_{hci}\Delta logh_{t-i}+\sum_{i=0}^{s}\theta_{rei}\Delta logRE_{t-i}+\lambda ECT_{t-1}+\mu_t \quad (8)$$

4. Empirical Results and Discussion

⑴ Descriptive Analysis

Descriptive statistics of the main variables are illustrated in Table 3. The sample period is 30 years from 1990 to 2019. The results show that GDP per capita and human capital per capita are normally distributed by a mean of 7.09 and 0.55, respectively, even though capital per capita and renewable energy do not follow a normal distribution with their mean of −1.37 and −3.27, respectively, due to applying the log transformation for consistency. However, the ARDL model solves the non-normality problem.

Table 3. Descriptive Statistics.

Variable	Obs	Mean	StdDev.	Min	Max	Variance
Log GDP pc（y）	30	7.0873	0.4491	6.4523	7.8493	0.2017
Log Capital（k）	30	−1.3744	0.1166	−1.6436	−1.0767	0.1361
Log Human Capital（h）	30	0.5506	0.7160	0.4140	0.6642	0.0051
Log Renewable Energy（RE）	30	−3.2738	1.0867	−4.8283	−1.5896	1.1808

Source: Authors' computation.

⑵ Stationary Test and Lag Structure

As the time series data are used, based on Wooldridge（2008）, this study takes the process of unit-root tests for a series of selected variables by employing Augmented Dickey-Fuller（ADF）and Phillips-Perron（P-P）. The results in Table 4 indicate that economic growth, capital, and renewable energy have unit-root at level; thus, their stationaries are consequently found in the first differences of higher-order series at the 1% and 5% significant levels, respectively. On the other hand only human capital is stationary at the 1% significance level（MacKinnon p-value 0.0103）. All variables are merely tested in different orders of integration for both $I(1)$ and $I(0)$, and the results could confirm that the ARDL method is explicitly suitable for applying the analytical framework in this case study of Lao PDR.

Table 4. Unit root tests.

	ADF		P-P	
Variable	Z(t)	P-value	Z(t)	P-value
Levels				
Log GDP pc (y)	3.421	(1.0000)	2.417	(0.9990)
Log Capital (k)	−2.275	(0.1717)	−2.440	(0.1309)
Log Human Capital (h)	−5.817***	(0.0000)	−3.420***	(0.0103)
Log Renewable Energy (RE)	−0.545	(0.8830)	−0.560	(0.8797)
First Differences				
⊿ Log GDP pc (y)	−3.278**	(0.0159)	−3.269**	(0.0163)
⊿ Log Capital (k)	−5.209***	(0.0000)	−5.213***	(0.0000)
⊿ Log Human Capital (h)	−2.114	(0.2389)	−2.147	(0.2261)
⊿ Log Renewable Energy (RE)	−4.404***	(0.0003)	−4.352***	(0.0004)

P-values in parentheses *p<.10, **p<.05, ***p<.01, Augmented Dickey-Fuller (ADF) and Phillips-Perron (P-P)
Note: *, **, and *** implies significance on 10%, 5%, and 1% level, respectively.

Based on ARDL estimation, the optimal lag length is depicted as a statistical inference to ensure sufficient degrees of freedom. Minimizing a smaller value of the AIC and BIC (possible combination of p and q-r-s lags), the result of selection shows that a one-period lag is an explicitly optimal fit to the case of this study (Table 5). The same optimal lag has existed for Final Prediction Error (FPE) and Hannan-Quinn Information Criteria (HQIC). The maximum admissible lag order must be selected for a sufficient estimation of the model based on Pesaran et. al, (2001) and Kripfganz and Schneider, (2020; 2022).

Table 5. Lag-order selection criteria.

Sample: 1992 through 2019 Number of observations = 28

Lag	LL	LR	df	p	FPE	AIC	HQIC	SBIC
0	105.704				8.2e-09	−7.26456	−7.20638	−7.07425
1	304.156	396.9*	16	0.000	1.8e-14*	−20.2968*	−20.0059*	−19.3453*
2	316.329	24.347	16	0.082	2.6e-14	−20.0235	−19.4999	−18.3107

*Optimal lag selected. LL: log-likelihood function and LR: likelihood-ration statistics.
Endogenous: Log GDP pc (y_t) Log Capital (k_t) Human Capital (h_t) Log Renewable Energy (RE_t)
Exogenous: cons

(3) Empirical Results

In Equation (7), the ARDL model is applied for the bounds test of cointegration in the long-run equilibrium. The results indicate that the value of the F-statistic (9.784) is larger than the critical value of the upper bounds (UCB) and statistically significant at the 1% level. Meanwhile, the value of the t-statistic (−3.212) falls within both the critical values of the upper and lower bounds, and is significant at the 5% and 10% levels, based on the Pesaran, Shin, and Smith (2001) bounds test (see Appendix A). Thus, the statistical evidence in favour of short-run dynamics, and the long-run equilibrium is inferred as an inconclusive decision for cointegration. However, the results of the t-test mildly support the long-run existence of cointegration (case 3 of the dimension to verify ex-ante was applied in this study). By the F-test, the critical value over the upper bounds is significant at the 1% level to fit the cointegration of the long run. Thus, the null hypothesis of no long-run relationship is firmly rejected, and cointegration is confirmed. The inferred bounds test was derived for finite and small sample sizes based on prior works (Narayan, 2005; Mahara, 2022; Wegari et al., 2023).

From the accepted criteria of the unit-root and bounds tests, the short-run dynamics of the ARDL model are solely applied in Equation (8). Therefore, the empirical results of the ARDL are confirmed determinant elasticities of the short-and long-run effects. Table 6 shows that capital, human capital, and renewable energy have positive and statistically significant effects on economic growth in the short-run dynamics. There are significant positive effects between the dependent and independent variables in the long-run equilibrium. These results confirm that the impact of economic growth is driven by renewable energy and human capital as potential factors in efficiency and productivity.

From table 6, a 1% increase amount in quadrillion Btu(2) of renewable energy production will stimulate economic growth by 0.02% in the short term, and 0.21% (10 times approximately) in the long-term economy. Likewise, a 1% increase in human capital affects economic growth by 0.40% in the short run and 4.50% in the long run. Meanwhile, capital has a positively significant effect on economic growth of 0.78% in the long-run economy (20 times in the short run). The F-test's result confirms that the constant return to scale of the exogenous growth model is patently valid based on economic growth theory. Essentially, the results show that the coefficient of the error correction term, ECT_{t-1} (−0.0904) is negative and statistically significant at the 1% level in the short-run dynamic model, confirming that the model is well-specified and has a stable long-run relationship among the variables. The negative sign is importantly indicative of a long-run equilibrium relationship among the variables, and the magnitude of the ECT implies that approximately 9% of the disequilibrium in the dependent variable is corrected within a year, indicating a relatively high speed of adjustment. This evidence of cointegration implies that long-run propensity among key variables in economic growth does exist and contribute to the development of the Lao PDR.

Table 6. Impact on GDP per capita in the ARDL model (1100), sample 1990-2019.

Variable		Coefficient	Standard Errors	T-statistic	P-value
LR (Long Run)					
$logk_{t-i}$	Capital	0.7808***	(0.2613)	(2.9886)	(0.0066)
$logh_{t-i}$	Human Capital	4.5005***	(1.3852)	(3.2489)	(0.0035)
$logRE_{t-i}$	Renewable Energy	0.2183**	(0.8074)	(2.4958)	(0.0202)
SR (Short Run)					
$\Delta logk_{t-i}$	Capital	0.0398*	(0.0225)	(1.7662)	(0.0906)
$\Delta logh_{t-i}$	Human Capital	0.4066**	(0.1479)	(2.7488)	(0.0114)
$\Delta logRE_{t-i}$	Renewable Energy	0.0197*	(0.0099)	(1.9850)	(0.0592)
_cons (β_1)		0.6208***	(0.2143)	(2.8970)	(0.0081)
(ECT_{t-1})	Speed of adjustment	−0.0904***	(0.0281)	(−3.2116)	(0.0039)
N 29	R-sq 0.6301	Adj. R-sq	0.5497	R-MSE	0.0090

p-values in parentheses *p< .10, **p< .05, ***p< .01. Delta is a difference (Δ).
Note: *, **, and *** implies significance on the 10%, 5%, and 1% level, respectively.

The robustness checks allow testing statistical inference and validity of empirical findings. Based on Wooldridge (2008), stability with diagnostic tests is conducted to determine the model specifications with the homoskedasticity assumption. The test results confirm to be lognormally distributed that the short-run dynamics and long-run estimations do not suffer from serial correlation, heteroscedasticity, normality, and structural break. The Breusch-Grodfrey's LM (Lagrange multiplier) test for autocorrelation and White's test heteroscedasticity do not reject the null hypothesis by prob-chi squared values of 0.2459 and 0.9106, respectively. The Skewness (0.6706) and Kurtosis (0.7589) appeared to be identically symmetric and normal distributions of explanatory variables, meaning that the variables are sufficient with constant variance over time and expectedly no correlation across time. The cumulative sum test for parameter stability is not rejected by the recursive test statistic of 0.7751 and all significant levels, showing that the model result has confirmed the parameter stability with the null hypothesis of no apparent structure break. (see Appendices B and C). Additionally, the study has checked estimators with the fully modified and dynamic ordinary least squares (FMOLS and DOLS) to confirm the robustness of no autocorrelation and related endogeneity in time series applications.

(4) Discussion

Overall, our empirical results indicate that renewable energy and human capital have the potentiality to contribute exogenously to the Lao PDR's economic growth, in both the short-run dynamics and long-run equilibrium of relationships. Much of the empirical results are consistent with those of prior works (Ahmad et al., 2021; Jain et al., 2022; Shao and Yang, 2014; Zhongwei and Liu, 2022; Cunha, 2021).

Important to note that human capital has a crucial effect on economic growth in the Lao PDR. The result has a statistically significant and positive effect, which is explicitly argued to be a negative effect of human capital, as the absorptive result found in a previous study on the Lao PDR (Nantharath et al., 2019). The schooling and training can understandably help in building a comprehensive stock of human resources, which can be key to stimulating economic performance, and plays a significant role in economic growth and long-term development. As an incubation condition, human capital is a puzzling part of dynamic, effective, and efficient mechanics of economic productivity, especially in the industrial sector. The findings follow the arguments of Shao and Yang (2014) that increasing human capital stock leads to higher productivity, and the leveraging effect of social degree attention depends on the substitutability between human capital accumulation and the educational opportunity cost of lower-skilled labour. These reflections on the intellect of human capital, which is crucial to improving social productivity in economic development, show that greater education investments affect economic productivity more, the return on human capital from education leads to higher wages, and thus, the potentiality for sustainable economic growth is substantially enhanced in the long run.

Critically, human capital may have played a key role in investment ensuring the relatively high speed of adjustment in the energy-growth nexus. That is, as investments are made into renewable energy, a well-educated and skilled workforce can more quickly adapt to and integrate new technologies into existing systems, leading to a faster adjustment in economic growth. Similarly, the sufficient level of human capital directly contributes to the efficiency and productivity of the renewable energy sector while also speeding up knowledge spillovers to other sectors of the national economy, leads to structure transformation. By doing so, the high level of human capital brings more flexibility and adaptation, which in turn improves the economy's ability to adjust rapidly to the new equilibrium brought about by renewable energy investments.

The finding that renewable energy boosts economic growth and sustainable development, is even more interesting in the context of Lao PDR. The prospect of renewable energy may be a key driving force by acting as a resource blessing in the power industry in Lao PDR. Renewable energy can play a significant role in the energy-industry infrastructure's sustainable transition. Hydropower is the main source of renewable energy, which can contribute to economic growth by earning income from the power trade and contribute to socio-economic development by helping in poverty alleviation. People who live around hydropower dams can gain access to electricity, employment, social benefits, and schooling projects. For example, the Nam Theun 2 Power Company Limited (NTPC), reservoirs and powerhouses are located in the central part of Lao PDR (Khammouane Province). It is one of the largest hydropower dams and is known for the most successful industrial endeavours with an international standard model in Lao PDR. As part of its target mission, the NTPC aims to generate electricity in a reliable (applying ICT) and sustainable (social and environmentally friendly) manner and serves as an important standard setter for the hydropower industry. The multipurpose project has provided schools for many cities' citizens, irrigation channels to agriculture upstream and downstream, livestock, and fisheries, social development with capacity building for local government and communities, diversified livelihoods on the Nakai Plateau, long-term scholarships program in higher education, and a social safety net program (healthcare service). It is also part of the Nakai-Nam Thuen National Park, which is a biodiversity area with wildlife served as a tourism attraction.

However, the present study has some limitations, particularly related to the scope and methodology. The study's reliance on time-series data from 1990-2019, while extensive properties, restricts the examination to historical patterns without incorporating the latest policy changes and technological advancements post-2019 that could significantly influence the Lao PDR's energy sector and economic growth trajectory for industrialization. Moreover, it was not possible to fully capture nonlinear dynamics and structure breaks in the continuity economy by using the augmented Solow Growth model and the ARDL model techniques, although they are robust. Expanding the database to include more recent years and using methodologies that can deal with potential nonlinearities and structure changes should be considered for further studies. This approach will provide a more nuanced understanding of the evolving relationship between renewable energy, human capital, and economic growth in the Lao PDR, enabling policymakers to diverse more effective strategies for sustainable development.

5. Conclusion and Policy Implications

This study examined the impact of renewable energy and human capital on economic growth applying data from 1990 to 2019. For the Lao PDR's economic growth, more attention should be paid to both renewable energy investment and human capital development. Human capital is crucial for driving economic growth with the potential efforts in renewable energy for sustainable industry in both the short-run dynamics and the long-run economic effects. Hence, the fundamental forces of hydropower capacity in renewable energy and the dynamic effectiveness of human capital may positively support economic growth in sustainability.

While the Lao PDR has experienced rapid economic growth along with its gradual industrial development (30-34% during 2011-2021), the challenges of resource embrace and level of human development (i.e., the form of education) are perceived in the improvement. Both renewable energy (hydropower capacity) and human capital (higher enrolment and skilled labor in technical vocation) have substantial short-and long-run impacts on economic growth. Thus, renewable energy and human capital may play central roles in the transitional efforts towards a sustainable power industry and energy efficiency in line with their social benefit returns. As such operating determinants, renewable energy and human capital should be allocated effectively as potential mechanisms for economic growth.

Human capital is a key resource investment in distribution widely to the economy and social benefits of returns. The adorable form of education engaged in human capital could stimulate the Lao PDR's economic growth and long-term development. To realize the 9th NSEDP, the educational system (primary, secondary, vocational training, on-the-job training in informal and relevant skills) should be improved in analogous quality and more incentive subsidy in private education. Education improvement of relatively average years of schooling could enhance more productive and effective in augmenting human skills distributing to the workforce, as the results diversifying economic development and the productivity of economic outputs. Hence, these primary efforts may be traced more to quality, accessibility, and skill upgrades as labor-augmenting for developing countries like Lao PDR as labor-abundant, while capital scare to portray the core effects on economic growth and social benefits from mobilizing the large-scale improvement and human resource development.

These fundamental factors may serve as cornerstones in the country's renewable energy strategy aimed at sustainable industrialization. Comprehensive policies promoting skills, knowledge, and clean energy technologies should be undertaken with particular priority influence, and can even serve as incentives for investing within the country. The rationale for an energy-mix policy should be considered by increasing renewable energy capacity. Allocations from potential hydropower sources to other biofuels, wind, and solar should be made in the renewable energy development strategy and vision of Lao PDR 2030 in line with the revised 2017 Electricity Law. Optimally sized renewable power plants should be invested in to support small power development for self-sufficiency, efficient grid interconnection, and becoming a regional supplier of renewable energy in the future.

This study makes two possible contributions to economic literature. Firstly, previous studies of the Lao PDR have mostly focused on causality effects between natural resources, electricity consumption, and economic growth nexus. This study emphasizes the impact of renewable energy through its resource-based capacity on economic growth to promote sustainability in the energy industry, as the absent causality. Secondly, this study incorporates the technological effect of renewable energy investment and the visibility of human capital to adjust economic growth in the long run propensity, which induces a crucial condition of human capital (employed in the final good production based on labor-augmenting prospect) enhancing efficiency and productivity in the Lao PDR.

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Appendix A:

Pesaran, Shin, and Smith (2001) bounds test

H0: no level relationship	F = 9.784
Case 3	t = −3.212

Finite sample (3 variables, 29 observations, 1 short-run coefficients)

Kripfganz and Schneider (2020) critical values and approximate p-values

10%		5%		1%		p-value	
I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
3.029	4.230	3.744	5.126	5.504	7.314	0.000	0.002
−2.579	−3.470	−2.945	−3.892	−3.709	−4.765	0.029	0.147

Do not reject H0 if either F or t are closer to zero than critical values for I(0) variables
(if either p-value > desired level for I(0) variables)
Reject H0 if both F and t are more extreme than critical values for I(1) variables
(if both p-values < desired level for I(1) variables)
Decision: no rejection (.a), inconclusive (.), or rejection (.r) at levels:
Results: 10% inconclusive (.), 5% inconclusive (.), 1% no rejection (.a)

Appendix B:

Diagnostic tests

Durbin-Watson d-statistic (6, 29) = 1.441696

Breusch-Grodfrey LM test for autocorrelation chi2	df	Prob>Chi2
1.346	1	0.2459

H0: no serial correlation

White's test

H0: Homoskedasticity	Ha: Unrestricted heteroskedasticity
chi2(20) = 12.15	Prob>chi2 = 0.9106

Cameron and Trivedi's decomposition of the IM-test

Source	chi2	df	p
Heteroskedasticity	12.15	20	0.9106
Skewness	3.19	5	0.6706
Kurtosis	0.09	1	0.7589
Total	15.44	26	0.9487

Appendix C:

Cumulative sum test for parameter stability

Sample: 1991through 2019 Number of observations = 29

H0: No structure break

		Critical value		
Type	Test statistic	1%	5%	10%
Recursive	0.7751	1.1430	0.9479	0.8499

Notes

1) According to the MRW 1992, the original model of augmented human capital in the Solow Growth (page 416).

2) According to the EIA, the British thermal unit (Btu) is used in the energy industry as a common yardstick to measure and compare different types of energy (oil, natural gas, coal, electricity power, etc.). One Btu is the amount of energy needed to heat 1 pound of water by 1 degree Fahrenheit at sea level. It's equivalent to 1.055 joules in the metric system.

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