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Green ODA and Carbon Emissions in Developing Countries: A Dynamic Panel Threshold Analysis Based on Renewable Energy Transition

Jae-Young Huh [1] and Han-Seon Park [2,*]

[1] Center for International Development Cooperation, Global Strategy Research Department, Korea Maritime Institute, Busan 49111, Republic of Korea; hjy1@kmi.re.k or jaeyounghu3@gmail.com
[2] Maritime Industry Research Division, Shipping Logistics and Maritime Affairs Research Department, Korea Maritime Institute, Busan 49111, Republic of Korea
* Correspondence: hspark@kmi.re.kr

Abstract

Green ODA supports renewable energy and low-carbon structural transformation. Limited studies have explicitly evaluated whether Green ODA reduces emissions or examined the structural conditions that enable climate-oriented aid to produce meaningful decarbonisation outcomes. In this study, we examined the relationship between Green ODA and carbon dioxide emissions and investigated whether this relationship differs across the stages of renewable energy transition. Using annual panel data for 63 developing countries selected from the OECD Development Assistance Committee (DAC) List of ODA Recipients, including low-income, lower-middle-income, and eligible upper-middle-income economies, between 2010 and 2021, a dynamic panel threshold regression model was employed, with renewable energy consumption as the threshold variable. Renewable energy consumption was significantly associated with lower carbon emissions. However, the effects of Green ODA varied depending on the level of renewable energy development. The estimated threshold value for renewable energy consumption was 78.2%. When renewable energy consumption remained below this threshold, Green ODA was associated with increased carbon emissions. Following threshold exceedance, the effect became negative, although it remained statistically insignificant. These findings suggest that the relationship between Green ODA and carbon emissions differs across the stages of renewable energy transition in recipient countries.

Keywords: Green ODA; carbon emissions; renewable energy transition; climate finance; developing countries

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1. Introduction

Climate change is widely considered the defining global challenge of the 21st century [1] with the potential for widespread risks to human populations and natural systems [2]. Since the adoption of the Paris Agreement in 2015, countries have committed to increasingly ambitious mitigation targets, and carbon neutrality by mid-century has become a widely shared policy objective.

Although developed economies account for most of the historical cumulative greenhouse gas emissions, future emission growth is expected to occur in developing economies owing to rapid industrialisation, urbanisation, and expanding energy demand [2,3]. Considering an ever-evolving policy landscape, climate-related official development assistance (ODA) has increased notably over the past decade [4,5].

According to the OECD data, climate-related ODA increased substantially in 2022. Bilateral ODA primarily targeted at climate mitigation increased from US$12.1 billion in 2021 to US$15.9 billion in 2022, representing an increase of approximately 31%. In addition, aid targeting both adaptation and mitigation increased from US$5.1 billion to US$9.3 billion, an increase of more than 80% [6]. Furthermore, Green Official Development Assistance (Green ODA) has evolved in scope from conventional environmental protection projects to include broader support for structural transformation, renewable energy deployment, and low-carbon development pathways [7].

However, the effectiveness of Green ODA in reducing carbon emissions has been challenged. The broader literature on ODA and environmental outcomes has resulted in inconsistent conclusions. Several studies suggest that aid may inadvertently stimulate economic expansion and fossil-fuel-intensive growth, thereby increasing emissions [8]. By contrast, other studies contend that targeted environmental assistance can promote cleaner technologies, strengthen institutional capacity, and ultimately reduce emissions [9–11]. However, most studies rely on aggregate ODA measures and assume linear relationships, thereby overlooking the structural conditions under which climate-oriented aid may generate meaningful decarbonisation effects.

One dimension that has attracted relatively limited attention in the literature is the stage of energy transition in recipient countries. The effectiveness of Green ODA is highly dependent on the recipient country's energy structure. In countries with heavily fossil-fuel-dependent energy systems and underdeveloped renewable energy infrastructures, climate-related financial assistance frequently encounters substantial absorptive capacity constraints and institutional impediments, which notably reduce its overall impact. These challenges are frequently compounded by a "climate investment trap", where high reliance on fossil fuels, limited technical capacity, and weak financial markets deter the effective deployment of renewable energy [12–14].

However, in countries where renewable energy systems are already widely implemented, external climate financing can reinforce ongoing structural changes and accelerate carbon emission reductions. Considering these factors, the relationship between Green ODA and carbon emissions is not linear and may vary depending on the energy transition stage [12,13,15].

Therefore, in this study, we investigated whether the relationship between Green ODA and carbon emissions differs according to the stage of renewable energy transition in recipient countries. In particular, we examined whether a threshold level of renewable energy penetration exists, beyond which the relationship between Green ODA and carbon emissions may differ. To address this question, we constructed a balanced panel dataset of 63 developing countries selected from the OECD DAC List of ODA Recipients for the period 2010–2021.

This study makes three main contributions to the literature. The empirical focus is shifted from aggregate ODA commitments to Green ODA, thereby aligning the analysis more closely with current debates on climate finance and low-carbon transition. Second, the energy transition stage is introduced as a structural conditioning factor, thus facilitating the identification of nonlinear relationships. Third, the dynamic panel threshold approach addresses the issues of persistence and potential endogeneity, thereby revealing regime-dependent effects on the relationship between Green ODA and carbon emissions.

Overall, the results provide new insights into the variation in the relationship between Green ODA and carbon emissions across the different stages of renewable energy transition. The findings also provide policy implications for the allocation of climate financing and the design of development cooperation strategies aimed at accelerating the transition to a low-carbon economy.

2. Literature Review

2.1. Definition of Green ODA

The concept of Green ODA remains without a universally accepted definition in the literature [16]. Different studies have employed various approaches, including environmental sector classification, Rio markers, and keyword-based identification methods [14,16]. Although environmental or Green ODA has been widely discussed, scholars and policymakers employ different operational criteria depending on the research objectives and policy frameworks [14,16,17].

Previous studies have proposed various approaches to defining Green ODA based on analytical perspectives and policy objectives. For example, several studies classified Green ODA based on Sustainable Development Goals (SDGs) related to environmental sustainability, such as clean water, climate action, and ecosystem protection [18]. Other approaches relied on environmental or Rio markers reported in the OECD DAC database to identify environmentally relevant development assistance [17]. In addition, keyword-based classifications have been used to categorise development projects according to their environmental relevance, distinguishing strictly defined environmental projects from broadly defined environmental activities [16]. These diverse approaches illustrate that the operational definition of Green ODA varies considerably depending on the research purpose and measurement framework.

The OECD Development Assistance Committee (DAC) marker system provides the most standardised and internationally comparable framework for identifying environmentally relevant aid. The DAC introduced policy markers to track the extent to which development activities support environmental sustainability and the objectives of the Rio Conventions [19,20]. Within this system, these two instruments are particularly relevant.

The environmental marker identifies aid activities that aim to improve the physical or biological environment of recipient countries or integrate environmental considerations into development policies through institutional strengthening and capacity building [17]. Projects are coded according to whether environmental objectives constitute a principal objective, a significant objective, or are not targeted.

Rio markers further classify development assistance according to their relevance to biodiversity conservation, climate change mitigation, climate change adaptation, and desertification control, consistent with the Rio Conventions [19]. Similar to the environmental markers, projects are categorised based on the intensity of environmental targeting. This classification system has emerged as the dominant international standard for measuring climate-related development finance [16,21].

However, the operationalisation of Green ODA remains subject to methodological choices. Several studies consider principal and significant objectives equally, potentially overstating the intensity of climate targeting [14]. Other studies have adopted weighted approaches that prioritize principal objectives while retaining significant objectives with lower weights [16]. These methodological differences could substantially affect the estimated scale of climate-related aid.

Based on this internationally recognised framework, this study defined Green ODA as bilateral ODA activities identified through the OECD DAC environmental and Rio marker systems. Considering the focus on carbon emissions, particular emphasis has been placed on climate change mitigation and adaptation. To capture the differences in environmental intensity, we used a weighted approach that assigned higher weights to projects coded as principal objectives and lower weights to those coded as significant objectives. This

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operationalisation ensures conceptual rigour while maintaining international comparability across countries and over time.

2.2. Relevant Literature on the Relationship Between Green Official Development Assistance and Carbon Emissions

The environmental consequences of ODA have attracted increasing scholarly attention in the contexts of global climate governance and sustainable development. Although the traditional aid-effectiveness literature has primarily focused on economic growth and poverty reduction, an increasing number of empirical studies have investigated whether development assistance contributes to environmental sustainability and carbon mitigation in recipient countries [22–25].

Barkat et al. [25] provided evidence from a large panel of developing countries that foreign aid can reduce carbon emissions through environmentally friendly investments and structural transformation; however, the effectiveness of aid depends on the economic development stage of the recipient countries. Similarly, Mahalik et al. [23] revealed that total foreign aid effectively reduced CO_2 emissions in India between 1978 and 2014. Sharma et al. [22] demonstrated that foreign aid effectively reduced CO_2 emissions in Nepal using the ARDL model. From this perspective, climate-oriented development assistance may alleviate financial constraints in developing economies, support clean energy infrastructure, and strengthen environmental governance, thereby accelerating low-carbon development.

By contrast, other studies have highlighted concerns regarding the environmental effectiveness of development assistance. From a scale-effect perspective, aid inflows may stimulate economic expansion, infrastructure development, and energy consumption, potentially increasing carbon emissions in recipient countries [11,23]. For example, Li et al. [11] observed that green aid increases CO_2 emissions in countries with weak institutional quality while contributing to emission reductions in countries with lower levels of corruption. Similarly, Bhattacharyya et al. [26] analysed energy-related aid flows in 128 countries between 1971 and 2011 and reported that this aid did not significantly reduce CO_2 emissions.

Importantly, most of the existing studies rely on aggregate ODA measures and assume a linear relationship between aid inflows and environmental outcomes. However, environmentally targeted development assistance, frequently referred to as Green ODA, differs from general development aid in both objectives and sectoral allocation. Green ODA explicitly aims to support climate mitigation, climate adaptation, renewable energy development, and environmental protection, suggesting that its environmental impact may occur through distinct structural channels [11,16].

Despite this conceptual distinction, empirical studies that explicitly examine the emission-reducing effectiveness of Green ODA remain limited. Additionally, limited studies have considered the structural conditions under which climate-oriented aid translates into meaningful decarbonisation outcomes. The stage of energy transition in recipient countries, typically expressed in the share of renewable energy in the national energy mix, may critically influence the effectiveness of Green ODA. In countries with limited renewable energy infrastructure and weak regulatory frameworks, climate finance may encounter notable absorptive constraints. Conversely, in economies that have already achieved a certain level of renewable energy development, external climate assistance may reinforce the existing transition dynamics and generate stronger mitigation effects.

These considerations suggest that the relationship between Green ODA and carbon emissions may be nonlinear and conditioned by the structural characteristics of the recipient countries. However, such regime-dependent dynamics remain underexplored in the existing literature. To address this gap, this study examined the effect of Green ODA on carbon emissions, while explicitly considering the threshold role of renewable energy development. The mixed empirical findings reported in previous studies may indicate substantial differences in the recipient country characteristics, stages of renewable energy transition, institutional quality, fossil fuel dependence, sample composition, study periods, and empirical methodologies. These sources of heterogeneity suggest that the environmental effectiveness of Green ODA is unlikely to be uniform across developing countries and provide a strong rationale for employing a dynamic panel threshold framework.

2.3. Theoretical Framework

The relationship between Green ODA and carbon emissions can be understood through a structural framework that integrates absorptive capacity, institutional quality, and the renewable energy transition stage. Although Green ODA is intended to promote renewable energy investment, technology transfer, and cleaner infrastructure [27], its environmental effectiveness depends on whether the recipient countries possess sufficient institutional and technical capacity to effectively utilise external climate finance [11,28]. In countries where renewable energy systems remain underdeveloped and fossil fuel dependence is high, institutional impediments and limited absorptive capacity may constrain the effective implementation of Green ODA. Under these conditions, Green ODA may initially support broader economic activity and infrastructure development, thereby increasing the risk of a climate investment trap in which economic expansion outpaces the diffusion of low-carbon technologies [24,29]. By contrast, as renewable energy deployment expands and institutional capacity improves, Green ODA may reinforce ongoing structural transformation through channels such as renewable energy investment, technology transfer, and cleaner infrastructure, as suggested in the literature [7,13]. This reasoning is broadly consistent with the Environmental Kuznets Curve (EKC), which suggests that environmental improvements are more likely as countries reach more advanced stages of economic and structural development [30,31]. Based on this theoretical framework, this study expects that the environmental effectiveness of Green ODA will differ according to the stage of renewable energy transition in recipient countries.

2.4. Research Hypotheses

Based on the above discussion, this study developed two testable hypotheses regarding the environmental impact of Green ODA.

First, climate-oriented development assistance aims to promote renewable energy investment, technology transfer, and environmental capacity-building in developing countries. These mechanisms are expected to facilitate low-carbon development and contribute to emissions reduction. Therefore, Green ODA may mitigate carbon emissions.

Hypothesis 1 (H1). *Green ODA is expected to be negatively associated with carbon emissions in developing countries.*

Second, the effectiveness of climate-oriented aid may depend on the stage of energy transition in the recipient countries. In economies where the renewable energy infrastructure is still underdeveloped, climate finance may encounter absorptive constraints and institutional impediments. Conversely, when renewable energy penetration reaches a certain level, external climate assistance may reinforce the ongoing structural transformation and generate stronger mitigation effects.

Hypothesis 2 (H2). *The emission-reducing effect of Green ODA is expected to be stronger in countries with higher renewable energy penetration than in those with lower renewable energy penetration.*

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3. Methodology

3.1. Empirical Model

This study examined the relationship between Green ODA and carbon dioxide emissions and investigated whether this relationship differed across the stages of renewable energy transition. In particular, we examined the presence of a nonlinear threshold effect associated with renewable energy consumption.

We used a dynamic panel threshold regression framework to capture the dynamic characteristics of carbon emissions and address potential endogeneity. The model incorporates a lagged dependent variable and allows the association between Green ODA and carbon emissions to vary across different regimes, as determined by a threshold variable.

The baseline specification is defined as follows:

$$lnCO2\_it = \alpha + \varrho\ lnCO2\_it - 1 + \beta_1\ lnGODA\_it + \delta X\_it + \mu\_i + \lambda\_t + \varepsilon\_it$$

where lnCO2_it represents the natural logarithm of carbon dioxide emissions for country i at time t, and lnCO2_it − 1 represents the lagged dependent variable capturing the persistence of carbon emissions. lnGODA_it represents weighted Green ODA commitments. X_it is a vector of control variables including GDP per capita, population, trade openness, and industrial structure. μ_i captures country-specific fixed effects, λ_t represents time-specific effects, and ε_it is the error term.

To investigate whether the impact of Green ODA depends on the stage of renewable energy transition, we extended the baseline model using a threshold specification following Hansen [32]. The renewable energy consumption was used as the threshold variable.

Dynamic panel threshold model:

$$lnCO2\_it = \alpha + \varrho\ lnCO2\_it - 1 + \beta_1\ lnGODA\_it\ I(RNEW\_it \leq \gamma) + \beta_2\ lnGODA\_it\ I(RNEW\_it > \gamma) + \delta X\_it + \mu\_i + \lambda\_t + \varepsilon\_it$$

This specification enables the marginal effect of Green ODA on CO_2 emissions to differ depending on whether renewable energy consumption is below or above the estimated threshold level. The empirical strategy follows the dynamic panel threshold framework proposed by Kremer et al. [33], which extends Hansen's [32] threshold methodology to dynamic panel settings by incorporating endogenous regressors into dynamic specifications. In this study, renewable energy consumption (RNEW) served as the threshold variable to classify observations into different regimes, enabling the effect of Green ODA on carbon emissions to vary across the different stages of the renewable energy transition. The potential endogeneity between Green ODA and carbon emissions was addressed through a System GMM estimator using internal instruments. Although Green ODA may contribute to renewable energy deployment over longer time horizons, the threshold variable is employed solely for regime classification, rather than for causal identification.

3.2. Estimation Method

The inclusion of a lagged dependent variable and the potential endogeneity of Green ODA may result in biased and inconsistent estimates when conventional estimators such as pooled OLS or fixed-effects models are applied. Therefore, we employed a two-step System GMM estimator. Following the dynamic panel threshold framework proposed by Kremer et al. [33], the estimation procedure integrates Hansen's [32] threshold estimation method with the two-step System GMM estimator to account for both nonlinear threshold effects and potential endogeneity. In the System GMM specification, the lagged dependent variable and Green ODA were considered endogenous variables because carbon emissions exhibit dynamic persistence, and Green ODA allocation may be jointly determined by the recipient countries' environmental conditions. RNEW was considered the threshold variable, which was used exclusively for regime classification and was not instrumented within the System

GMM estimation. GDP per capita, population, trade openness, and industrial value added were treated as strictly exogenous control variables, while country and year fixed effects were included to control for unobserved heterogeneity. Internal instruments were generated from lagged values (t−2 and t−3) using the collapsed instrument approach to mitigate instrument proliferation. The two regime-specific Green ODA variables were generated by interacting Green ODA with the threshold indicator functions, I(RNEW $\leq \gamma$) and I(RNEW > γ). Because these interaction terms inherit the endogeneity of Green ODA, they were also considered endogenous and instrumented using the same collapsed lagged instrument matrix (lags t−2 to t−3) within the System GMM framework.

Following Hansen [32], the threshold value was identified using a grid search procedure that minimises the residual sum of squares (RSS). Statistical inference of the threshold effect was conducted using Hansen's [32] bootstrap procedure under the null hypothesis of no threshold effect. Consistent with Kremer et al. [33], the threshold value identified through Hansen's [32] grid-search procedure was subsequently incorporated into the two-step System GMM estimation proposed by Arellano and Bover [34] and Blundell and Bond [35] to obtain regime-specific coefficient estimates.

Bootstrap replicates were used to evaluate the statistical significance of the estimated thresholds. The same collapsed instrument specification was maintained across both threshold regimes to ensure that the differences in the estimated coefficients indicated regime-specific effects rather than differences in instrument construction. The corresponding diagnostic statistics, including the Hansen test, AR(1), AR(2), number of instruments, and lag structure, are reported in the Section 4.

All statistical analyses were conducted using R version 4.6.0 (R Foundation for Statistical Computing, Vienna, Austria) and Stata/MP 18.0 (StataCorp LLC, College Station, TX, USA). Threshold estimation and bootstrap procedures were implemented in R, whereas the two-step System GMM estimation and diagnostic tests were performed using Stata.

3.3. Data and Variables

This study used annual panel data for 63 developing countries covering the period from 2010 to 2021. The sample comprised 63 developing countries selected from the OECD Development Assistance Committee (DAC) list of ODA recipients. The OECD DAC List includes developing countries eligible to receive ODA, including low-, lower-middle-, and upper-middle-income countries. Countries were included in the final sample based on data availability and completeness of observations for all variables used in the empirical analysis. Countries with substantial missing data were excluded from the final sample. A transparent data completion procedure was applied to construct a balanced panel with a limited number of missing observations in the selected control variables.

To ensure data completeness and consistency across the panel data set, missing observations in the selected control variables were addressed using a transparent data completion procedure. First, the original World Bank World Development Indicators (WDI) database was reviewed to determine whether updated observations were available. For the remaining missing values, country-specific linear interpolation was applied where adjacent-year observations were available. For missing observations at the beginning or end of a country-specific series, the nearest available observations were used to supplement the series. This procedure was applied only to the control variables (GDP per capita, trade openness, and industry value added) and was not applied to the dependent (CO_2 emissions), main explanatory variable (Green ODA), or threshold (renewable energy consumption) variables. Consequently, the final dataset consisted of a balanced panel of 756 country-year observations.

Green ODA was constructed using the OECD DAC Creditor Reporting System (CRS) Rio Marker. Consistent with the OECD definition of climate-related development finance, Green ODA in this study combined climate change mitigation and climate change adaptation activities. Following the OECD DAC reporting methodology, projects classified as having climate-change mitigation or adaptation as the principal objective (Rio Marker = 2) were assigned a weight of 100%, whereas those classified as having mitigation or adaptation as a significant objective (Rio Marker = 1) were assigned a weight of 40%. Projects with a Rio Marker score of zero were excluded from the calculations. The weighted Green ODA commitments were aggregated at the country-year level and subsequently transformed into natural logarithms for the empirical analysis.

Dependent Variable

The dependent variable was carbon dioxide emissions (CO_2) (Table 1). CO_2 emissions were measured as total carbon dioxide emissions excluding emissions from land-use change and forestry (LULUCF). Data were obtained from the World Bank World Development Indicators (WDI) based on the EDGAR and International Energy Agency (IEA) databases. All variables were transformed into natural logarithms for estimation.

Table 1. Descriptive statistics of the variables.

Variable	N	Mean	Std.Dev	Min	Max
lnCO2	756	2.336	1.845	−1.182	7.862
lnGODA	756	4.515	1.706	−3.534	8.647
RNEW	756	52.342	30.279	0.100	97.000
lnGDPpc	756	7.294	0.729	5.535	9.100
lnPOP	756	16.679	1.418	13.142	21.070
OPEN	756	70.937	39.280	4.128	347.720
IND	756	26.369	8.863	2.759	66.179

Observations = 756 (63 countries × 12 years, 2010–2021).

Main Explanatory Variable

The key explanatory variable was Green Official Development Assistance (Green ODA). Green ODA was defined using the OECD DAC Rio Markers for Climate Change Mitigation and Adaptation. To capture medium-term associations, a three-year centred moving average of total Green ODA commitments (constant 2010 US dollars) was used and log-transformed in the regression. The moving average was used to reduce substantial year-to-year fluctuations in Green ODA commitments resulting from project approval, commitment timing, and reporting practices in the OECD DAC CRS database. This smoothing procedure was intended to capture medium-term exposure to Green ODA, rather than short-term annual volatility. Accordingly, the estimated relationships should be interpreted as dynamic associations, rather than definitive causal effects. As the three-year centred moving average incorporates information from adjacent years, the empirical findings should be interpreted with appropriate caution regarding temporal ordering.

Threshold Variable

The threshold variable was renewable energy consumption (RNEW), which was measured as the share of renewable energy consumption in total final energy consumption (Table 2). This variable indicates the energy transition stage in each country. Data were obtained from the World Bank WDI (indicator: EG.FEC.RNEW.ZS). In the estimation, renewable energy consumption was used solely as the threshold variable to determine regime classification, enabling the impact of Green ODA on carbon emissions to differ across the stages of renewable energy transition.

Table 2. Variable definitions and data sources.

Variable (Role)	Abbr.	Description and Unit	Data Source	Period
Explained variable	CO_2	Carbon dioxide (CO_2) emissions (total), excluding LULUCF (Mt CO_2e). Log-transformed in estimation.	World Bank WDI (EN.GHG.CO2.MT.CE.AR5), based on EDGAR and IEA	2010–2021
Main explanatory variable	G-ODA	Aggregated Green ODA commitments (constant 2010 US dollars) based on weighted OECD DAC Rio Markers (Principal = 100%; Significant = 40%). Log-transformed in estimation	OECD DAC CRS	2010–2021
Threshold variable (q)	RNEW	Renewable energy consumption as a percentage of total final energy consumption (%). Used as the threshold (transition-stage) variable.	World Bank WDI (EG.FEC.RNEW.ZS)	2010–2021
Control variable	GDPpc	GDP per capita (constant 2010 US$). Log-transformed.	World Bank WDI	2010–2021
Control variable	POP	Total population. Log-transformed.	World Bank WDI	2010–2021
Control variable	OPEN	Trade openness measured as (exports + imports)/GDP (%).	World Bank WDI	2010–2021
Control variable	IND	Industry value added as a percentage of GDP (%). Used to capture industrial structure effects on emissions.	World Bank WDI	2010–2021

Control Variables

Several control variables were included to account for the structural determinants of carbon emissions. The GDP per capita (GDPpc) measured the level of economic development and indicated the Environmental Kuznets Curve relationship between income and environmental degradation. Population (POP) accounted for the scale effects of economic activity and energy demand on carbon emissions. Trade openness (OPEN), measured as the ratio of exports and imports to GDP, controlled for the influence of international trade on emissions. Industry value-added (IND), measured as the share of industry in the GDP, quantified the effect of the industrial structure on carbon emissions.

4. Empirical Results and Discussion

4.1. Correlation Analysis

Table 3 presents the pairwise correlation matrices of the main variables used in the empirical analysis. Several meaningful relationships were observed. First, carbon dioxide emissions (lnCO2) positively correlated with Green ODA (lnGODA) and GDP per capita (lnGDPpc). This finding suggests that countries receiving substantial volumes of Green ODA and those with increased levels of economic development exhibit higher carbon emissions [11,23]. This indicates that many developing economies rely on carbon-intensive production structures during their early stages of development.

Table 3. Correlation matrix.

Variable	lnCO2	lnGODA	RNEW	lnGDPpc	OPEN	IND
lnCO2	1.000	0.433 ***	−0.597 ***	0.478 ***	−0.193 ***	0.225 ***
lnGODA	0.433 ***	1.000	−0.032	−0.091 **	−0.186 ***	−0.183 ***
RNEW	−0.597 ***	−0.032	1.000	−0.756 ***	−0.244 ***	−0.146 ***
lnGDPpc	0.478 ***	−0.091 **	−0.756 ***	1.000	0.240 ***	0.294 ***
OPEN	−0.193 ***	−0.186 ***	−0.244 ***	0.240 ***	1.000	0.100 ***
IND	0.225 ***	−0.183 ***	−0.146 ***	0.294 ***	0.100 ***	1.000

Notes: *** $p < 0.01$, ** $p < 0.05$.

Second, renewable energy consumption (RNEW) strongly negatively correlated with carbon emissions (−0.597), suggesting that countries with an increased share of renewable energy tend to produce reduced levels of CO_2 emissions. This finding is consistent with the expectation that the expansion of renewable energy contributes to carbon mitigation and supports the rationale for examining renewable energy as a threshold variable in this study.

Third, GDP per capita exhibited a relatively strong negative correlation with renewable energy consumption (−0.756). This indicates the energy transition in developing economies, where economic growth is frequently associated with increased reliance on fossil fuels before the deployment of large-scale renewable energy projects [30].

Overall, although several correlations were statistically significant owing to the relatively large sample size, the magnitudes of most coefficients remained within acceptable ranges. These results suggest that severe multicollinearity is unlikely to be a major concern in the subsequent regression analyses.

4.2. Multicollinearity Test

The variance inflation factor (VIF) was calculated to further examine potential multicollinearity among the explanatory variables. Table 4 presents the VIF values of the main explanatory variables included in the regression models. The VIF values ranged from 3.14 to 5.01, which were below the commonly accepted threshold value of 10. These results suggest that severe multicollinearity is unlikely to present a major concern for the estimated models. Therefore, the explanatory variables were retained in the regression analysis.

Table 4. Variance inflation factor results.

Variable	VIF
lnGODA	4.34
RNEW	3.14
lnGDPpc	5.01
OPEN	4.70
IND	4.53

4.3. Baseline and Threshold Regression Results

Table 5 presents the estimation results of the dynamic panel regression models examining the impact of Green ODA on carbon emissions in developing countries. Model 1 presents the baseline specification, including only Green ODA as the main explanatory variable. The coefficient of Green ODA was positive and not statistically significant, suggesting that larger Green ODA commitments are not associated with an immediate reduction in carbon emissions.

Model 2 incorporated renewable energy consumption (RNEW) into the baseline specifications. The coefficient of RNEW was negative and statistically significant at the 1% level. This indicates that an increased share of renewable energy consumption is associated with reduced carbon emissions [10,15]. Specifically, countries with an increased reliance on renewable energy tend to generate reduced emissions, which is consistent with the expectation that expanding renewable energy systems is associated with decreased carbon emissions.

Model 3 introduced additional control variables, including GDP per capita, population, trade openness, and industry share. Both GDP per capita and population were positively related to carbon emissions. This indicates the scale effect of economic growth and population expansion, which tend to increase energy demand and production activities [23,30]. Trade openness also exhibited a positive and statistically significant relationship with emissions, suggesting that increased trade activity may result in high levels of energy consumption in developing economies [31]. In contrast, the coefficient of industry share was not statistically significant, indicating that the industrial structure variable did not exert a strong direct effect on emissions in the present specification.

Model 4 revealed the results of the dynamic panel threshold model, in which renewable energy consumption was used as the threshold variable. The estimated threshold value was 78.2%, indicating that the relationship between Green ODA and carbon emissions differed when renewable energy accounted for approximately 78% of total energy consumption. These findings suggest that the relationship between Green ODA and carbon emissions differs depending on whether the REC is below or above this threshold level. When renewable energy consumption was below the threshold (RNEW $\leq \gamma$), Green ODA was positively associated with carbon emissions, and the coefficient was statistically significant. However, when renewable energy consumption exceeded the threshold (RNEW $> \gamma$), the coefficient of Green ODA was negative and not statistically significant.

Table 5. Distribution of country-year observations across the estimated renewable energy threshold regimes.

Year	RNEW $\leq$ 78.2	RNEW > 78.2	Total
2010	39	24	63
2011	41	22	63
2012	43	20	63
2013	42	21	63
2014	43	20	63
2015	43	20	63
2016	45	18	63
2017	47	16	63
2018	47	16	63
2019	47	16	63
2020	47	16	63
2021	48	15	63
Total	532	224	756

Notes: The estimated renewable energy threshold (γ) is 78.2%. The balanced panel consists of 756 country-year observations (63 countries $\times$ 12 years).

In terms of economic significance, the estimated coefficient on Green ODA in the below-threshold regime was relatively modest. As both CO_2 emissions and Green ODA are expressed in natural logarithms, the estimated coefficient (0.0155) indicated that a 1% increase in Green ODA was associated with an approximately 0.016% increase in CO_2 emissions, maintaining other variables constant. In comparison, the estimated coefficients of GDP per capita (0.6502) and population (1.3746) were substantially larger, suggesting that structural economic factors correlate more strongly with carbon emissions than with Green ODA. Therefore, although Green ODA was statistically significant in the below-threshold regime, its practical magnitude was relatively small compared with the major structural control variables.

Following Hansen's [32] threshold estimation procedure, Figure 1 illustrates the residual sum of squares (RSS) obtained over the candidate threshold values. The estimated threshold (γ = 78.2%) corresponded to the global minimum of the RSS function. This figure provides a visual representation of the threshold search procedure and shows that the estimated threshold is identified at the point where the RSS reaches its minimum value. This graphical evidence complements the formal threshold-estimation procedure and improves the transparency of the empirical identification of the threshold. To further improve the transparency of the threshold classification, Appendix A reports a complete list of the 26 countries that entered the above-threshold renewable energy regime (RNEW > 78.2%) at least once during the sample period (2010–2021). The bootstrap test indicated that the estimated threshold was statistically significant (bootstrap test statistic = 13.97, $p = 0.023$). The approximate 95% confidence interval ranged from 26.9% to 86.4% with an estimated threshold value of 78.2%. These results provide additional statistical support for the estimated threshold beyond the RSS profile shown in Figure 1.

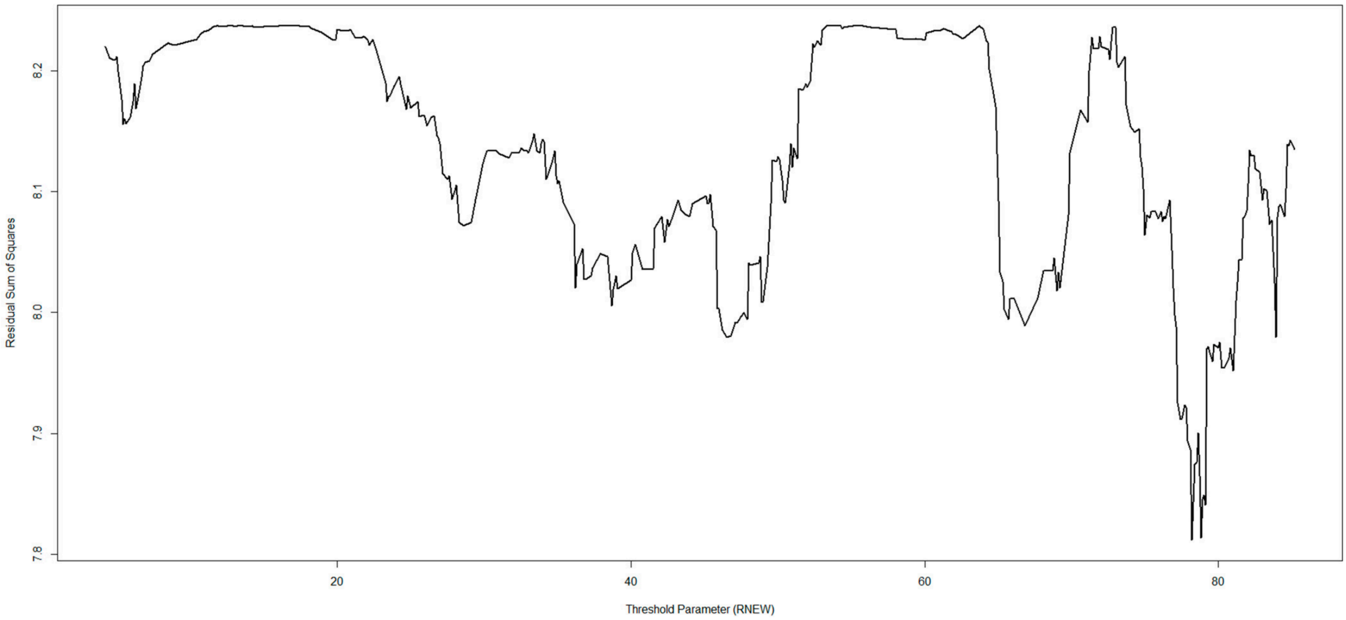

Figure 1. Threshold estimation. Notes: The estimated threshold value (γ = 78.2%) corresponds to the global minimum of the residual sum of squares (RSS) obtained through Hansen's [32] threshold estimation procedure.

To provide additional information on the estimated threshold regimes, Table 5 presents the distribution of country-year observations across the two renewable energy regimes. Overall, 532 of the 756 country-year observations (70.4%) were below the estimated threshold (RNEW $\leq$ 78.2%), whereas 224 observations (29.6%) belonged to the above-threshold regime (RNEW > 78.2%). The above-threshold regime comprised 26 developing countries with relatively high energy consumption. Appendix A provides a complete list of the countries classified under the above-threshold regime.

Importantly, the empirical results do not support Hypothesis 1 (H1), which proposes that Green ODA is negatively associated with carbon emissions in developing countries. Green ODA was positively associated with carbon emissions in the below-threshold regime. Hypothesis 2 (H2) is also not supported because the above threshold coefficient is negative and statistically not significant. However, the threshold results indicated regime heterogeneity, suggesting that the relationship between Green ODA and carbon emissions differs across the renewable energy transition stages. Collectively, these results indicate regime heterogeneity in the estimated relationship between Green ODA and carbon emissions.

4.4. Robustness Check

For comparability across the alternative specifications, the estimated threshold value (γ = 78.2%) from the baseline model was maintained fixed throughout all robustness analyses. To examine the robustness of the baseline results, we estimated the dynamic panel threshold model using three alternative approaches. Specifically, Green ODA was alternatively measured using (i) a three-year trailing moving average and (ii) a one-year lagged Green ODA variable. (iii) An additional sample-based robustness check was conducted by excluding countries where hydropower accounted for more than 80% of the

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total electricity generation (Bhutan, Nepal, Ethiopia, the Democratic Republic of the Congo, Uganda, Zambia, Malawi, and Mozambique), based on publicly available country-level electricity generation statistics. In contrast to the centred moving-average specification used in the baseline model, the first two alternative specifications rely exclusively on current and past information and therefore eliminate the potential influence of forward-looking information. The robustness test results are presented in Table 6.

Table 6. Alternative robustness checks.

Variables	Trailing MA	Lagged Green ODA	Hydropower Excluded
Green ODA (Below Threshold)	0.0125 *	0.0098 *	0.0123 *
	(0.0074)	(0.0056)	(0.0072)
Green ODA (Above Threshold)	−0.0046	−0.0061	−0.0118
	(0.0105)	(0.0088)	(0.0121)
Country Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
Observations	756	756	660
Number of Countries	63	63	55
AR(1) test (*p*-value)	<0.001	<0.001	<0.001
AR(2) test (*p*-value)	0.503	0.624	0.800
Hansen test (*p*-value)	0.794	0.239	0.751
Number of instruments	19	19	19
Instruments Lags	t−2 to t−3	t−2 to t−3	t−2 to t−3

Notes: All robustness specifications were estimated using the same two-step System GMM framework with collapsed internal instruments (lags t−2 to t−3). The threshold value estimated from the baseline model (γ = 78.2%) was maintained fixed across all robustness specifications. AR(1) and AR(2) show the *p*-values of the Arellano–Bond serial correlation tests, and Hansen shows the *p*-value of the test of overidentifying restrictions. * $p < 0.10$.

Under the three-year trailing moving-average specification, the coefficient of Green ODA below the renewable energy threshold remained positive (0.0125) and marginally significant, whereas the coefficient above the threshold remained negative and was not statistically significant (−0.0046). Similarly, when Green ODA was specified as a one-year lagged variable, the below-threshold coefficient remained positive (0.0098), whereas the above-threshold coefficient remained negative (−0.0061) and was not statistically significant. An additional sample-based robustness check excluding countries with very high hydropower dependence produced qualitatively similar results. The below-threshold coefficient remained positive (0.0123), whereas the above-threshold coefficient remained negative (−0.0118) and was not statistically significant. The additional System GMM diagnostic statistics reported in Table 6 indicated that all robustness specifications satisfied the conventional instrument validity requirements, with statistically significant AR(1), insignificant AR(2), and Hansen tests that did not reject the validity of the instrument set. The robustness analysis, excluding hydropower-dependent countries, further suggests that the estimated threshold relationship was not driven solely by countries with exceptionally high hydropower dependence, thereby providing additional support for the robustness of the identified regime heterogeneity. Overall, the robustness analyses consistently supported the baseline findings reported in Table 7, whereas the accompanying diagnostic statistics reported in Table 6 indicated that the alternative specifications satisfied the same System GMM validity requirements as the baseline model.

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Table 7. Baseline and threshold regression results.

Variables	Model 1 (Baseline)	Model 2 (RNEW)	Model 3 (Full Controls)	Model 4 (Threshold)
CO_2emissions (t−1) (ln)	0.812 *** (0.031)	0.656 *** (0.036)	0.584 *** (0.037)	0.582 *** (0.037)
Green ODA (ln)	0.0134 (0.0096)	0.0176 ** (0.0055)	0.0093 (0.0069)	
RNEW		−0.0400 *** (0.0047)	−0.0323 *** (0.0050)	−0.0280 *** (0.0047)
GDP per capita (ln)			0.6346 *** (0.2374)	0.6502 *** (0.2334)
Population (ln)			1.7101 *** (0.03300)	1.3746 *** (0.3122)
Trade openness			0.0015 ** (0.0007)	0.0015 ** (0.0006)
Industry share			−0.0047 (0.0036)	−0.0040 (0.0034)
Green ODA (Below Threshold, RNEW ≤ 78.2%)				0.0155 ** (0.0075)
Green ODA (Above Threshold, RNEW > 78.2%)				−0.0123 (0.0103)
Country FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	756	756	756	756
AR(1) test (p-value)	<0.001	<0.001	<0.001	<0.001
AR(2) test (p-value)	0.421	0.404	0.467	0.072
Hansen test (p-value)	0.912	0.887	0.880	0.491
Number of instruments	12	14	18	17
Number of groups	63	63	63	63

Notes: The estimated renewable energy threshold value (γ) is 78.2%. "Below Threshold" and "Above Threshold" represent observations with renewable energy consumption below and above the estimated threshold, respectively. Robust standard errors are shown in parentheses. All four model specifications were estimated using the same two-step System GMM estimator. AR(1) and AR(2) show the p-values of the Arellano–Bond tests for first- and second-order serial correlations, respectively. Hansen reported the p-value of the Hansen test for overidentifying restrictions used to assess instrument validity. The number of instruments and groups was reported for each model specification to facilitate the assessment of model validity and potential instrument proliferation. Country and year fixed effects were included in all models. *** $p < 0.01$, ** $p < 0.05$.

5. Discussion

This study examined whether the relationship between Green ODA and carbon emissions was nonlinear when renewable energy consumption was used as a threshold variable. These results indicate that transitioning to renewable energy sources is currently a major policy effort to reduce greenhouse gas emissions, particularly those of carbon dioxide. Increased renewable energy consumption was associated with reduced CO_2 emissions, suggesting its potential contribution to environmental sustainability.

Second, the threshold estimation results indicated that the relationship between Green ODA and carbon emissions was not uniform across countries; however, it differed according to the stage of renewable energy transition. Notably, the empirical findings do not support Hypothesis 1 because Green ODA was positively associated with carbon emissions in the below-threshold regime. This may be attributable to Green ODA, which may be initially accompanied by infrastructure expansion and broader economic activities that increase energy demand and carbon emissions. This interpretation is consistent with the scale-expansion effect of development assistance, whereby aid-funded investments stimulate economic activity before the environmental benefits of low-carbon technologies fully materialize [8,29,36].

Third, when renewable energy deployment reached a sufficiently high level, the estimated coefficient of Green ODA became negative, although it was not statistically significant. Therefore, the present findings do not provide sufficient empirical evidence that Green ODA contributes to the reduction of carbon emissions under advanced renewable energy conditions. Rather, the results indicate that the relationship between Green ODA and carbon emissions differs across the stages of renewable energy transition. Previous studies [11,12,37,38] have suggested that Green ODA may influence environmental outcomes through several potential transmission channels, including renewable energy investment, technology transfer, institutional capacity building, and cleaner infrastructure. However, this study did not directly examine these channels.

Additionally, many developing countries likely remain locked into carbon-intensive energy systems during the early stages of the renewable energy transition. Under these conditions, institutional impediments and limited absorptive capacity may reduce the effectiveness of Green ODA, while aid directed toward transitional infrastructure may initially support energy access and economic activity rather than immediate emission reductions. As renewable energy systems and institutional capacities improve, the relationship between Green ODA and carbon emissions may differ from that observed in countries with limited renewable energy development. However, this study does not provide sufficient empirical evidence to conclude that Green ODA reduces carbon emissions under these conditions.

Therefore, these mechanisms should be interpreted as theoretical explanations suggested in the existing literature rather than as empirically verified mechanisms in the present study. The estimated threshold value of 78.2% should not be interpreted as a universal policy benchmark or optimal renewable energy target. Rather, it was endogenously estimated using the panel threshold estimation procedure as the empirical value that best separated the sample into two regimes with distinct Green ODA effects. In the present sample, the estimated threshold divided the balanced panel into 532 below-threshold and 224 above-threshold country-year observations, indicating that the above-threshold regime was supported by a substantial number of observations, rather than only a limited number of extreme cases. Therefore, the estimated threshold should be interpreted as a sample-specific empirical value, which may vary across datasets, country groups, and periods. The primary contribution of this study is in identifying the heterogeneous relationship between Green ODA and carbon emissions across the different stages of renewable energy transition. Rather than providing definitive evidence that Green ODA universally reduces carbon emissions, our findings suggest that the environmental effects of Green ODA vary, depending on the renewable energy transition regime. Overall, the results highlight the importance of considering structural conditions, particularly the energy transition stage, when evaluating the environmental effectiveness of Green ODA.

6. Limitations

This study has several limitations. First, although the dynamic panel threshold model combined with the System GMM estimator mitigated potential endogeneity, the use of observational macro-panel data did not eliminate concerns regarding omitted time-varying factors, aid allocation decisions, or reverse causality. Therefore, the estimated relationships should be interpreted as dynamic associations, rather than as definitive causal effects. Additionally, because Green ODA was measured using a three-year centred moving average, the explanatory variable incorporated information from adjacent years. Although the additional lagged and trailing specifications produced qualitatively similar results, the centred moving average specification remained the baseline measure and should be interpreted with caution regarding strict temporal ordering. Future research could further assess the temporal dynamics using longer-lag structures, alternative smoothing windows, or project-level disbursement data.

Second, Green ODA was constructed using the OECD DAC Rio Marker methodology with weighted principal and significant objectives. Although this approach follows internationally accepted practices, it may not fully capture the differences in the implementation quality or actual effectiveness of climate-related development assistance across recipient countries. Furthermore, although country- and year-fixed effects were included to account for unobserved heterogeneity, cross-country differences in institutional quality, governance capacity, policy implementation, and administrative capacity may still influence the estimated relationships and cannot be comprehensively captured by the empirical model. Third, this study explored several potential transmission channels, including renewable energy investment, technology transfer, institutional capacity building, and cleaner infrastructure, based on existing literature. However, these mechanisms were not directly examined in the empirical model and therefore should be regarded as theoretical explanations rather than empirically verified mechanisms. Finally, although this study identified a threshold effect associated with renewable energy transition, further research should incorporate institutional quality, governance capacity, financial development, and other structural factors to better explain the heterogeneous environmental effects of Green ODA across developing countries.

Although renewable energy consumption was employed as the threshold variable, Green ODA may have contributed to renewable energy deployment over time. Therefore, a potential feedback relationship between Green ODA and the threshold variable cannot be excluded. Future studies could address this issue by employing alternative threshold specifications that explicitly account for endogenous threshold variables.

7. Conclusions and Policy Implications

This study examined the relationship between Green ODA and carbon emissions, with a focus on determining whether this relationship differs across the stages of renewable energy transition. A dynamic panel threshold regression model was employed to explore the effects of Green ODA and carbon emissions in 63 developing countries from 2010 to 2021, with renewable energy consumption as the threshold variable.

Renewable energy consumption is notably associated with reduced carbon emissions, highlighting the importance of energy structure transformations in developing countries.

Second, the findings indicate that the impact of Green ODA on carbon emissions is nonlinear and depends on the stage of the renewable energy transition. The estimated threshold value for renewable energy consumption was 78.2%. Model 4 indicated that Green ODA was significantly and positively associated with CO_2 emissions when renewable energy consumption was below the threshold. The results did not indicate an emission-reducing association between Green ODA and carbon emissions in the below-threshold regime. In contrast, when renewable energy consumption exceeded the threshold, the effect was negative, although it was not statistically significant. Therefore, the present findings do not provide sufficient empirical evidence that Green ODA significantly reduces CO_2 emissions when renewable energy consumption exceeds an estimated threshold. However, the results indicate that the relationship between Green ODA and carbon emissions differs across the stages of renewable energy transition. The findings support the existence of regime heterogeneity rather than an emissions-reducing effect in the above-threshold regimes.

These findings have several policy implications, although they should be interpreted with caution because the above-threshold coefficient was not statistically significant. First, Green ODA alone is insufficient to reduce carbon emissions in countries where renewable energy consumption remains below the estimated threshold. Therefore, donor countries should consider the stage of renewable energy transition in recipient countries when designing and allocating Green ODA. Second, recipient countries with relatively low renewable energy consumption may need to prioritize expanding the role of renewable energy in their energy structures. These recommendations are directly contingent upon the variables estimated in this study and should not be interpreted as evidence of unobserved institutional or technological mechanisms.

Therefore, the recipient countries should formulate renewable energy development policies based on their development conditions and priorities. According to the results of this study, increased assistance does not necessarily lead to better developmental outcomes. Governments should continue to promote renewable energy deployment based on the domestic development conditions and energy transition strategies. These recommendations should be interpreted as policy considerations that are broadly consistent with the empirical findings rather than direct causal implications of the estimated model. The principal contribution of this study is the identification of regime heterogeneity in the relationship between Green ODA and carbon emissions across different stages of renewable energy transition, rather than establishing that Green ODA universally reduces carbon emissions.

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Abbreviations

The following abbreviations are used in this manuscript:

CRS	Creditor reporting system
DAC	Development Assistance Committee
EKC	Environmental Kuznets Curve
IEA	International Energy Agency
KMI	Korea Maritime Institute
ODA	Official development assistance
RSS	Residual sum of squares
SDG	Sustainable Development Goals
VIF	Variance inflation factor
WDI	World Development Indicators

Appendix A

Table A1. Countries classified in the above-threshold renewable energy regime (RNEW > 78.2%).

NO.	Country
1	Bhutan
2	Burkina Faso
3	Burundi
4	Cameroon
5	Chad
6	Democratic Republic of the Congo
7	Ethiopia
8	Guinea
9	Guinea-Bissau
10	Haiti
11	Liberia
12	Madagascar
13	Malawi
14	Mali
15	Mozambique
16	Myanmar
17	Nepal
18	Niger
19	Nigeria
20	Rwanda
21	Sierra Leone
22	Tanzania
23	Togo
24	Uganda
25	Zambia
26	Zimbabwe

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