 Vol. 9 No. 1 (2026) 1 – 16 | doi.org/10.33116/ije.v9i1.288

IJE | INDONESIAN JOURNAL OF ENERGY
P-ISSN: 2549-1016 | E-ISSN: 2549-760X
available online at www.ije-pyc.org

Published by:

# The Nexus of Climate Adaptation, Public-Private Partnership Investment Flows, and Renewable Energy Transition: Evidence from a Cross-Country Panel Study

Faiz Attaqi [1, *], Siti Komariah [1], Muhammad I. Pratama [1]

[1] Department of Economics, Universitas Indonesia, Kukusan, Beji, Depok, West Java 16242, Indonesia

*Corresponding Author: fattaqi08@gmail.com

**Article History**

Received 21 June 2025
Accepted 16 September 2025
Available 27 February 2026

**Abstract**

What role does climate vulnerability play in directing public-private and private energy investments worldwide? Our study investigates the determinants of Public-Private Partnership (PPP) energy investment, private energy investment, and renewable energy output using a random-effects panel data model covering 214 countries from 2010–2022. We examine the role of climate vulnerability and readiness, as measured by the ND-GAIN index, alongside institutional, economic, and energy-specific control variables. Our findings reveal that higher climate readiness (lower vulnerability) significantly boosts both PPP and private energy investments. Key institutional factors, such as voice and accountability, together with structural indicators like population size and trade openness, also positively influence private energy investment. For renewable energy output, existing renewable energy consumption patterns, foreign direct investment inflows, and lower energy intensity (greater efficiency) emerge as significant positive drivers. While PPP energy investment does not show a statistically significant direct impact on the share of renewable energy output in our comprehensive models, its role in overall energy sector development, combined with the crucial influence of climate adaptation capacity, underscores the complex dynamics shaping the global energy landscape. These results highlight the importance of enhancing climate resilience and institutional quality to mobilize capital for a sustainable energy future.

**Keywords:**
climate vulnerability, renewable energy output, panel data analysis, private investment, Public-Private Partnership (PPP) investment

## 1. Introduction

The global climate crisis has prompted the international community to take collective action to accelerate the transition to renewable energy. The global response has been reflected in various agreements, from the Kyoto Protocol in 1997 to the Glasgow Climate Pact in 2021, which designated the 2020s as the decade of climate action. The 2015 Paris Agreement and the 2015 Sustainable Development Goals (SDGs) further affirmed the world's commitment to mitigating global warming and achieving sustainable development. So far, the increasing vulnerability of many regions to the impacts of climate change, from flash floods to heat waves, has driven investment in renewable energy as a mitigation measure. The development of renewable energy is often shaped by a confluence of factors, including economic growth, technological advancements, and supportive government policies (Xu et al., 2019), alongside broader socio-economic conditions such as human development and education (İçen, 2025). The Intergovernmental Panel on Climate Change (IPCC) has emphasized that climate change "affects every region of the planet in different ways". Figure 1 shows the Notre Dame Global Adaptation Initiative (ND-Gain) index, which indicates the vulnerability and readiness of each country to face climate change. A higher index score reflects greater preparedness and lower vulnerability. Shear et al. (2023) show that countries can offset the adverse impact of climate vulnerability on investment by strengthening their economic, institutional, and social environment.

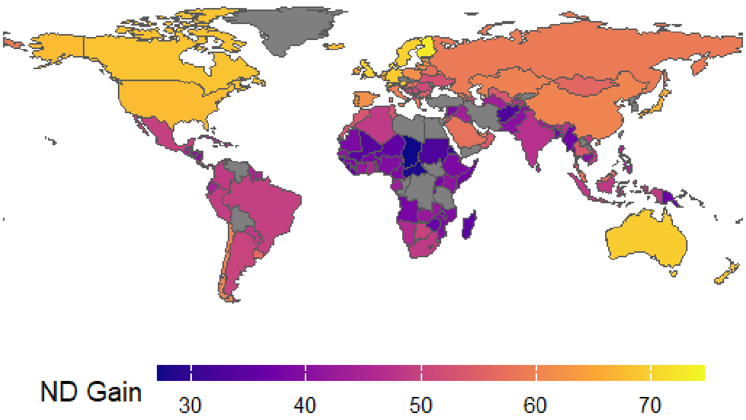


**Figure 1.** ND-Gain Index across nations.

Despite recent progress, actual investments still fall significantly short of what is required. In 2022, global investment in energy transition technologies, including enhancements in energy efficiency, reached a record high of USD 1.3 trillion. Nevertheless, IRENA's World Energy Transitions Outlook 2023 indicates that to align with the 1.5°C pathway, this figure must increase by at least four times annually. Moreover, the distribution of financing remains disproportionately allocated, with a substantial share of energy investments continuing to flow into fossil fuel sectors rather than renewable energy. Multinational financial institutions are channeling an average of USD 750 billion annually into oil and gas ventures. These trends underscore the inadequate scale and pace of the transition from fossil fuels to renewable sources.

Both developed and developing countries require a massive increase in climate finance to achieve net-zero emissions targets. Global clean energy investment must more than triple by 2030, reaching approximately USD 5 trillion per year, to keep the 2050 net-zero pathway affordable (IEA, 2021). The bulk of this additional investment must flow to developing countries. Developing economies will need around USD 2 trillion annually through 2030 for climate mitigation, approximately five times current investment levels, to meet the 2050 net-zero target. There is a stark disparity in climate finance flows between developed and developing countries. Emerging and developing economies account for two-thirds of the world's population yet receive only about one-fifth of global clean energy investment. A range of structural challenges drives this gap: higher financing costs, limited access to capital, and greater perceived investment risks hinder investment flows into climate projects. As a result, a new funding goal was agreed, doubling the commitment to developing countries, from the previous pledge of USD 100 billion per year to USD 300 billion per year by 2035 and calling for the mobilization of USD 1.3 trillion annually from public and private sources by 2035 (UNFCC, 2024).

Given the limited fiscal capacity of governments, private capital plays an increasingly vital role in bridging the investment gap in the energy sector. The private sector has consistently accounted for most global investment in renewable energy, contributing approximately 75% of the total between 2013 and 2020 (IRENA, 2023). This highlights the dominant role of private investors in financing clean energy transitions across regions. Figure 2 presents a comparative overview of investments in the energy sector, illustrating the distribution between Public-Private Partnership (PPP) schemes and full private investment.

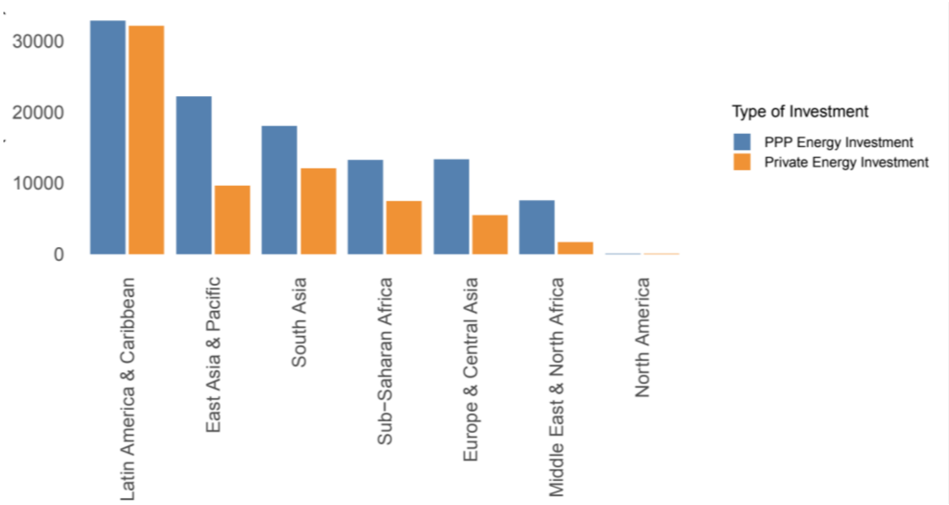


**Figure 2.** Energy investment per region 2019-2022 (in million USD).

Despite the growing urgency of energy transition and increasing attention to the role of PPPs, several research gaps remain insufficiently addressed. First, there is limited empirical evidence incorporating climate vulnerability indicators, such as the Climate Change Vulnerability Index, into analyses of energy investment. As a result, the influence of a country's climate vulnerability level on energy investment flows, including those through PPP schemes, remains poorly understood. A recent study by Wen et al. (2023), covering 107 countries, provides early evidence that high climate vulnerability tends to reduce green investment in both mitigation and adaptation efforts. While this highlights a potential negative relationship, further investigation is needed to explore how this dynamic unfolds within the energy sector and PPP-specific contexts. Second, there is a lack of comparative research on PPP-based energy investments versus fully private-sector investments. Existing literature often focuses either on aggregate investment figures or case-specific analyses, making it difficult to discern the differential contribution of PPP models compared to purely private investment in renewable energy capacity development. Third, the impact of PPP investment on renewable energy outcomes remains inconclusive. In some cases, PPP participation has not led to improvements in clean energy performance. For instance, Hossin et al. (2024) found that an increase in PPP-based energy investments in Southeast Asia was associated with a 52.6% rise in greenhouse gas emissions, undermining regional efforts to achieve SDG 7 on clean energy. On the other hand, PPPs, alongside factors such as globalization and urbanization, can serve as significant catalysts for renewable energy development (Qamruzzaman & Karim, 2023; Yin & Qamruzzaman, 2024), although the specific policy context and market maturity can strongly influence their effectiveness (Zhang et al., 2022).

Our study seeks to complement previous research highlighting the importance of PPPs in driving renewable energy progress, including Hossin et al. (2024), Raghutla & Kolati (2023), and Qamruzzaman & Karim (2023). While previous studies focus on the impact of PPPs on renewable energy consumption, our study examines renewable energy production and a country's vulnerability readiness, as represented by the ND-GAIN index. We structure the paper with an introduction and a literature review for each dependent variable (i.e., PPP investment in energy, private investment in energy, and renewable energy production). The methodology section provides a detailed explanation of the random-effects panel data approach and the dataset used. The results section presents descriptive statistics and interprets the three estimation models. Finally, the paper concludes with a summary of our findings.

## 2. Methods and Materials

Our conceptual framework in Figure 3 illustrates how climate change risks shape a country's ND-GAIN Index (vulnerability and readiness). This index, reflecting adaptation capacity, is posited to drive the urgency of energy sector investment, which subsequently materializes as PPP investment and private investment. Ultimately, these investments, particularly PPP investment in one of our models, are assessed for their contribution to renewable energy production and subsequent clean energy transition outcomes. The empirical analysis focuses on three dependent variables, which are PPP investments in energy, private investments in energy, and renewable electricity output.

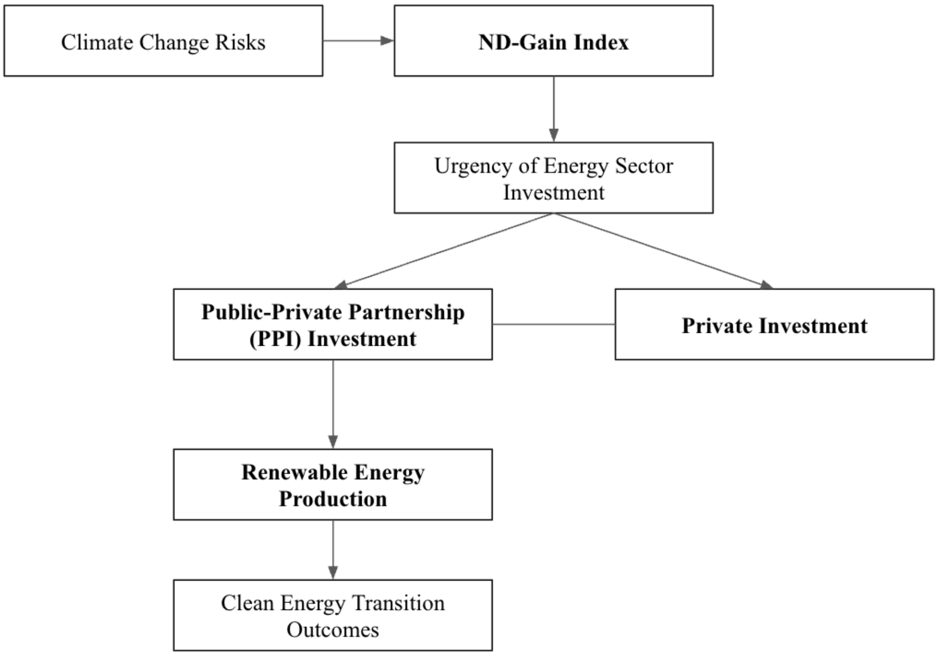


**Figure 3.** Research conceptual framework.

### *2.1 Modeling Equations and Software*

To estimate the relationship between climate vulnerability, energy investment (both PPP and private), and renewable energy production, we employ a static panel model with a Random Effects (RE) specification. This approach assumes that unobserved country-specific effects are uncorrelated with the explanatory variables. The panel data structure is advantageous for controlling unobserved heterogeneity and capturing dynamic adjustments over time. Although previous studies on similar topics, such as Iqbal et al. (2023), Qamruzzaman & Karim (2023), and Yin & Qamruzzaman (2024), used the Auto-Regressive Distributed Lag (ARDL) time series model; we adopt a panel data approach due to the large number of missing values, particularly from North American countries. ARDL requires sequential and complete data for each country; missing years or variables disrupt lag modeling, leading to the loss of many observations or rendering the model unworkable. By contrast, the RE panel model can accommodate unbalanced panels, meaning not all countries must have complete data for all years. As long as the panel structure is maintained, estimation remains feasible. Given that the dependent variables (i.e., PPP energy investment, private energy investment, and renewable electricity output) may be influenced by both time-invariant country characteristics and time-varying factors, the RE model provides greater efficiency in estimation. Moreover, since our analysis includes institutional readiness, trade openness, and climate vulnerability, some of which may not vary substantially over time within a country, the RE specification is particularly suitable for capturing between-country differences while retaining time-invariant regressors.

The panel regression model is formulated in Equations 1 – 3. The ND-GAIN Index is the main variable of interest in Equations 1 and 2, representing a country's level of vulnerability and readiness to climate change. For Equation 3, the variable of interest is PPP investment in energy, which in earlier models served as a dependent variable. The control variables in the model include institutional indicators (e.g., voice and accountability), structural indicators (e.g., logarithm of population, trade openness, and real interest rates), and energy sector-specific variables (i.e., the Energy Intensity Level of primary energy

(EIL) and Renewable Energy Consumption (REC)). The inclusion of these controls is guided by established literature on energy investment and renewable energy adoption. For instance, institutional quality, represented by voice_accountability, is widely recognized as a crucial factor in investment decisions. Economic development (proxied by GDP per capita, implicitly captured in ln GDPCC in Equation 3) and population size (ln_pop) are standard controls reflecting market size and demand (Aguirre & Ibikunle, 2014; Hunt et al., 2024). Similarly, trade openness (trade_open) can influence technology transfer and economic integration, while energy intensity (EIL) reflects a country's energy efficiency. All of these are considered relevant determinants in the energy sector (İçen, 2025; Su et al., 2024).

$$Ln\ PPP\ Energy\ Invest_{it} = \beta_0 + \beta_1 ND\ Gain_{it} + \beta_2 Voice\ Accountability_{it} + \beta_3 EIL_{it} + \beta_4 ln\ Pop_{it} + \beta_5 Trade\ Open_{it} + \beta_6 real\ interest_{it} + \varepsilon_{it} \quad (1)$$

$$Ln\ Private\ Energy\ Invest_{it} = \beta_7 + \beta_8 ND\ Gain_{it} + \beta_9 Voice\ Accountability_{it} + \beta_{10} EIL_{it} + \beta_{11} ln\ Pop_{it} + \beta_{12} Trade\ Open_{it} + \beta_{13} real\ interest_{it} + \varepsilon_{it} \quad (2)$$

$$Renewable\ Electricity\ Output_{it} = \beta_{14} + \beta_{15} ln\ PPP\ Energy\ Invest_{it} + \beta_{16} Voice\ Accountability_{it} + \beta_{17} EIL_{it} + \beta_{18} lnPop_{it} + \beta_{19} FDI\ Inflows_{it} + \beta_{20} REC_{it} + \beta_{21} ln\ GDPCC_{it} + \varepsilon_{it} \quad (3)$$

To ensure valid inference in this cross-country panel, we employ cluster-robust standard errors at the country level, correcting for heteroskedasticity and intra-country error correlation. Ignoring such dependence can severely bias results (Hoechle, 2007). Cluster-robust methods are specifically designed to account for both cross-sectional and temporal dependence in FE/RE panel models (Basak & Das, 2018). As emphasized by Cameron & Miller (2015), when regression errors are independent across clusters but correlated within clusters, default standard errors can substantially understate estimator variability and overstate precision. Given the cross-country nature of our dataset, where observations are naturally clustered at the country level, the use of cluster-robust standard errors provides a more reliable basis for statistical inference.

The choice of the Random Effects method is based on the results of the Hausman Test (see Appendix), which indicates that the null hypothesis cannot be rejected (p-value > 0.05). Accordingly, the Random Effects approach is more appropriate than Fixed Effects. To address heteroskedasticity and autocorrelation, estimation is carried out using robust standard errors. All data processing was conducted in STATA 16.

### *2.2 Data collection*

Our study employs a panel dataset covering 214 countries from 2010 to 2022. Table 1 provides a comprehensive overview of all variables used in the analysis, detailing their definitions, operationalization, units of measurement, expected signs in the regression models, and specific data sources. The three primary dependent variables are the logarithm of PPP energy investment (ln_ppp_energy_invest), the logarithm of private energy investment (ln_private_energy_invest), and renewable electricity output as a percentage of total electricity output (renew_electric_output). The main independent variable of interest for the investment models (Models 1 and 2) is the ND-GAIN Index (ND_gain), which captures a country's climate vulnerability and readiness. For the renewable energy output model (Model 3), the logarithm of PPP energy investment serves as the primary independent variable. A suite of control variables is incorporated to account for institutional quality (e.g., voice_accountability), economic structure (e.g., ln_pop, trade_open, ln_gdppc), energy-specific factors (e.g., EIL, REC), and financial conditions (e.g., real_interest, FDI_inflows). Data are primarily sourced from the World Bank's World Development Indicators (WDI), Private Participation in Infrastructure (PPI) Database, World Governance Indicators (WGI), and the University of Notre Dame's Global Adaptation Initiative (ND-GAIN).

**Table 1.** Research the operational table.

| Variable | Definition | Unit | Source |
|---|---|---|---|
| **Dependent variables** | | | |
| ln_ppp_energy_invest | PPP investment in energy (Commitments) | Log (Current US$) | WDI |
| ln_private_energy_invest | Private investment in energy (with private participation) | Log (Current US$) | PPI |
| renew_electric_output | Share of renewable electricity in total electricity output | % | WDI |
| **Independent variables** | | | |
| ND_gain | Composite index of climate vulnerability (exposure and adaptive capacity) and readiness (ability to attract and utilize investments for adaptation) | Index Score (0-100) | ND-Gain |
| ln_ppp_energy_invest | PPP investment in energy (Commitments) | Log (Current US$) | WDI |
| **Control Variables** | | | |
| voice_accountability | Perceptions of citizens' ability to participate in government selection, freedom of expression, association, and media | Standardized Index | WGI |
| EIL | Energy intensity level of primary energy | MJ / $2017 PPP GDP | WDI |
| ln_pop | Total Population | Log (Number) | WDI |
| trade_open | Trade openness (Exports and imports as a share of gross domestic product) | % of GDP | WDI |
| real_interest | Real lending interest rate (adjusted for inflation) | % | WDI |
| FDI_inflows | Net foreign direct investment inflows | % of GDP | WDI |
| REC | Renewable energy consumption share in total final energy consumption | % | WDI |
| ln_gdppc | GDP per capita | Log (Constant 2015 US$) | WDI |

## 3. Results and Discussions

### *3.1 Descriptive Statistics*

Table 2 presents the descriptive statistics for the variables used in this study across six geographical regions. Substantial heterogeneity is evident in renewable electricity output. South Asia (mean 47.37%) and Sub-Saharan Africa (mean 43.35%) record the highest average shares, while the Middle East & North Africa (mean 2.54%) lags far behind, reflecting stark regional disparities in renewable generation capacity. PPP and private energy investments display more consistent mean levels across regions, generally ranging between 18 and 20, suggesting relatively similar investment magnitudes when adjusted for scale. In contrast, the ND-GAIN index, which reflects climate adaptation capacity, varies considerably: Europe & Central Asia achieves the highest average score (mean 60.25), while Sub-Saharan Africa records the lowest (mean 38.43). The number of observations differs across variables and regions, reflecting limitations in data availability, continuity over time, and the extent to which countries report specific indicators. The wide standard deviations, particularly for renewable electricity output, highlight significant within-region variation, motivating deeper investigation into the determinants of energy investment and production outcomes.

**Table 2.** Core variables descriptive statistics among different regions

| Core Variables | Obs. | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| **East Asia & Pacific** | | | | | |
| ln_ppp_energy_invest | 87 | 20.04281 | 1.784423 | 15.67181 | 22.9025 |
| ln_private_energy_invest | 81 | 20.16242 | 1.776725 | 15.67181 | 22.9025 |
| renew_electric_output | 201 | 17.31631 | 25.15907 | 0 | 100 |
| ND_gain | 337 | 49.50135 | 10.50159 | 34.26065 | 73.99697 |
| **Europe & Central Asia** | | | | | |
| ln_ppp_energy_invest | 74 | 19.16965 | 1.739508 | 15.24103 | 22.93177 |
| ln_private_energy_invest | 74 | 19.356 | 1.852968 | 16.24031 | 23.33268 |
| renew_electric_output | 318 | 36.09359 | 31.17593 | 0 | 100 |
| ND_gain | 547 | 60.247 | 8.237508 | 41.91249 | 76.48223 |
| **Latin-North America & Caribbean** | | | | | |
| ln_ppp_energy_invest | 97 | 19.84885 | 1.767414 | 15.86963 | 24.11541 |
| ln_private_energy_invest | 101 | 19.91865 | 1.770909 | 15.86963 | 24.13597 |
| renew_electric_output | 240 | 32.23171 | 30.8442 | 0 | 99.99826 |
| ND_gain | 377 | 49.45645 | 7.760709 | 34.92472 | 72.83206 |
| **Middle East & North Africa** | | | | | |
| ln_ppp_energy_invest | 34 | 19.57197 | 1.480591 | 16.1181 | 22.05879 |
| ln_private_energy_invest | 31 | 19.50713 | 1.428923 | 16.1181 | 21.73621 |
| renew_electric_output | 126 | 2.541403 | 3.95027 | 0 | 17.4341 |
| ND_gain | 208 | 51.14264 | 6.596451 | 38.31747 | 64.63737 |
| **South Asia** | | | | | |
| ln_ppp_energy_invest | 47 | 20.10599 | 1.681289 | 16.42448 | 23.76832 |
| ln_private_energy_invest | 46 | 20.07522 | 1.831732 | 16.42448 | 24.26349 |
| renew_electric_output | 48 | 47.37042 | 39.91745 | 0.315654 | 100 |
| ND_gain | 104 | 41.86538 | 4.859481 | 30.98616 | 50.1726 |
| **Sub-Saharan Africa** | | | | | |
| ln_ppp_energy_invest | 108 | 18.73866 | 1.51897 | 13.99783 | 22.45468 |
| ln_private_energy_invest | 89 | 18.77182 | 1.596231 | 13.99783 | 22.45468 |
| renew_electric_output | 282 | 43.3472 | 37.48507 | 0 | 100 |
| ND_gain | 533 | 38.42927 | 5.797206 | 25.59662 | 57.78708 |

Table 3 presents the descriptive statistics for the control variables across the full sample of countries. Voice accountability has a mean close to zero with a standard deviation of approximately 1, consistent with the standardized nature of governance indicators. The average EIL is 4.81 MJ per $2017 PPP GDP, reflecting typical energy efficiency levels across countries. Trade openness shows a high mean of 92.30% of GDP, with a considerable standard deviation (59.66), indicating wide variation in the degree of economic integration. FDI inflows also demonstrate substantial variability, with a mean of 9.30% of GDP and a large standard deviation (72.21), underscoring the uneven distribution of foreign investment across countries. REC averages 31.84%, with a significant spread (Std. Dev. 28.56), highlighting differences in renewable adoption. Logged GDP per capita (ln_gdppc) has a mean of 9.53, reflecting the diversity of income levels across the sample. The number of observations varies considerably across these controls, with real_interest having the fewest (1,618) and voice_accountability the most (2,709). This variation underscores the challenge of missing data, stemming from incomplete time series for certain countries and the absence of specific indicators for others, a common constraint in cross-country panel analyses.

**Table 3.** Control variables descriptive statistics among all countries.

| Control Variables (All Countries) | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| voice_accountability | 2,709 | -4.75E-10 | 0.9977819 | -2.259265 | 1.780675 |
| EIL | 2,424 | 4.808771 | 2.813474 | 0.22 | 21.42 |
| ln_pop | 2,678 | 15.4043 | 2.307198 | 9.209641 | 21.07773 |
| trade_open | 2,322 | 92.3038 | 59.66073 | 2.698834 | 679.2328 |
| real_interest | 1,618 | 5.480439 | 9.57722 | -81.13212 | 61.8826 |
| FDI_inflows | 2,425 | 9.297524 | 72.2098 | -1303.108 | 1709.827 |
| REC | 2,364 | 31.83528 | 28.55957 | 0.1 | 97 |
| ln_gdppc | 2,515 | 9.52616 | 1.170416 | 6.754783 | 12.06627 |

### *3.2 ND-Gain Impact on Public-Private Partnership (PPP) and Private Investment*

Our first model investigates the relationship between the ND-GAIN Index and PPP investment in energy, presented in two specifications (columns 1 and 2). The regression results in Table 4 show a significant and positive association between ND-GAIN and PPP energy investment in the model without control variables (column 1). However, the effect becomes statistically insignificant once control variables are introduced (column 2). In the bivariate specification (column 1), the coefficient for ND-GAIN is 0.0349, statistically significant at the 5% level. This indicates that a one-unit increase in a country's ND-GAIN score corresponds to a 3.49% increase in PPP investment in energy, holding other factors constant (ceteris paribus). This finding suggests that countries with stronger climate readiness and lower vulnerability are more likely to attract PPP investments in the energy sector. This result aligns with arguments in the literature that lower climate-related risks enhance investor confidence and perceived project viability.

To improve the robustness of the estimation, column (2) incorporates a set of relevant control variables: voice and accountability, EIL, population, trade openness, and real interest rate. After including these controls, the coefficient for ND-GAIN decreases to 0.0191 and loses statistical significance, suggesting that the initial effect observed in column (1) may be partially explained by institutional and economic factors. Among the control variables, voice_accountability emerges as highly significant and positive (0.530, $p<0.01$), underscoring the crucial role of institutional quality and governance in facilitating PPP investment in the energy sector. The coefficient for EIL is negative (–0.0964) and statistically significant at the 10% level, consistent with the notion that countries with higher energy inefficiency are less attractive for PPP-based energy investment. Other controls also show meaningful relationships: population and trade openness both exhibit positive and significant effects, reflecting the importance of market size and economic integration in attracting PPP investment. By contrast, the real interest rate does not display a statistically significant effect, suggesting that financing costs may not be a decisive factor in PPP energy investment flows within this sample. The model's explanatory power improves with the inclusion of controls, as reflected in the $R^2$ value of 0.3824, indicating that approximately 38% of the variation in PPP energy investment is explained by the included variables.

Our second model examines the relationship between the ND-GAIN Index and private investment in energy, presented in two specifications (columns 3 and 4). The regression results indicate a significant and positive association between ND-GAIN and private energy investment in both specifications. In column (3), the model estimates a bivariate relationship, excluding all other potential influencing factors. The coefficient for ND-GAIN is 0.0417, implying that a one-unit increase in a country's ND-GAIN score corresponds to a 4.17% increase in private energy investment, ceteris paribus. While this finding underscores the importance of climate readiness and reduced vulnerability in attracting private capital, a model without controls is prone to omitted variable bias. Excluding relevant variables can lead to biased estimates and even reverse coefficient signs (Mullet, 1976; Wilms et al., 2021). To address this limitation, column (4) introduces a set of control variables.

**Table 4.** First and second model regression results.

| **Dependent Variable:** | **ln_ppp_energy_invest** | | **ln_private_energy_invest** | |
|---|---|---|---|---|
| **Regression Model** | **M1** | **M1** | **M2** | **M2** |
| **Variables** | **(1)** | **(2)** | **(3)** | **(4)** |
| ND_gain | 0.0349** | 0.0191 | 0.0417** | 0.0306** |
| | (0.0160) | (0.0150) | (0.0178) | (0.0154) |
| voice_accountability | | 0.530*** | | 0.543*** |
| | | (0.177) | | (0.151) |
| EIL | | -0.0964* | | -0.107** |
| | | (0.0524) | | (0.0467) |
| ln_pop | | 0.700*** | | 0.709*** |
| | | (0.0697) | | (0.0679) |
| trade_open | | 0.0110*** | | 0.00985** |
| | | (0.00411) | | (0.00435) |
| real_interest | | 0.0143 | | 0.0160 |
| | | (0.0159) | | (0.0189) |
| Constant | 17.48*** | 6.268*** | 17.34*** | 5.766*** |
| | (0.713) | (1.329) | (0.795) | (1.433) |
| Observations | 408 | 296 | 388 | 308 |
| Number of group | 83 | 58 | 78 | 56 |
| $R^2$ | 0.0445 | 0.3824 | 0.0502 | 0.4009 |

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The regression in column (4) examines the relationship between the ND-GAIN Index and private energy investment after incorporating control variables. At the 5% significance level, the ND-GAIN coefficient of 0.0306 remains positive and statistically significant, indicating that countries better prepared for climate change or less vulnerable to its impacts tend to attract greater private investment in the energy sector. This finding reinforces the broader understanding that stable and predictable environments, often associated with higher climate readiness, are conducive to private capital flows, as investors seek to minimize exposure to climate-related physical and transition risks. Several control variables also show significant effects as follows:

- Voice_accountability: Positive and highly significant, suggesting that political and press freedom enhances investor confidence in energy projects.
- ln_pop (population): Positive and significant, reflecting the role of larger market size and demand in attracting private investment.
- trade_open (trade openness): Positive and significant, highlighting the importance of economic integration and openness to global markets in facilitating energy investment.

- EIL (energy intensity level): Negative and significant, consistent with the notion that higher energy inefficiency reduces attractiveness for investment. Countries with lower EIL (greater efficiency) are more appealing to private investors.
- real_interest (real interest rate): Not statistically significant, suggesting that financing costs may be less decisive in energy investment decisions, which often rely on non-market mechanisms such as PPPs, grants, or concessional financing.

Overall, the model achieves an $R^2$ value of 0.4009, indicating that about 40% of the variation in private energy investment is explained by the included variables.

### *3.3 Public-Private Partnership (PPP) Impact on Renewable Energy Output*

Table 5 presents the regression estimates for the determinants of renewable energy output, employing a stepwise modeling approach. In column (1), the bivariate specification indicates no statistically significant direct relationship between PPP energy investment and renewable electricity output, with a very low explanatory power ($R^2$ = 0.0202). The inclusion of general investment climate controls (i.e., voice_accountability, EIL, and ln_pop) in column (2) does not alter this finding. None of these controls are statistically significant, and the model's explanatory power remains negligible ($R^2$ = 0.0006). A substantive shift occurs in column (3), where the specification focuses on variables more directly relevant to renewable energy development: FDI_inflows, REC (renewable energy consumption), and ln_gdppc (logged GDP per capita). In this model, both REC (0.882, $p<0.01$) and ln_gdppc (11.77, $p<0.01$) emerge as strong, positive, and highly significant determinants of renewable electricity output. These results suggest that existing renewable consumption patterns and national income levels are key drivers of renewable electricity generation. The strong positive influence of national income aligns with Su et al. (2024), who found GDP per capita to enhance renewable energy development efficiency, and with Xu et al. (2019), who emphasized the role of economic growth in shaping renewable energy expansion. Importantly, this specification substantially improves explanatory power, with an $R^2$ of 0.5296.

**Table 5.** Third model regression results.

| **Dependent Variable** | **Renewable Energy Output** | | | |
|---|---|---|---|---|
| **Regression Model** | **M3** | **M3** | **M3** | **M3** |
| | **(1)** | **(2)** | **(3)** | **(4)** |
| ln_ppp_energy_invest | -0.0139 | -0.0218 | 0.0325 | -0.0212 |
| | (0.251) | (0.250) | (0.203) | (0.203) |
| voice_accountability | | -2.121 | | 1.316 |
| | | (3.097) | | (2.829) |
| EIL | | -1.395 | | -2.824** |
| | | (1.547) | | (1.294) |
| ln_pop | | -0.785 | | 0.0742 |
| | | (2.295) | | (1.691) |
| FDI_inflows | | | 0.387* | 0.528** |
| | | | (0.202) | (0.229) |
| REC | | | 0.882*** | 0.881*** |
| | | | (0.171) | (0.163) |
| ln_gdppc | | | 11.77** | 7.681 |
| | | | (5.218) | (5.373) |
| Constant | 38.76*** | 58.94 | -103.7** | -53.26 |
| | (6.038) | (40.53) | (51.32) | (59.13) |
| Observations | 181 | 180 | 180 | 180 |

| | | | | |
|---|---|---|---|---|
| Number of id | 61 | 60 | 60 | 60 |
| Controls | NO | YES | YES | YES |
| *overall* $R^2$ | 0.0202 | 0.0006 | 0.5296 | 0.5241 |

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The comprehensive specification in column (4) integrates all previously considered variables. The results confirm the robust positive impact of REC (0.881, p<0.01), underscoring a demand-pull mechanism: established renewable consumption patterns signal market viability and drive production. This dynamic is consistent with findings by İçen (2025), who emphasized the role of socio-economic factors such as HDI and education in shaping renewable energy consumption. FDI_inflows (0.528, p<0.1) also achieve statistical significance, highlighting the contribution of foreign investment. Beyond capital, FDI often brings advanced technology and expertise crucial for renewable energy infrastructure development (Aguirre & Ibikunle, 2014; İçen, 2025). By contrast, EIL (–2.824, p<0.05) shows a significant negative association, suggesting that higher energy inefficiency reduces renewable energy output. This finding implies that economies locked into inefficient energy systems may face barriers to renewable adoption (Su et al., 2024). Interestingly, ln_gdppc loses statistical significance in this fuller model, while ln_ppp_energy_invest and other initial controls remain insignificant. The overall explanatory power of the model remains strong, with an $R^2$ of 0.5241.

Collectively, these results suggest that while direct PPP energy investment shows no significant link to the share of renewable energy output in our models, existing renewable energy consumption, FDI inflows, and energy efficiency are important drivers. The lack of a significant direct impact from PPP investment on the share of renewable output, while seemingly contrasting with studies that highlight PPPs as catalysts for renewable energy consumption or overall development (Qamruzzaman & Karim, 2023; Yin & Qamruzzaman, 2024), may be explained by the specific focus of our dependent variable (output share vs. consumption or total development) or by the varying effectiveness of PPPs depending on market maturity and policy design, a point noted by Wen et al. (2023). The influence of GDP per capita is positive but appears sensitive to model specification.

## 4. Discussion

The results of our study show that climate readiness (ND-GAIN) has a positive and significant effect on private investment, while its relationship with PPP is only significant without controls and becomes insignificant when institutional and economic variables are added. This suggests that private capital tends to be more responsive to climate adaptation capacity. Countries with strong institutions, prepared societies, and lower climate risks are more attractive to private investors. Conversely, PPPs require a combination of other factors (including governance and market conditions) to be realized, making their impact more complex.

This finding is consistent with global literature showing that public finance alone cannot address climate finance needs. The IRENA (2023) report emphasized that the private sector must play a dominant role in financing the clean energy transition, with governments serving as de-risking agents and incentive providers. Therefore, global financing solutions must combine public and private investments. Public sources provide the regulatory framework, basic infrastructure, and risk guarantees (e.g., through blended finance or climate-smart PPPs), while private sources respond to climate and institutional readiness to channel funds at scale. In other words, the empirical results of this paper provide evidence that the energy transition financing gap can only be bridged if the roles of PPP (public) and private investment are strategically combined: the public sector to create an enabling environment, and the private sector to fulfill the scale-up investment needs toward net zero.

## 5. Conclusions

Our study investigated the determinants of PPP energy investment, private energy investment, and renewable energy output across a global panel of 214 countries (2010–2022) using a random-effects model, with a key focus on the ND-GAIN Index as a measure of climate vulnerability and readiness. Our findings show that higher climate readiness significantly boosts private investment and, to a lesser extent, PPP energy investments. Private investment is also driven by strong institutions, large populations, and trade openness, while high energy intensity deters it. Renewable energy output is primarily influenced by existing renewable consumption, FDI inflows, and energy efficiency. PPP investment does not directly affect renewable output, suggesting an indirect role in shaping energy development.

The policy contribution of this study lies in its recommendations for governments in developing countries to enhance their capacity to attract energy investments, particularly in the renewable sector. First, climate adaptation and vulnerability indicators (e.g., the ND-GAIN Index) should be systematically integrated into national energy planning and PPP frameworks. This can be achieved by mandating climate risk assessments, incorporating flexible mechanisms such as adjustable tariffs and climate insurance, and ensuring infrastructure upgrades in climate-vulnerable regions. Second, governments must strengthen institutional governance by improving transparency, upholding the rule of law, and enhancing public accountability. Our findings reaffirm that strong institutional indicators, particularly voice and accountability, are critical drivers of both PPP and private energy investment. Lastly, to mobilize greater financial and technical support, domestic policies should be aligned with international climate commitments. Active participation in global initiatives such as the Just Energy Transition Partnerships, the Green Climate Fund, and World Bank climate programs can help unlock concessional funding and expertise essential for advancing national clean energy goals.

Our research contributes to the literature by offering a comprehensive cross-country examination of these interconnected drivers within the context of climate vulnerability. Compared to Hossin et al. (2024), Raghutla & Kolati (2023), and Qamruzzaman & Karim (2023), our study focuses on renewable energy production, whereas others emphasize consumption. Key limitations include data availability for PPP investments and the correlational nature of our panel data approach. Future research could benefit from employing causal inference methods and incorporating more granular data on specific policies and project types. Ultimately, a concerted effort focusing on climate resilience, strong institutions, demand-side renewable energy promotion, energy efficiency, and strategic international partnerships is essential for mobilizing the necessary capital to achieve a sustainable and resilient global energy future.

## Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## References

Aguirre, M., & Ibikunle, G. (2014). Determinants of renewable energy growth: A global sample analysis. *Energy Policy*, *69*, 374–384. https://doi.org/10.1016/j.enpol.2014.02.036

Basak, G. K., & Das, S. (2018). Understanding Cross-Sectional Dependence in Panel Data. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3167337

Cameron, A. C., & Miller, D. L. (2015). A Practitioner's Guide to Cluster-Robust Inference. *Journal of Human Resources*, *50*(2), 317–372. https://doi.org/10.3368/jhr.50.2.317

Hoechle, D. (2007). Robust Standard Errors for Panel Regressions with Cross-Sectional Dependence. *The Stata Journal: Promoting Communications on Statistics and Stata*, *7*(3), 281–312. https://doi.org/10.1177/1536867X0700700301

Hossin, M. A., Alemzero, D., Abudu, H., Yin, S., Mu, L., & Panichakarn, B. (2024). Examining public private partnership investment in energy towards achieving sustainable development goal 7 for ASEAN region. *Scientific Reports*, *14*(1), 16398. https://doi.org/10.1038/s41598-024-66800-9

Hunt, L. C., Kipouros, P., & Lamprakis, Z. (2024). The Drivers of Renewable Energy: A Global Empirical Analysis of Developed and Developing Countries. *Energies* , *17*(12). https://doi.org/10.3390/en17122902
İçen, N. M. E. (2025). What are the determinants of renewable energy consumption? An application for variable selection. *Renewable Energy*, *239*. https://doi.org/10.1016/j.renene.2024.122029
IEA. (2021). *Net Zero by 2050*. International Energy Agency (IEA). https://www.iea.org/reports/net-zero-by-2050
Iqbal, S., Wang, Y., Ali, S., Haider, M. A., & Amin, N. (2023). Shifting to a green economy: Asymmetric macroeconomic determinants of renewable energy production in Pakistan. *Renewable Energy*, *202*, 234–241. https://doi.org/10.1016/j.renene.2022.11.071
IRENA. (2023). *World Energy Transitions Outlook 2023: 1.5°C Pathway*. International Renewable Energy Agency (IRENA). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Jun/IRENA_World_energy_transitions_outlook_2023.pdf
Mullet, G. M. (1976). Why regression coefficients have the wrong sign. *Journal of Quality Technology*, *8*(3), 121–126. https://doi.org/10.1080/00224065.1976.11980732
Qamruzzaman, M., & Karim, S. (2023). Does public-private investment augment renewable energy consumption in BIMSTEC nations? Evidence from symmetric and asymmetric assessment. *Energy Strategy Reviews*, *49*. https://doi.org/10.1016/j.esr.2023.101169
Raghutla, C., & Kolati, Y. (2023). Public-private partnerships investment in energy as new determinant of renewable energy: The role of political cooperation in China and India. *Energy Reports*, *10*, 3092–3101. https://doi.org/10.1016/j.egyr.2023.09.139
Shear, F., Ashraf, B. N., & Butt, S. (2023). Sensing the heat: Climate change vulnerability and foreign direct investment inflows. *Research in International Business and Finance*, *66*. https://doi.org/10.1016/j.ribaf.2023.102005
Su, H., Ali, F., Lyulyov, O., Pimonenko, T., & Chen, Y. (2024). Renewable energy development efficiency: Spatial dynamic evolution and influencing factors. *Natural Resources Forum*, *48*(4), 1392–1416. https://doi.org/10.1111/1477-8947.12368
UNFCC. (2024, November 24). *COP29 UN climate conference agrees to triple finance to developing countries, protecting lives and livelihoods*. United Nations Climate Change (UNFCC).
Wen, J., Zhang, S., Chang, C. P., Anugrah, D. F., & Affandi, Y. (2023). Does climate vulnerability promote green investment under energy supply restriction? *Energy Economics*, *124*. https://doi.org/10.1016/j.eneco.2023.106790
Wilms, R., Mäthner, E., Winnen, L., & Lanwehr, R. (2021). Omitted variable bias: A threat to estimating causal relationships. In *Methods in Psychology* (Vol. 5). Elsevier B.V. https://doi.org/10.1016/j.metip.2021.100075
Xu, X., Wei, Z., Ji, Q., Wang, C., & Gao, G. (2019). Global renewable energy development: Influencing factors, trend predictions and countermeasures. *Resources Policy*, *63*. https://doi.org/10.1016/j.resourpol.2019.101470
Yin, C., & Qamruzzaman, M. (2024). Empowering renewable energy consumption through public-private investment, urbanization, and globalization: Evidence from CS-ARDL and NARDL. *Heliyon*, *10*(4). https://doi.org/10.1016/j.heliyon.2024.e26455
Zhang, W., Hu, J., & Hao, J. (2022). Proportion of renewable energy consumption and economic growth: theoretical and empirical analysis. *Environmental Science and Pollution Research*, *29*(19), 28884–28895. https://doi.org/10.1007/s11356-022-18500-y

## Appendix

### *Appendix A*

Hausman test for Model 1:

| | Coefficients (b) FE | (B) RE | (b-B) Difference | sqrt(diag(V_b-V_B)) S.E. |
|---|---|---|---|---|
| ND_gain | -.0342616 | .0191061 | -.0533678 | .0393743 |
| voice_acco~y | 1.33961 | .5302688 | .8093415 | .7532256 |
| EIL | .3948004 | -.0963528 | .4911532 | .2392921 |
| ln_pop | -1.18997 | .6996488 | -1.889619 | 1.866358 |
| trade_open | .0083702 | .0109937 | -.0026236 | .0104822 |
| real_inter~t | .032379 | .0143415 | .0180375 | .0180927 |

```
                          b = consistent under Ho and Ha; obtained from xtreg
           B = inconsistent under Ha, efficient under Ho; obtained from xtreg

    Test:  Ho:  difference in coefficients not systematic

                  chi2(6) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                          =       12.08
                Prob>chi2 =      0.0601
```

Hausman test for Model 2:

| | Coefficients (b) fe | (B) re | (b-B) Difference | sqrt(diag(V_b-V_B)) S.E. |
|---|---|---|---|---|
| ND_gain | -.0537388 | .0305984 | -.0843372 | .0392211 |
| voice_acco~y | 1.257358 | .543236 | .7141216 | .7038645 |
| EIL | .4130258 | -.1072982 | .520324 | .2214744 |
| ln_pop | 1.040037 | .7093511 | .3306857 | 1.93324 |
| trade_open | .0118589 | .0098467 | .0020122 | .0111757 |
| real_inter~t | .0143732 | .0160026 | -.0016294 | .0193334 |

```
                          b = consistent under Ho and Ha; obtained from xtreg
           B = inconsistent under Ha, efficient under Ho; obtained from xtreg

    Test:  Ho:  difference in coefficients not systematic

                  chi2(6) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                          =       11.18
                Prob>chi2 =      0.0829
```

Hausman test for Model 3:

| | —— Coefficients —— | | | |
|---|---|---|---|---|
| | (b) fe_model | (B) re_model | (b-B) Difference | sqrt(diag(V_b-V_B)) S.E. |
| ln_ppp_ene~t | -.1019126 | -.0211683 | -.0807443 | .0208746 |
| voice_acco~y | .495354 | 1.316216 | -.820862 | 2.411785 |
| EIL | -4.047888 | -2.824476 | -1.223411 | 1.528615 |
| ln_pop | 17.64739 | .0741823 | 17.57321 | 14.3422 |
| FDI_inflows | .3510798 | .5276366 | -.1765568 | .1661879 |
| REC | .6629738 | .8812101 | -.2182363 | .2292242 |
| ln_gdppc | 5.785677 | 7.681167 | -1.89549 | 6.87751 |

```
                          b = consistent under Ho and Ha; obtained from xtreg
           B = inconsistent under Ha, efficient under Ho; obtained from xtreg

    Test:  Ho:  difference in coefficients not systematic

                  chi2(7) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                          =       8.44
                Prob>chi2 =     0.2951
                (V_b-V_B is not positive definite)
```

## *Appendix B*

List of countries used in this paper:

**East Asia & Pacific:** American Samoa; Australia; Brunei Darussalam; Cambodia; China; Cook Islands; Fiji; Guam; Hong Kong SAR, China; Indonesia; Japan; Kiribati; Korea, Dem. Rep.; Korea, Rep.; Lao PDR; Macao SAR, China; Malaysia; Marshall Islands; Micronesia, Fed. Sts.; Mongolia; Myanmar; Nauru; New Zealand; Niue; Palau; Papua New Guinea; Philippines; Samoa; Singapore; Solomon Islands; Taiwan, China; Thailand; Timor-Leste; Tonga; Tuvalu; Vanuatu; Viet Nam.

**Europe & Central Asia:** Albania; Andorra; Armenia; Austria; Azerbaijan; Belarus; Belgium; Bosnia and Herzegovina; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Georgia; Germany; Greece; Greenland; Hungary; Iceland; Ireland; Italy; Jersey, Channel Islands; Kazakhstan; Kosovo; Kyrgyz Republic; Latvia; Liechtenstein; Lithuania; Luxembourg; Moldova; Monaco; Montenegro; Netherlands; North Macedonia; Norway; Poland; Portugal; Romania; Russian Federation; Reunion; San Marino; Serbia; Slovak Republic; Slovenia; Spain; Sweden; Switzerland; Tajikistan; Turkmenistan; Turkiye; Ukraine; United Kingdom; Uzbekistan.

**Latin America & Caribbean:** Anguilla; Antigua and Barbuda; Argentina; Aruba; Bahamas, The; Barbados; Belize; Bolivia; Brazil; Cayman Islands; Chile; Colombia; Costa Rica; Cuba; Dominica; Dominican Republic; Ecuador; El Salvador; French Guiana; Grenada; Guatemala; Guyana; Haiti; Honduras; Jamaica; Martinique; Mexico; Netherlands Antilles (former); Nicaragua; Panama; Paraguay; Peru; Puerto Rico; St. Kitts and Nevis; St. Lucia; St. Vincent and the Grenadines; Suriname; Trinidad and Tobago; Uruguay; Venezuela, RB; Virgin Islands (U.S.).

**Middle East & North Africa:** Algeria; Bahrain; Djibouti; Egypt, Arab Rep.; Iran, Islamic Rep.; Iraq; Israel; Jordan; Kuwait; Lebanon; Libya; Malta; Morocco; Oman; Qatar; Saudi Arabia; Syrian Arab Republic; Tunisia; United Arab Emirates; West Bank and Gaza; Yemen, Rep.

**North America:** Bermuda; Canada; United States.

**South Asia:** Afghanistan; Bangladesh; Bhutan; India; Maldives; Nepal; Pakistan; Sri Lanka.

**Sub-Saharan Africa:** Angola; Benin; Botswana; Burkina Faso; Burundi; Cameroon; Cape Verde; Central African Republic; Chad; Comoros; Congo, Dem. Rep.; Congo, Rep.; Cote d'Ivoire; Equatorial Guinea; Eritrea; Eswatini; Ethiopia; Gabon; Gambia, The; Ghana; Guinea; Guinea-Bissau; Kenya; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Mauritius; Mozambique; Namibia; Niger; Nigeria; Rwanda; Senegal; Seychelles; Sierra Leone; Somalia; South Africa; South Sudan; Sudan; Sao Tome and Principe; Tanzania; Togo; Uganda; Zambia; Zimbabwe.