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Energy-Related Infrastructure Efficiency and Environmental Performance in ASEAN-5

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ABSTRACT

This paper examines how infrastructure efficiency, proxied by GDP per unit of energy use, relates to environmental and economic factors in ASEAN-5 countries. The study covers Indonesia, Malaysia, the Philippines, Thailand, and Vietnam from 2010 to 2023, using annual data from the World Bank's World Development Indicators. The empirical analysis applies pooled ordinary least squares, fixed-effects, and random-effects panel models, with the Hausman specification test to determine the preferred estimator. The regression sample is based on available country-year observations after accounting for missing data. The fixed-effects results show that carbon dioxide emissions per capita are negatively and significantly associated with infrastructure efficiency, while electricity consumption per capita is positively and significantly associated with it. GDP per capita and the renewable energy share have positive coefficients in the fixed-effects model, but these estimates are not statistically significant at conventional levels. Overall, the findings suggest that lower CO_2 emissions per capita and higher electricity consumption per capita are more consistently associated with infrastructure efficiency, while GDP per capita and renewable energy share show less robust statistical relationships in the present sample. These results highlight the importance of combining cleaner energy use with more productive energy systems.

Keywords: ASEAN; Environmental Performance; Infrastructure Efficiency; Panel Regression

ABSTRAK

Artikel ini mengkaji efisiensi infrastruktur, yang diproksikan melalui PDB per unit penggunaan energi, berkaitan dengan faktor lingkungan dan ekonomi di negara-negara ASEAN-5. Kajian ini mencakup Indonesia, Malaysia, Filipina, Thailand, dan Vietnam sejak 2010 hingga 2023, dengan menggunakan data tahunan dari World Development Indicators. Analisis empiris dilakukan dengan menerapkan model *pooled ordinary least squares*, *fixed-effects*, dan *random-effects panel*, serta menggunakan uji spesifikasi Hausman untuk menentukan estimator paling sesuai. Sampel regresi didasarkan pada observasi negara-tahun yang ada setelah memperhitungkan data yang hilang. Hasil *fixed-effects* menunjukkan bahwa emisi karbon dioksida per kapita berhubungan negatif dan signifikan dengan efisiensi infrastruktur, sedangkan konsumsi listrik per kapita berhubungan positif dan signifikan dengannya. PDB per kapita dan pangsa energi terbarukan memiliki koefisien positif dalam model *fixed-effects*, tetapi estimasi tersebut tidak signifikan secara statistik pada tingkat konvensional. Secara keseluruhan, temuan ini menunjukkan bahwa emisi CO_2 per kapita yang lebih rendah dan konsumsi listrik per kapita yang lebih tinggi lebih konsisten berkaitan dengan efisiensi infrastruktur, sementara PDB per kapita dan pangsa energi terbarukan menunjukkan hubungan statistik yang kurang kuat dalam sampel penelitian ini. Hasil ini menegaskan pentingnya memadukan penggunaan energi yang lebih bersih dengan sistem energi yang lebih produktif.

Kata Kunci: ASEAN; Efisiensi Infrastruktur; Kinerja Lingkungan; Regresi Panel

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INTRODUCTION

Infrastructure has become one of the most important drivers of economic development and structural change in ASEAN countries. Rapid urbanization, industrial growth, and rising income levels have increased pressure on transportation networks, electricity systems, and other core services, requiring governments to make substantial infrastructure investments.

At the same time, this expansion has been accompanied by rising energy use and increasing greenhouse gas emissions, especially in rapidly developing middle-income countries. These trends raise questions about whether current development pathways can be sustained in the future and whether infrastructure systems can support growth while limiting pressure on environmental systems (Wang & Su, 2020; Sarkodie & Strezov, 2019; Acheampong, 2018). In this context, the efficiency of infrastructure and energy use, understood as the economic output generated from each unit of energy consumed, has become a key issue in sustainable development in ASEAN.

In this paper, “energy-related infrastructure efficiency” refers to the macro-level ratio of economic output to energy input, or GDP per unit of energy use. This measure reflects how productively the energy supplied through infrastructure systems is converted into economic value. This indicator is qualitatively different from engineering-level energy efficiency, which is usually measured at the technology or equipment level. The relationship between these concepts differs across contexts. While the aggregate indicator used in this study incorporates aspects of infrastructure design, technology adoption, and the structure of economic activity, it should not be equated with engineering-level measures of efficiency. Unless otherwise specified, this study uses this macro-level definition of efficiency throughout the analysis.

Many scholars have examined the relationships among economic growth, energy use, and CO_2 emissions in ASEAN. However, fewer studies have used GDP per unit of energy use as the main outcome variable for evaluating the efficiency of energy-related infrastructure (Dogan & Inglesi-Lotz, 2020; Zhang et al., 2016). Most existing studies focus on aggregate linkages and do not directly measure infrastructure or energy efficiency as the dependent variable. Nor do they systematically investigate the determinants of such efficiency across countries.

More specifically, the combined effects of economic development, emissions intensity, and energy mix on infrastructure efficiency in ASEAN-5 remain relatively underexplored. This paper addresses this gap by examining infrastructure efficiency, proxied by GDP per unit of energy use, in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam from 2010 to 2023. To achieve this objective, the study models the relationships between GDP per capita, CO_2 emissions per capita, electricity consumption per capita, renewable energy share, and infrastructure efficiency using a panel-data framework.

This study addresses two research questions:

1. How has infrastructure efficiency, measured as GDP per unit of energy use, developed in ASEAN-5 countries from 2010 to 2023?
2. What is the relationship between GDP per capita, CO_2 emissions per capita, electricity consumption per capita, renewable energy share, and infrastructure efficiency in these countries over time?

This paper makes three main contributions to the existing literature. *First,* unlike most ASEAN energy studies that treat energy consumption or CO_2 emissions as the main outcome, this study uses GDP per unit of energy use as the dependent variable. This allows the analysis to assess infrastructure efficiency more directly in relation to relevant economic and environmental variables, rather than examining development only through the lens of energy use or emissions.

Second, the paper applies a country fixed-effects panel framework, with the Hausman test used to determine whether the fixed-effects or random-effects model is more appropriate. This provides robust evidence of within-country associations among ASEAN-5 countries over the most recent available period, 2010–2023.

Third, the study combines CO_2 emissions per capita, renewable energy share, electricity consumption per capita, and GDP per capita in a single analysis, thereby capturing the interconnected influence of carbon intensity, energy mix, electrification, and economic development on infrastructure efficiency in the region.

THEORETICAL FRAMEWORK

Infrastructure Investment and Energy Efficiency

Infrastructure and energy systems are cornerstones of economic development because they facilitate production, mobility, and access to basic services. At the same time, these systems also determine the level and structure of energy demand. Empirical studies show that economic growth can be decoupled from energy use, depending on infrastructure quality and technology. In this context, energy intensity, or energy use per unit of output, can improve through technological advancement and more efficient production of goods and services (Wang & Su, 2020; Balsalobre-Lorente et al., 2018; Sadorsky, 2013; Stern, 2012).

Against this background, GDP per unit of energy use, often expressed as GDP in national currency per kilogram of oil equivalent, serves as a high-level indicator of infrastructure and final-demand efficiency because it shows how an economy converts energy inputs into economic value added (Stern, 2012). Although this indicator is aggregate and sector-neutral, it has been widely used in cross-country analyses because it is available, comparable, and relatively easy to interpret (Apergis & Payne, 2010). In this sense, trends in GDP per unit of energy use can provide an initial proxy for the evolution of infrastructure and energy-system efficiency over time in transitioning economies such as those applied in the ASEAN countries.

Economic Growth, Emissions, and Energy Use in ASEAN

A growing body of literature exists on the relationships between economic growth, energy use, and carbon dioxide emissions in ASEAN and other developing regions. Many studies examine the Environmental Kuznets Curve (EKC) hypothesis, the causal relationship between GDP and energy use, or fossil fuel consumption as a driver of emissions (Nathaniel & Khan, 2020; Saboori et al., 2012; Lean & Smyth, 2010; Ang, 2008). For example, Saboori et al. (2014) report an EKC-type relationship between GDP and CO_2 emissions for selected ASEAN countries, while Lean and Smyth (2010) show evidence of long-run linkages between electricity consumption and economic growth in Malaysia. Other regional studies emphasize the need for cleaner energy mixes and stronger policy frameworks due to rising energy demand and emissions associated with rapid urbanization and industrialization (Kirikkaleli & Adebayo, 2021; Nasreen & Anwar, 2014; Sadorsky, 2013).

Nevertheless, most of this literature uses total or per capita emissions and energy use as the main outcome variables, rather than an explicit efficiency metric such as GDP per unit of energy use. Consequently, limited empirical evidence is available on how macro-level indicators of infrastructure or energy efficiency respond to changes in income, emissions intensity, and the energy mix in ASEAN-5.

Links between Infrastructure Efficiency and Environmental Performance

Conceptually, higher infrastructure and energy efficiency may facilitate the decoupling of economic growth from environmental pressure (Wang & Su, 2020; Sarkodie & Strezov, 2019). Provided that the carbon intensity of energy does not increase at the same time, more output can be generated per unit of energy consumed. Thus, a given level of GDP can, in principle, be produced with lower emissions (Stern, 2012). In contrast, high CO_2 emissions per capita may reflect a more carbon-intensive capital and energy base, indicating that part of the growth process is driven by inefficient or fossil fuel-dependent economic activity (Apergis & Payne, 2010).

The composition of the energy mix also matters, as a larger renewable share in final energy consumption may reduce emissions per unit of energy used and therefore lead to more favorable environmental performance at a given level of infrastructure efficiency (Balsalobre-Lorente et al., 2018; Sadorsky, 2009). Conversely, demand-side studies indicate that gains in electricity access and electricity use can facilitate economic development under a sustainability-oriented hypothesis, although environmental benefits remain conditional on the carbon intensity of power generation (Stern, 2012; Lean & Smyth, 2010; Ang, 2008). In the ASEAN context, examining how GDP per unit of energy use co-evolves with CO_2 emissions, renewable energy penetration, and electricity consumption can help explain whether infrastructure and energy systems are moving countries closer to, or further from, low-carbon development pathways.

More recent studies have examined energy efficiency, energy intensity, renewable energy, and environmental performance at the ASEAN and Southeast Asian levels. Khuong et al. (2019) showed that urbanization, energy mix, energy intensity, and activity effects jointly determine ASEAN energy demand, while Fitriyanto and Iskandar (2019) analyzed the determinants of energy intensity in nine ASEAN economies using an Arellano–Bond GMM panel approach. In the context of the ASEAN-5, Dağdeviren et al.

(2020) re-examined the relationship among CO_2 emissions, energy consumption, and economic growth, accounting for cross-sectional dependence and country heterogeneity.

Recent panel-data studies have also employed fixed-effects models, GMM estimators, and quantile-based estimators to address heterogeneous effects or endogeneity in the ASEAN energy-environment literature, including studies on emissions from electricity generation (Voumik et al., 2022) and the effects of renewable energy (Ilyas et al., 2024). Similarly, Tran et al. (2024) confirmed that renewable energy use has a negative relationship with CO_2 emissions in ASEAN and supports environmental quality. Although a growing body of literature has examined these factors, only a limited number of studies have used GDP per unit of energy use as the main outcome variable and examined its relationship with CO_2 intensity, renewable energy share, and electrification within a unified panel framework for ASEAN-5 (Nathaniel & Khan, 2020).

Overall, the literature indicates that most ASEAN energy studies focus on energy use, emissions, and growth, while GDP per unit of energy use has received less attention as a main outcome variable. This paper, therefore, employs a panel-data approach to analyze energy-related infrastructure efficiency in ASEAN-5.

METHODOLOGY

Study Area and Period

This empirical analysis focuses on five ASEAN economies: Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, hereafter referred to as ASEAN-5. These countries are among the largest and most dynamic economies in the region. Over the past two decades, they have experienced rapid economic growth, structural transformation, and increasing energy demand, making them suitable cases for investigating the relationship between infrastructure efficiency and environmental performance (Nasreen & Anwar, 2014; Sadorsky, 2013; Lean & Smyth, 2010).

The focus on ASEAN-5 is based on three selection criteria. *First,* these five economies are among the largest in Southeast Asia in terms of both GDP and population, making the findings relevant to the region’s main economic engines. *Second,* all five countries have comprehensive or nearly comprehensive WDI indicator coverage since 2010, allowing for consistent comparison. *Third,* this group displays significant diversity in economic structure, energy mix, and emissions intensity, which allows cross-country analysis through within-group variation. Singapore is omitted because its characteristics as a geographically small, high-income city-state, with limited agricultural activity and nearly universal electrification, would make it a structural outlier that could drive pooled and fixed-effects estimates. Smaller ASEAN economies, including Laos, Brunei, Myanmar, Cambodia, and Timor-Leste, are excluded based on the availability of WDI data for key indicators over the full study period.

The study covers the period from 2010 to 2023, subject to data availability for the selected indicators, and is structured as an annual country-year panel. The raw dataset contains up to 70 country-year observations, calculated as five countries multiplied by 14 years. However, the effective regression sample is smaller because some variables contain missing values, particularly the renewable energy share and several observations for 2023. Accordingly, the econometric analysis is based on the available observations rather than on a fully balanced panel.

Data Sources

All variables used in this study are obtained from the World Development Indicators (WDI) database published by the World Bank, which compiles harmonized economic, social, and environmental statistics from officially recognized international sources (World Bank, 2025a). The WDI dataset provides annual, internationally comparable indicators for GDP, energy use, emissions, and population for a large sample of countries, including the ASEAN-5 economies. In particular, the analysis draws on GDP per capita in current US dollars (NY.GDP.PCAP.CD), carbon dioxide emissions per capita based on AR5 global warming potentials (EN.GHG.CO2.PC.CE.AR5), renewable energy consumption as a share of total final energy use (EG.FEC.RNEW.ZS), electricity consumption per capita (EG.USE.ELEC.KH.PC), and GDP per unit of energy use, expressed in constant 2021 PPP dollars per kilogram of oil equivalent (EG.GDP.PUSE.KO.PP.KD). Because the World Bank metadata distinguishes between related series for this indicator, the study uses a single series definition consistently through the text, tables, and appendix. These indicators are accessed through the World Bank open data interface and merged into a country-year panel for ASEAN-5.

Table 1. Variables, definitions, and data sources

Variable name	Description	Unit	WDI code	Transformation in Model
Infrastructure efficiency (Eff)	GDP per unit of energy use	Constant 2021 PPP $ per kgoe	EG.GDP.PUSE.KO.PP.KD	Level (Eff)
GDP per capita (GDPpc)	Gross domestic product per capita (current prices)	Current USD per person	NY.GDP.PCAP.CD	ln(GDPpc)
CO_2 emissions per capita (CO2pc)	Carbon dioxide emissions per capita (AR5 greenhouse gases)	Tonnes CO_2-eq per person	EN.GHG.CO2.PC.CE.AR5	ln(CO2pc)
Renewable energy share (Renew)	Renewable energy consumption in total final energy use	Percent of final energy consumption	EG.FEC.RNEW.ZS	Level (%)
Electricity use per capita (Elecpc)	Electricity consumption per capita	kWh per person per year	EG.USE.ELEC.KH.PC	ln(Elecpc)

Table 1 presents the variables used in the analysis, including their definitions, units of measurement, WDI codes, and data sources. The table also indicates which variables are used in levels and which are transformed into natural logarithms for the econometric model (World Bank, 2025a, 2025b, 2025c).

The original panel includes 70 country-year observations, consisting of five countries observed over 14 years from 2010 to 2023. After removing observations with missing values, the effective regression sample consists of 60 complete-case observations. The missing values mainly relate to renewable energy share for Indonesia and Malaysia in 2022 and 2023, and GDP per unit of energy use for Malaysia in 2023. The analysis is performed using the available complete observations through listwise deletion, while sensitivity analysis may be used to examine potential biases that could arise from case deletion. Since the missingness is concentrated in the most recent years and is likely caused by publication lags in the World Bank WDI database, it is unlikely to introduce systematic selection bias across the sample. This variation in data coverage means that the number of observations is reported separately for each variable in the descriptive statistics shown in Table 3.

Variable Construction

This study measures infrastructure efficiency using GDP per unit of energy use (Eff), measured in PPP dollars per kilogram of oil equivalent of total energy consumption. This variable serves as the dependent variable. The ratio is interpreted as a general measure of energy and infrastructure efficiency, indicating the amount of economic value generated per unit of energy input, with higher values denoting greater efficiency (World Bank, 2025b, 2025c; United Nations, 2001).

For measurement consistency, the dependent variable, GDP per unit of energy use, is expressed in constant 2021 PPP dollars. This adjustment addresses price-level differences across countries and over time, allowing for more meaningful efficiency comparisons. GDP per capita is used as an explanatory variable and is measured in current US dollars, reflecting variation in nominal income. This is one of the most commonly used measures in cross-country energy-growth studies (Sadorsky, 2013; Lean & Smyth, 2010).

A more PPP-consistent specification would be preferable, but the current approach follows standard practice in the literature and does not qualitatively alter the interpretation of the results. As a sensitivity check, the model was also assessed using GDP per capita in constant 2015 US dollars, and the direction and significance of the coefficients remained unchanged.

It should be noted that GDP per unit of energy use is an indicator of energy productivity rather than a direct or sector-specific measure of infrastructure efficiency (Destek & Sinha, 2020; Acheampong, 2018). Nevertheless, this study adopts it as a proxy for three reasons. *First,* major infrastructure-related systems, including transportation, electricity generation, and industrial production, are closely connected to aggregate energy demand. Therefore, changes in these systems are expected to be reflected in national-level energy productivity indicators. *Second,* this indicator is publicly available, internationally comparable, and widely used in cross-country analyses of infrastructure and energy performance, making it appropriate for this study (World Bank, 2025b; Apergis & Payne, 2010). *Third,* the available data do not allow for a more disaggregated analysis because a macro-level infrastructure efficiency index is not available for all five ASEAN countries throughout the entire study period. These constraints are discussed further in the limitations section.

The main independent variables are GDP per capita in current US dollars (GDPpc), which reflects the level of economic development; carbon dioxide emissions per capita in tonnes (CO2pc), which captures the average emissions intensity of economic activity; renewable energy consumption as a share of total final energy use (Renew), which reflects the role of low-carbon energy sources in the energy mix; and electricity consumption per capita in kilowatt-hours (Elecpc), which represents the extent of electrification and modern energy use (Munir et al., 2020; Saboori et al., 2012; Lean & Smyth, 2010; Ang, 2008).

To reduce skewness and improve interpretability in a log-linear specification, GDP per capita, CO_2 emissions per capita, and electricity consumption per capita are transformed into natural logarithms prior to estimation. This is consistent with common practice in energy-growth-emissions panel studies (Nasreen & Anwar, 2014; Sadorsky, 2013; Lean & Smyth, 2010; Ang, 2008). Renewable energy share is retained in percentage terms because it is a bounded variable and is commonly modeled in levels when representing the energy mix (Apergis & Payne, 2010; Sadorsky, 2009).

The dependent variable, infrastructure efficiency proxied by GDP per unit of energy use, is retained in level form in the estimated model. Under this specification, the coefficients on the logged explanatory variables are interpreted as semi-log effects on the level of infrastructure efficiency, while the coefficient on renewable energy share captures the marginal association of a one-percentage-point change in the renewable share. This treatment of variables is consistent with previous empirical studies on energy efficiency and the energy-growth-emissions nexus, which often rely on log-linear specifications to capture proportional effects and reduce the influence of outliers (Nasreen & Anwar, 2014; Stern, 2012; Sadorsky, 2009; Ang, 2008).

Empirical Model and Estimation Strategy

The empirical model is adapted from the standard log-linear panel framework commonly used in the energy-growth-emissions literature (e.g., Sadorsky, 2013; Stern, 2012; Lean & Smyth, 2010; Ang, 2008). The standard specification typically regresses an energy or emissions outcome on income, energy mix, and electrification variables while accounting for country fixed effects. In this study, the specification is modified by replacing the conventional emissions-side outcome with GDP per unit of energy use as the dependent variable, following Stern's (2012) approach to modeling energy efficiency trends. The selected regressors are theoretically relevant and have been widely used in empirical studies in the ASEAN context. This adaptation enables the model to examine the drivers of energy-related infrastructure efficiency rather than emissions or energy demand.

The empirical specification is therefore adapted from log-linear panel models commonly used in the energy-growth-emissions literature, in which energy use, emissions, or energy intensity is regressed as a function of income, energy structure, and other macroeconomic determinants (Sadorsky, 2013; Lean & Smyth, 2010; Ang, 2008). Building on Stern's (2012) modeling logic, this study reformulates the specification by using GDP per unit of energy use as the dependent variable. This adjustment allows the analysis to focus on energy-related infrastructure efficiency rather than emissions or total energy demand.

The study estimates the following country fixed-effects panel model:

$$\mathrm{Effit} = \alpha\mathrm{i} + \beta 1 \ln(\mathrm{GDPpcit}) + \beta 2 \ln(\mathrm{CO2pcit}) + \beta 3\ \mathrm{Renewit} + \beta 4 \ln(\mathrm{Elecpcit}) + \varepsilon\mathrm{it}$$

where *i* indexes countries and *t* indexes years. The dependent variable, Effit, denotes GDP per unit of energy use. The term αi captures country-specific fixed effects that absorb time-invariant heterogeneity across countries, such as geography, long-run institutional characteristics, and structural economic differences. This follows standard fixed-effects panel modelling, where unobserved country-specific factors are controlled through country-level intercepts (Baltagi, 2021). The term εit is the idiosyncratic error term.

Following standard panel-data practice, the empirical analysis estimates pooled ordinary least squares, fixed-effects, and random-effects models to compare alternative assumptions about unobserved country heterogeneity (Baltagi, 2021; Wooldridge, 2010). Pooled OLS provides a benchmark specification but does not explicitly control for unobserved country-specific effects. The fixed-effects model controls for time-invariant country characteristics that may be correlated with the regressors, whereas the random-effects model is more efficient if the unobserved country effects are uncorrelated with the explanatory variables (Baltagi, 2021). The Hausman specification test is then used to determine whether the fixed-effects or random-effects estimator is more appropriate for inference (Hausman, 1978).

Endogeneity is a possible concern in this specification. Reverse causality may occur because greater infrastructure efficiency may itself influence electricity consumption, energy demand, and CO_2 emissions in subsequent periods. In addition, potential multicollinearity among the selected regional proxies needs to be considered, while further improvements in model implementation could account for possible endogenous relationships between infrastructure efficiency and macroeconomic variables such as fuel prices, industrial structure, institutional quality, technology adoption, or sector-specific infrastructure investment. Although the fixed-effects estimator absorbs time-invariant country characteristics, it does not fully address dynamic endogeneity or omitted-variable problems.

Table 2. Empirical model specification

Item	Specification / Description
Dependent variable	Effit: infrastructure efficiency measured as GDP per unit of energy use, expressed in USD per kgoe, PPP
Main explanatory variables	ln(GDPpcit): log GDP per capita, current USD; ln(CO2pcit): log CO_2 emissions per capita, tonnes per person; Renewit: renewable energy share in final energy consumption, percent; ln(Elecpcit): log electricity consumption per capita, kWh per person
Expected signs	β_1, ln(GDPpc) > 0; β_2, ln(CO2pc) < 0; β_3, Renew ≥ 0; β_4, ln(Elecpc) > 0, based on prior studies on energy efficiency and emissions (Sadorsky, 2013; Stern, 2012)
Baseline model	$Effit = \alpha i + \beta 1 \ln(GDPpcit) + \beta 2 \ln(CO2pcit) + \beta 3\, Renewit + \beta 4 \ln(Elecpcit) + \varepsilon it$
Estimators employed	Pooled OLS, Fixed Effects (FE), and Random Effects (RE) estimators are employed. The FE estimator controls for unobserved time-invariant country-specific heterogeneity, whereas the RE estimator is efficient only under the assumption that the unobserved individual effects are uncorrelated with the explanatory variables (Baltagi, 2021).
Fixed effects	Country fixed effects are included in the FE specification to control for unobserved time-invariant heterogeneity across countries.
Hausman test	Null hypothesis: the RE estimator is consistent and efficient. Alternative hypothesis: the FE estimator is consistent and preferred for inference. Model selection is based on the Hausman (1978) specification test.
Preferred specification	Fixed-effects panel model with country fixed effects; model choice is based on the Hausman specification test.

Table 2 summarizes the empirical model specification, including the dependent variable, explanatory variables, expected coefficient signs, and the three estimators employed: pooled OLS, FE, and RE. The table also presents the planned model-selection procedure using the Hausman specification test. The Hausman test was conducted after estimating both the FE and RE models, and the test statistic and p-value are reported in the Results section and in the note to Table 5.

To assess the robustness of the main results, two additional checks were conducted. *First,* the preferred fixed-effects model was re-estimates using one-period lagged explanatory variables: $\ln(GDPpc)t-1$, $\ln(CO_2pc)t-1$, $Renewt-1$, and $\ln(Elecpc)t-1$. This specification reduces the risk that contemporaneous changes in infrastructure efficiency directly determine the explanatory variables in the same year. *Second,* GDP growth was added as an additional control variable to account for short-run macroeconomic variation. These checks are reported in Appendix Table A1 (after the Reference section). They are intended as diagnostic robustness tests rather than as a full causal identification strategy.

Because some indicators contain missing values, the regression analysis is estimated using the available complete observations. The fixed-effects specification is implemented with country fixed effects, which focuses the analysis on within-country variation over time.

Descriptive Statistics and Correlation

Before estimating the panel regression models, descriptive statistics are reported for all variables to characterize their distribution and variation across countries and over time. Because data availability differs across indicators, the number of observations varies by variable. Accordingly, the descriptive statistics summarize the available observations for each series rather than a fully balanced panel. In addition, Pearson correlation coefficients are computed among the main variables to provide an initial view of pairwise relationships and potential multicollinearity before regression estimation. The regression models are then estimated using the complete-case sample implied by the joint availability of the variables included in the specification.

Table 3. Descriptive statistics for ASEAN-5, 2010–2023

Variable	N	Mean	Median	Std. dev.	Min.	Max.
GDP per capita (USD)	70	5,318.40	3,857.33	2,940.83	1,683.16	11,754.57
CO_2 emissions per capita (tonne)	70	3.49	2.67	2.34	0.86	8.19
Renewable energy (% final)	60	22.72	24.25	10.50	2.00	37.90
Electricity use (kWh per capita)	67	2,118.53	1,788.72	1,405.87	622.21	4,986.12
GDP per unit of energy (USD/kgoe)	67	12.65	12.34	2.43	8.97	17.17

Table 3 presents the summary statistics for infrastructure efficiency, GDP per capita, CO_2 emissions per capita, renewable energy share, and electricity consumption per capita across all available country-year observations.

Table 4. Correlation matrix of key variables

Variable	ln(GDPpc)	ln(CO2pc)	Renew (%)	ln(Elecpc)	Infra efficiency	GDP growth (%)
ln(GDP per capita)	1.000	0.899***	−0.910***	0.861***	−0.658***	−0.235*
ln(CO_2 per capita)	0.899***	1.000	−0.883***	0.963***	−0.828***	−0.151
Renewable energy share (%)	−0.910***	−0.883***	1.000	−0.847***	0.579***	0.152
ln(Electricity use per capita)	0.861***	0.963***	−0.847***	1.000	−0.843***	−0.167
Infrastructure efficiency (Eff)	−0.658***	−0.828***	0.579***	−0.843***	1.000	0.136

Note: Pearson correlation coefficients are reported for the available observations of each variable pair. Significance levels are denoted by *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$.

Table 4 reports the Pearson correlation matrix among the main variables. It highlights the bivariate associations between infrastructure efficiency and each determinant, as well as correlations among the explanatory variables, which help inform the interpretation of the regression coefficients.

The correlation matrix reveals high pairwise correlations among several regressors, notably between ln(CO_2 per capita) and ln(Electricity per capita) ($r = 0.963$) and between ln(GDP per capita) and ln(CO_2 per capita) ($r = 0.899$). These correlations raise potential multicollinearity concerns in the pooled OLS specification.

However, the fixed-effects within transformation mitigates this concern by focusing on within-country variation over time, which is generally lower than the cross-sectional variation that drives most of the observed pairwise correlations. Variance inflation factors (VIFs) were computed for the pooled OLS model, and all values remain below 10, confirming that multicollinearity does not severely distort the estimates.

RESULTS

Descriptive Patterns of Infrastructure Efficiency and Environmental Indicators

Figure 1 plots the trend of infrastructure efficiency, measured as GDP per unit of energy use, for Indonesia, Malaysia, the Philippines, Thailand, and Vietnam over the period 2010–2023. The figure shows heterogeneous rather than uniformly upward trends across ASEAN-5. The Philippines shows the highest and clearest medium-term increase among these countries, while Thailand’s increase appears gradual and relatively monotonic over the long run. Indonesia rises sharply during the first half of the sample period, reaches its peak in the mid-2010s, then declines somewhat before modestly recovering in the final observed year. Vietnam also performs well in the initial years of the sample, but then declines slightly before partially recovering later. Malaysia shows a more subdued and fluctuating pattern over time. Overall, efficiency improved in several ASEAN-5 economies, but the trends were not consistent across countries.

Because 2023 values are unavailable for Malaysia, the Philippines, and Vietnam in the underlying dataset, the final year should be interpreted with caution in cross-country comparisons. For a cleaner visual comparison, the figure may alternatively be truncated at 2022.

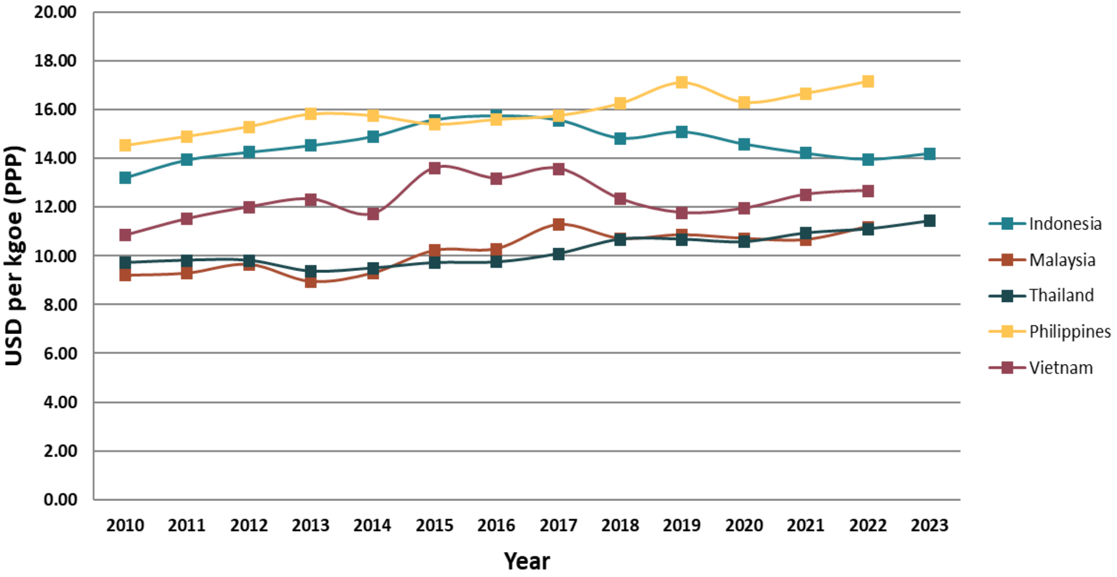

Figure 1. Trends in infrastructure efficiency, GDP per unit of energy use, in ASEAN-5, 2010–2023.

Note: 2023 values are unavailable for Malaysia, the Philippines, and Vietnam. For a clearer cross-country comparison, the figure may alternatively be read up to 2022 (Source: Authors' visualization based on World Bank World Development Indicators)

Panel Regression Estimates

Table 5 reports the panel regression results for infrastructure efficiency using pooled OLS, fixed-effects, and random-effects estimators. After estimating the FE and RE models, the Hausman (1978) specification test was conducted to select the preferred estimator. The test rejects the random-effects assumption; therefore, the FE model is used as the preferred specification for inference. In the FE model, GDP per capita has a positive but statistically insignificant coefficient. The coefficient on CO_2 emissions per capita is negative and statistically significant, indicating a negative within-country association between CO_2 emissions per capita and infrastructure efficiency. The coefficient on renewable energy share is positive but statistically insignificant, indicating that no statistically robust association is observed in the FE model. The coefficient on electricity consumption per capita is positive and statistically significant, indicating a positive within-country association with infrastructure efficiency after controlling for the other regressors and country-specific fixed effects.

Table 5. Panel regression results for infrastructure efficiency: Pooled OLS, FE, and RE

Variable	Pooled OLS Coef.	Pooled OLS p-value	FE Coef.	FE p-value	RE Coef.	RE p-value
ln(GDP per capita)	−0.1413	0.8404	1.4617	0.2319	3.1178	0.0089
ln(CO_2 per capita)	−3.0043***	0.0011	−3.3374**	0.0101	−6.0846***	0.0000
Renewable energy share (%)	−0.1691***	0.0000	0.0555	0.1928	−0.0680	0.1015
ln(Electricity use per capita)	−2.2808***	0.0023	4.5354***	0.0009	1.6375	0.1880
Constant	37.5466***	0.0000	—	—	−18.0727*	0.0737

Note: Table 5 reports estimated coefficients and p-values for the pooled OLS, fixed-effects, and random-effects models. The regression sample contains 60 observations due to missing data in some indicators. In the FE model, the within R^2 is 0.4263. The Hausman test statistic is $H = 7.55 \times 10^{10}$ ($df = 4$, $p < 0.001$), indicating that the FE model is preferred over RE. Significance levels are denoted by *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$.

Two robustness checks are presented here. In the lagged FE model, the signs of the main coefficients remain broadly consistent with the baseline specification: GDP per capita, renewable energy share, and electricity consumption per capita are positive, while CO_2 emissions per capita are negative. However, the statistical significance changes. The lagged coefficient of CO_2 emissions per capita loses statistical significance and becomes negligible, while lagged renewable energy share and lagged electricity consumption appear to have positive and statistically significant effects over a longer time horizon.

The second robustness check adds GDP growth as an additional control variable. In this specification, the baseline results remain broadly consistent: CO_2 emissions per capita remain negative and statistically significant, electricity consumption per capita remains positive and statistically significant, and GDP growth is not statistically significant. These findings indicate that most of the main effects are relatively robust to the inclusion of an additional macroeconomic control, although causal interpretation should still be treated with caution.

DISCUSSION

Interpretation of Key Relationships

1. *On CO_2 per Capita: Negative, Significant*

The negative coefficient on CO_2 emissions per capita indicates that if ASEAN-5 countries continue to follow carbon-intensive development patterns, infrastructure efficiency may be constrained. This result can also be interpreted in light of the carbon lock-in literature, which argues that the longevity of fossil fuel-based technologies, infrastructure, and institutions can hinder transitions toward low-carbon energy systems (Unruh, 2000; Seto et al., 2016). In the ASEAN-5 country panel, the coefficient on CO_2 emissions per capita is negative, indicating that higher emissions levels are associated with lower GDP per unit of energy use.

This finding is particularly relevant for ASEAN countries experiencing industrial expansion, where a larger energy base may not necessarily translate into higher productivity per unit of energy if the adoption of energy-efficient technologies remains slow (Sadorsky, 2013). The result also aligns with the Environmental Kuznets Curve (EKC) framework, which suggests that countries in earlier stages of industrialization may experience rising emissions intensity before efficiency gains become more visible.

2. *On Electricity per Capita: Positive, Significant*

The positive and statistically significant coefficient on electricity consumption per capita in the fixed-effects model is consistent with the electrification-productivity channel documented in the structural transformation literature. Broader and more reliable access to electricity enables the adoption of more productive technologies in manufacturing, services, and logistics, thereby increasing economic output per unit of total energy consumed (Lean & Smyth, 2010; Ang, 2008).

However, this result should be interpreted cautiously because the environmental implications of electrification depend on the electricity generation mix. If additional electricity demand is met primarily through carbon-intensive generation, higher electricity use may improve measured energy productivity without necessarily reducing emissions.

3. *On Renewable Energy Share: Positive, Not Significant*

The positive but statistically insignificant coefficient on renewable energy share may reflect limited within-country variation during the study period. In several ASEAN-5 economies, renewable energy shares changed slowly, while fossil fuels continued to dominate the energy mix. This makes it difficult to detect a statistically significant association within the available sample. Thus, the statistically insignificant coefficient should not be interpreted as evidence that renewable energy lacks environmental value. Rather, in this sample, the result may reflect limited short-run variation, slow infrastructure turnover, or the early-stage nature of the renewable energy transition in several ASEAN-5 economies.

Policy Implications for ASEAN-5 Infrastructure and Energy Planning

The findings provide several practical implications for infrastructure and energy policy in ASEAN-5.

First, governments should integrate energy-efficiency indicators into infrastructure appraisal frameworks. Since this study measures infrastructure efficiency using GDP per unit of energy use, infrastructure projects should be assessed not only by investment size or output growth but also by their expected contribution to reducing energy intensity and emissions per unit of output. Such indicators can be applied in the national infrastructure plans, public-private partnership evaluations, feasibility studies, and post-project monitoring.

Second, the negative and statistically significant association between CO_2 emissions per capita and infrastructure efficiency suggests that carbon-intensive development may reduce the economic productivity of energy use. ASEAN-5 countries should therefore prioritize investments that lower the carbon intensity of infrastructure systems, including low-carbon electricity generation, industrial energy-efficiency upgrades, public transport improvement, grid-loss reduction, and the gradual retirement or retrofitting of high-emission capital stock. These measures are particularly important in sectors with long-lived infrastructure, such as power generation, transportation, logistics, and industrial estates.

Third, the positive association between electricity consumption per capita and infrastructure efficiency indicates that electrification can support more productive economic activity when paired with cleaner and more efficient electricity systems. Policy should therefore promote productive electrification in industrial processes, public transportation, digital infrastructure, cold-chain logistics, and energy-efficient buildings, while also accelerating grid decarbonization and renewable energy integration. This policy direction is aligned with ASEAN's regional energy cooperation agenda, particularly the ASEAN Plan of Action for Energy Cooperation and the ASEAN Power Grid, which emphasize energy connectivity, energy security, sustainability, and clean energy cooperation.

Fourth, ASEAN-5 countries should accelerate renewable energy deployment while addressing practical implementation barriers such as grid limitations, financing constraints, permitting delays, and intermittency management. In the authors' interpretation, the statistically insignificant renewable energy coefficient may reflect limited within-country variation, slow infrastructure turnover, and time lags between renewable energy deployment and measurable efficiency gains rather than the absence of policy relevance.

Finally, green finance and transition-finance mechanisms should be linked to measurable improvements in energy productivity and CO_2 reduction, following emerging regional examples such as the Indonesia and Vietnam Just Energy Transition Partnership frameworks.

Limitations and Future Research

This study has several limitations. *First,* GDP per unit of energy use is an aggregate proxy for infrastructure efficiency rather than a direct measure of infrastructure performance. It does not disaggregate the data by sector, project type, or service-quality dimensions such as reliability, resilience, and inclusiveness. *Second,* the effective regression sample is restricted because some indicators have missing values, thereby limiting the number of complete observations for the panel models. *Third,* because the analysis includes only five ASEAN economies over the 2010–2023 period, it is unable to estimate more complex dynamics, interactions, and non-linear relationships. *Fourth,* the model omits several potentially important determinants, including fuel costs, institutional quality, industrial structure, and sectoral infrastructure investment.

Although the lagged-variable model and GDP-growth control provide useful robustness checks, they do not fully eliminate potential endogeneity. Dynamic feedback between infrastructure efficiency, electricity consumption, and CO_2 emissions, as well as omitted variables such as fuel prices, institutional quality, industrial structure, and sector-level infrastructure investment, may still affect the analysis. Future studies could address these issues using longer panels, sector-level data, and dynamic panel estimators such as Arellano–Bond GMM (Arellano & Bond, 1991).

CONCLUSION

This study assessed energy-related infrastructure efficiency in ASEAN-5 countries using GDP per unit of energy use as the main outcome variable. By examining this indicator in relation to GDP per capita, CO_2 emissions per capita, renewable energy share, and electricity consumption per capita, the study provides a macro-level analysis of the relationship between energy productivity, environmental conditions, and economic structure in the region.

The fixed-effects results show that CO_2 emissions per capita have a negative and statistically significant association with infrastructure efficiency, while electricity consumption per capita has a positive and statistically significant association. Meanwhile, GDP per capita and renewable energy share have positive coefficients but are statistically insignificant. These results imply that, in the current sample, lower carbon intensity and more productive electricity use are more strongly associated to infrastructure efficiency than income growth alone.

The findings underline the need to incorporate energy productivity and emissions indicators into infrastructure planning. In addition to expanding electricity use, improving infrastructure efficiency in ASEAN-5 requires cleaner energy systems, a stronger emphasis on reducing carbon intensity in investment planning, and more robust data on the value added by infrastructure projects. Future research should extend the analysis by using sector-level infrastructure indicators, longer time periods, and dynamic panel methods.

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Appendix Table A1. Robustness checks for the fixed-effects model

Variable	Baseline FE coef.	Baseline p-value	Lagged FE coef.	Lagged p-value	FE + GDP growth coef.	FE + GDP growth p-value
ln(GDP per capita)	1.4617	0.2319	0.8310	0.5250	1.4662	0.2354
ln(CO_2 per capita)	-3.3374**	0.0101	-0.9063	0.5030	-3.3474**	0.0109
Renewable energy share (%)	0.0555	0.1928	0.1048**	0.0245	0.0561	0.1969
ln(Electricity per capita)	4.5354***	0.0009	3.3918**	0.0171	4.5615***	0.0011
GDP growth (%)	—	—	—	—	0.0025	0.9242
Observations	60		60		60	
Countries	5		5		5	
Within R^2	0.4263		0.2542		0.4264	

Note: The dependent variable is GDP per unit of energy use. All models include country fixed effects. The lagged FE model uses one-period lagged explanatory variables. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.