Available online at
www.heca-analitika.com/eje

Ekonomikalia
Journal of Economics

Vol. 2, No. 1, 2024

Enhancing Environmental Quality: Investigating the Impact of Hydropower Energy Consumption on CO_2 Emissions in Indonesia

Putri Maulidar [1], Sintia Fadila [2], Iffah Hafizah [3] Naswatun Zikra [1] and Ghalieb Mutig Idroes [4,5,*]

[1] Department of Development Economics, Faculty of Economics and Business, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia; putrimaulidar0@gmail.com (P.M.); naswatunzikra@gmail.com (N.Z.)
[2] Electrical and Instrumentation, PT. Solusi Bangun Andalas, Aceh Besar 23363, Indonesia; sintia.fsbi.ext@sig.id (S.F.)
[3] The Bartlett School of Environment, Energy and Resources, University College London, London WC1E 6BT, United Kingdom; iffah.hafizhah.23@ucl.ac.uk (I.H.)
[4] Energy and Green Economics Unit, Graha Primera Saintifika, Aceh Besar 23371, Indonesia; ghaliebidroes@outlook.com (G.M.I.)
[5] Renewable Energy and Sustainable Economics, Konstanta Utama, Aceh Besar 23371, Indonesia

* Correspondence: ghaliebidroes@outlook.com

Article History

Received 15 February 2024
Revised 10 April 2024
Accepted 19 April 2024
Available Online 28 April 2024

Keywords:
Global warming
Environmental sustainability
CO_2 emissions
Hydropower energy consumption
Economic growth
ARDL
Granger causality

Abstract

Achieving sustainable environmental quality has become a critical global issue, necessitating the reduction of carbon dioxide (CO_2) emissions and greenhouse gas (GHG) emissions to mitigate environmental pollution. Hydropower energy has the potential to play a significant role in this effort by providing a clean, renewable energy source that can help reduce reliance on fossil fuels and decrease CO_2 emissions. This study examines the dynamic impact of hydropower energy consumption, economic growth, capital, and labor on Indonesia's CO_2 emissions from 1990 to 2020. Applying the Autoregressive Distributed Lag (ARDL) method, the findings demonstrate that hydropower energy consumption has a negative effect on CO_2 emissions in both the short and long term, indicating that increasing hydropower energy consumption leads to a reduction in CO_2 emissions. Conversely, labor exhibits a positive influence on CO_2 emissions in both the short and long term, suggesting that a rise in labor contributes to higher levels of CO_2 emissions in Indonesia. Furthermore, the Granger causality analysis reveals a bidirectional relationship between CO_2 emissions and hydropower energy consumption. The robustness of ARDL results is confirmed through additional tests using Fully-Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regressions (CCR) methods. The findings underscore the importance of promoting sustainable hydropower energy for effective environmental management in Indonesia. Policymakers should prioritize investments in sustainable hydropower infrastructure, encourage the adoption of energy-efficient technologies, and develop a skilled workforce to mitigate the environmental impact of increased labor force participation.

1. Introduction

In the last few decades, maintaining sustainable environmental quality has become a critical issue worldwide. To preserve biodiversity, it is crucial to reduce carbon dioxide (CO_2) and greenhouse gas (GHG) emissions, which are major contributors to the increasing ecological footprint and global environmental pollution [1–5]. Global efforts to limit temperature rise and mitigate the worst impacts of climate change require ambitious targets [6, 7]. Humanity faces the challenge of achieving the new Sustainable Development Goals (SDGs), which aim to ensure access to affordable, reliable, sustainable, and modern energy for all [8, 9]. These goals focus on universal energy access, increasing the share of renewable energy, improving energy efficiency, and expanding and upgrading infrastructure for sustainable energy supply [10]. Continued collaboration and investment in renewable energy infrastructure are crucial for addressing climate change, promoting economic growth, and enhancing global prosperity [11].

However, the impacts of atmospheric warming resulting from global GHG emissions vary among nations, influenced by their natural features and socioeconomic characteristics [12]. Countries like Malaysia, the Philippines, Indonesia, Singapore, and Thailand face heightened environmental challenges due to economic advancement [13–15]. Economic growth increases energy consumption as industries expand, leading to higher demand [16–19]. Historically, fossil fuels have been the primary energy source driving economic development. Thus, economic growth and energy consumption are often associated with the rising global CO_2 emissions, largely stemming from fossil fuel combustion, which significantly contributes to the increasing GHG emissions in the atmosphere [20].

Recognizing the urgent need to address environmental degradation and energy insecurity, transitioning to a low-carbon economy has been emphasized as a crucial step in supporting sustainable development goals [13, 20, 21]. Renewable energy sources, such as solar, wind, geothermal, and hydropower, offer environmentally friendly alternatives by emitting fewer GHG and CO_2 emissions, and causing minimal environmental harm [22–25]. Promoting renewable energy helps nations mitigate the adverse effects of CO_2 emissions on economic growth, combat climate change, and secure a sustainable long-term energy supply [24].

Hydropower energy stands out among renewable energy sources due to its substantial energy generation capacity, storage capabilities, and economic benefits [26]. Its flexibility makes it particularly conducive to ensuring grid stability, providing a reliable alternative to volatile renewable energy sources [13, 20]. Additionally, hydropower offers accessibility and sustainability advantages over fossil fuels [11, 22, 27], leading to its remarkable growth and significant contribution to global electricity generation [6, 10, 21].

However, despite the vast untapped potential of hydropower resources worldwide, which could offer substantial energy and economic benefits, their deployment often faces obstacles due to negative impacts on riverine ecosystems [28]. While the global installed hydropower capacity reached 1360 GW in 2021, generating a total of 4250 terawatt-hours (TWh) of electricity [29], its deployment rate lags significantly behind that of solar PV, being ten times slower [30]. This slower rate can be attributed primarily to the limited availability of suitable rivers for damming and frequent opposition based on social and environmental concerns.

Hydropower is the most preferred renewable energy technology in Indonesia due to its cost-effectiveness and reliability [31, 32]. The country's assessed potential for large hydropower stands at 75 gigawatts (GW) [30, 33]. As of 2020, non-fossil fuel renewable energy sources, such as hydro, wind, and solar power, accounted for only 11.5% of Indonesia's total electricity production. Among these sources, hydropower was the largest contributor, comprising 8% of the total [34]. According to the International Energy Agency [35], hydropower accounted for 60% of the total renewable electricity generation in Indonesia in 2021, making it the most significant non-combustible renewable energy source. Indonesia's geographic location, with its numerous rivers and abundant rainfall, makes it particularly well-suited for the development of hydropower technology [36]. As an agrarian country situated on the equator, local communities frequently utilize hydropower technology to address sustainable energy supply in remote areas [37]. From an environmental perspective, hydropower energy has demonstrated its ability to reduce emissions with negative abatement costs and significant potential for further emission reductions [13, 38]. The utilization of hydropower not only enhances Indonesia's energy security but also fosters economic growth by providing affordable and clean electricity to industries and households [39, 40].

Numerous researchers globally have explored the relationship between hydropower, economic growth, and CO_2 emissions. Umalla et al. [11] focused on BRICS countries from 1990 to 2016, employing panel autoregressive distributed lag (ARDL) modeling and panel quantile regression (PQR). They found that hydropower energy consumption positively influences both long-term and short-term economic growth while negatively impacting CO_2 emissions in the long term. Alsaleh & Abdul-Rahim [26] investigated the impact of hydropower industry growth on CO_2 emissions in 28 European Union (EU) countries from 1990 to 2018, utilizing panel fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and pooled ordinary least squares (pooled OLS). The findings suggested that increasing hydropower energy can effectively reduce CO_2

Table 1. The summary of variables.

Variable	Symbol	Unit	Description	Source
CO_2 Emissions	CO2	Kilotonnes (kt)	CO_2 emissions reflect environmental impact, primarily from burning fossil fuels.	WDI [41]
Hydropower Energy Consumption	HYDRO	Electricity generation in gigawatt-hour (GWh)	Hydropower energy measures electricity generated from water flow, offering a renewable and cleaner energy option.	IEA [35]
Economic Growth	GDP	Constant (2015 US$)	Economic growth indicates a nation's rising production and GDP, leading to improved living standards and prosperity.	WDI [41]
Capital	GFCF	Constant (2015 US$)	Gross fixed capital formation represents investments in a nation's physical assets like buildings and infrastructure over a period.	WDI [41]
Labor	LF	Total (person)	The labor force is the sum of all employed and job-seeking individuals in a region, key to evaluating workforce engagement and productivity.	WDI [41]

emissions in EU28 nations. Similarly, Sinaga et al. [42] examined hydropower's role in mitigating environmental degradation in Malaysia from 1978 to 2016 using the ARDL model. Bello et al. [43] discovered that hydroelectricity plays a significant role in mitigating environmental degradation. Bildirici & Gökmenoğlu [22] investigated the relationship between environmental pollution, economic growth, and hydropower energy consumption in G7 countries, revealing bidirectional causality between hydropower consumption and CO_2 emissions. Solarin et al. [44] provided empirical evidence supporting hydropower as a substitute for fossil fuels in Italy. In contrast to previous studies, Pata [45] found no significant reduction in CO_2 emissions in Turkey from 1974 to 2014 despite the presence of hydropower, using both ARDL and FMOLS models within the Environmental Kuznets Curve (EKC) framework, which was attributed to insufficient adoption of renewable energy. Similarly, Zou [46] did not find evidence supporting the substitution of coal with hydropower.

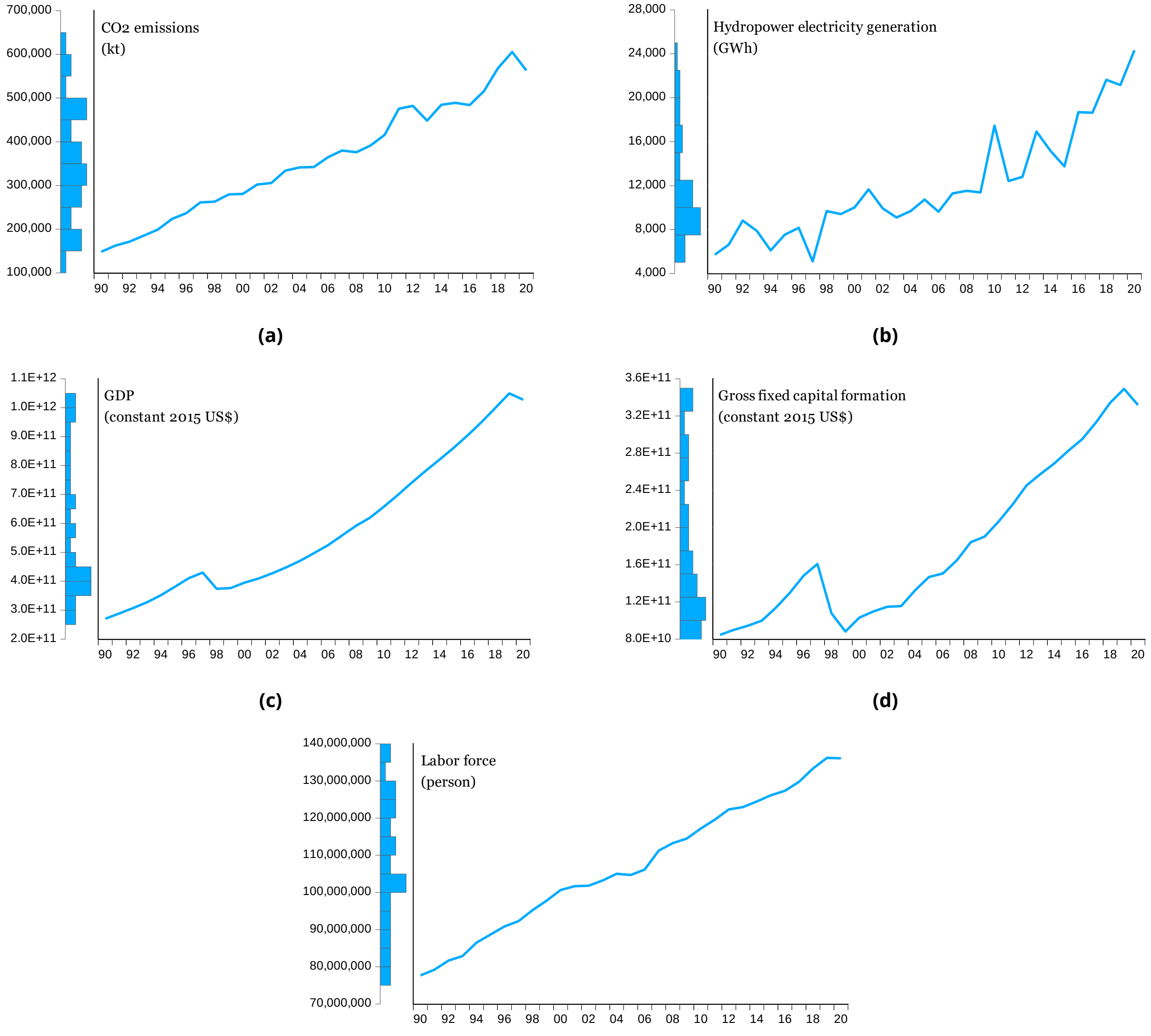
A recent study by Ridzuan et al. [47] investigated the impact of hydroelectricity on CO_2 emissions in the ASEAN-3 countries (Malaysia, Indonesia, and Thailand) using the ARDL method. The results showed that hydroelectricity had a significant long-term effect on reducing CO_2 emissions only in Malaysia, while the findings for Indonesia and Thailand were insignificant. In a similar study, Danmaraya & Danlami [13] examined the ASEAN-4 countries (Malaysia, Indonesia, the Philippines, and Thailand) using the ARDL approach. They found that hydropower energy consumption negatively impacted CO_2 emissions in Malaysia but had no significant impact in Indonesia, the Philippines, and Thailand.

Despite these studies, there remains a significant research gap, particularly in the case of Indonesia. The limited availability of research in this context underscores the need for further investigation. To address this gap, this study aims to employ a more comprehensive and up-to-date dataset, a robust model, and suitable modeling techniques such as ARDL, Granger causality, as well as methods for robustness like FMOLS, DOLS, and CCR, to analyze the dynamic impact of hydropower energy consumption, economic growth, capital, and labor on CO_2 emissions in Indonesia. Given the pressing need to promote sustainable development and mitigate potential environmental damage, it is crucial to empirically examine the correlation between these factors. By testing hypotheses related to hydropower, economic growth, capital, labor and CO_2 emissions, this study seeks to provide policymakers with the necessary insights to make informed decisions. The findings of this research will contribute to the development of effective strategies that balance economic growth with environmental sustainability, ultimately fostering a more sustainable future for Indonesia.

2. Materials and Methods

2.1. Variable Description and Data Sources

This study utilizes annual data from Indonesia covering the period from 1990 to 2020. It is worth noting that in this study, we use the concept of a 'proxy' for several variables. CO_2 emissions are used as a proxy for environmental degradation, while hydropower electrical generation serves as a proxy for hydropower energy consumption. Additionally, to simplify the terminology, we use the abbreviation 'capital' to refer to gross fixed capital formation and 'labor' to refer to the labor force. The World Development Indicators (WDI) database, published by the World Bank, provided the data for CO_2 emissions, economic growth, capital, and labor [41]. Meanwhile, the International Energy Agency (IEA) platform was the source for data on hydropower energy consumption [35]. Table 1 presents a detailed description of the variables used in this study. To mitigate the



(a) **(b)** **(c)** **(d)** **(e)**

Figure 1. Trends of the study variables: (a) CO_2 emissions, (b) hydropower energy, (c) economic growth, (d) capital, and (e) labor.

potential impact of heteroscedasticity, all data were transformed into natural logarithms prior to analysis.

Furthermore, Figure 1 illustrates the trends of the variables used in this study. Figure 1a presents the data trend for CO_2 emissions, while Figure 1b displays the trend for hydropower energy consumption. Figure 1c depicts the trend for economic growth, and Figure 1d showcases the trend for capital. Lastly, Figure 1e exhibits the trend for labor. Upon examining the overall trends, it is evident that each variable demonstrates a consistent upward trajectory over the years, indicating a steady increase in their respective values.

2.2. Theoretical Framework and Empirical Model

The theoretical framework emphasizes the importance of integrating renewable energy to reduce CO_2 emissions. Transitioning to renewables promotes mitigating environmental degradation [7, 48]. The Green Solow Model (GSM) by Brock & Taylor [49] extends Solow's growth theory [50] by incorporating environmental factors. It assumes production creates negative externalities through environmental degradation. Our study employs a Cobb-Douglas [51] production function, which includes capital and labor in the model, enhanced with hydropower consumption and economic growth variables. To achieve the stated objective, we express the initial function as Equation 1.

$$CO2 = f\,(HYDRO, GDP, GFCF, LF) \tag{1}$$

Before analyzing the data, we convert all variables to their logarithmic forms. This simplifies the analysis and makes the results easier to interpret. As a result, Equation 1 becomes a log-linear econometric model, as shown in Equation 2.

$$lnCO2_t = \beta_0 + \beta_1 lnHYDRO_t + \beta_2 lnGDP_t + \beta_3 lnGFCF_t + \beta_4 lnLF_t + \varepsilon_t \quad (2)$$

In this Equation 2, β_0 is a constant term, and ε_{it} represents the error term. The parameters from β_1-β_4 are the estimated coefficients. Drawing upon the principles of the Environmental Kuznets Curve (EKC), there is an expectation that the values of β_1-β_4 will alternately display positive and negative associations.

2.3. Estimation Techniques

2.3.1. Autoregressive Distributed Lag (ARDL)

The Autoregressive Distributed Lag (ARDL) model has emerged as a powerful econometric tool for analyzing the dynamic impact and interrelationships among economic variables. This approach has gained significant attention from researchers due to its ability to assess the long-term influence of certain factors on other variables. In recent studies, the ARDL model has been applied to investigate the impact of various variables on environmental indicators, particularly focusing on CO₂ emissions [3, 48, 52, 53].

$$\Delta lnCO2_t = \beta_0 + \sum_{i=1}^{q} \beta_1 \Delta lnCO2_{t-i} + \sum_{i=0}^{p} \beta_2 \Delta lnHYDRO_{t-i} + \sum_{i=0}^{p} \beta_3 \Delta lnGDP_{t-i} + \sum_{i=0}^{p} \beta_4 \Delta lnGFCF_{t-i} + \sum_{i=0}^{p} \beta_5 \Delta lnLF_{t-i} + \pi ECT_{t-1} + \psi_1 lnCO2_{t-1} + \psi_2 lnHYDRO_{t-1} + \psi_3 lnGDP_{t-1} + \psi_4 lnGFCF_{t-1} + \psi_5 lnLF_{t-1} + \varepsilon_t \quad (3)$$

The ARDL model offers several advantages over other econometric techniques, as highlighted by Idroes et al. [3], Maulidar et al. [54], and Adebayo et al. [55]. One of its key strengths lies in its ability to capture both short-term and long-term effects, providing a comprehensive understanding of the dynamic relationships between variables. This feature is particularly valuable for policymakers and researchers seeking to develop effective strategies for addressing environmental challenges. Another advantage of the ARDL model is its robustness in handling datasets with limited sample sizes. This characteristic is especially beneficial when dealing with restricted data availability, a common issue in many empirical studies. Furthermore, the ARDL approach effectively addresses the problem of autocorrelation, ensuring the reliability and accuracy of the estimated coefficients. By accounting for the serial correlation in the error terms, the ARDL model yields more precise and unbiased estimates of the relationships between variables.

By estimating the ARDL model, we can gain insights into the short-term and long-term dynamics, as well as the speed of adjustment toward the long-term equilibrium. The mathematical representation of the ARDL model is given in Equation 3.

Equation 3 reveals the dynamic impact of the dependent variable on the independent variables, capturing both immediate and lagged effects for a specific country (i). The first difference operator (Δ) measures changes in variables over time, while coefficients ψ_1 to ψ_5 and β_1 to β_5 represent long-term and short-term impacts, respectively. The error correction term (ECT) indicates the speed of adjustment towards long-term equilibrium. Lagged changes of the dependent variable (q) and past values of each independent variable (p) are considered for current predictions.

Before conducting the regression analysis, it is crucial to undertake a series of preliminary tests to ensure the robustness and accuracy of the model. Firstly, we must assess the stationarity of the data using unit root tests, such as the Augmented-Dickey Fuller (ADF) test developed by Dickey and Fuller [56] and the Phillips–Perron (P-P) test proposed by Phillips and Perron [57]. These tests help us determine whether the statistical properties of the variables remain constant over time, which is a fundamental assumption for reliable regression analysis. Secondly, we should evaluate the presence of long-term relationships among the variables using cointegration tests, such as the ARDL bounds test. This test allows us to examine whether the variables are linked by a stable, long-term equilibrium despite potential short-term deviations. Lastly, we must perform diagnostic tests to validate the model assumptions, such as normality, homoscedasticity, and absence of autocorrelation in the residuals. These tests ensure that our regression model is well-specified and that the estimates are unbiased and efficient.

2.3.2. Robustness Test

To further validate the robustness of our ARDL model and ensure the consistency of the results, we employed three well-established econometric techniques: Fully Modified Ordinary Least Squares (FMOLS), developed by Phillips and Hansen [58], which corrects for endogeneity and serial correlation in the regressors; Dynamic Ordinary Least Squares (DOLS), proposed by Stock and Watson [59], which includes leads and lags of the differenced regressors to eliminate the long-term correlation between the cointegrating equation and the innovations of the regressors; and Canonical Cointegrating Regression (CCR), introduced by Park [60], which addresses the endogeneity problem by

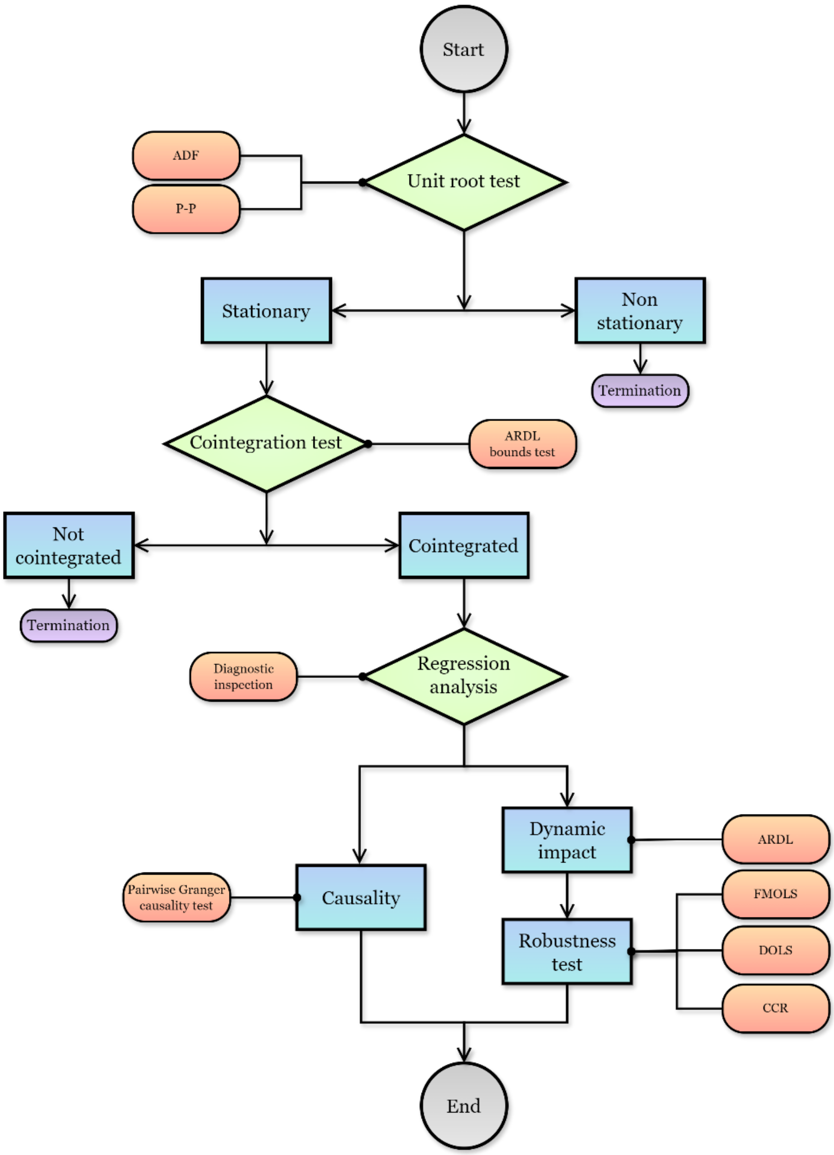


Figure 2. The flowchart of the analysis.

transforming the variables to remove the long-term dependence between the cointegrating equation and the stochastic regressors. By applying these three methods alongside our ARDL model, we aim to provide a comprehensive and robust analysis of the long-term relationships among the variables, strengthening the validity of our findings and allowing for more reliable policy implications and recommendations. This robustness test approach has also been applied by several researchers who tested their main models using FMOLS, DOLS, and CCR [3, 7, 61].

2.3.3. Paiwise Granger Causality

In pairwise Granger causality analysis, we assess the causal relationships between each pair of variables in our dataset. By examining the ability of one variable to predict another while controlling for the reverse relationship, this method helps us identify specific directional influences among variables. By systematically evaluating these pairwise interactions, we can construct a comprehensive understanding of the causal structure within the dataset, providing valuable insights into the interdependencies among the variables under investigation [62].

2.4. The Summary of the Analysis Process Stages

This study encompasses a multi-phase research process, starting with data summary and essential model tests, including unit root tests (ADF and P-P) and cointegration tests (ARDL bounds test). The analysis progresses to regression analysis, surpassing diagnostic tests, then examining the dynamic impact using ARDL and robustness checks with FMOLS, DOLS, and CCR. Finally, the study explores causal relationships among variables using the pairwise Granger causality test. Figure 2

Table 2. Descriptive statistics.

Variable	**lnCO2**	**lnHYDRO**	**lnGDP**	**lnGFCF**	**lnLF**
Mean	12.71558	9.316763	27.00337	25.82466	18.47906
Median	12.74300	9.280333	26.93313	25.73803	18.46961
Max.	13.31346	10.09926	27.67917	26.57848	18.72965
Min.	11.90728	8.538172	26.32265	25.15961	18.16796
Std. Dev.	0.395544	0.400561	0.408464	0.456156	0.167298
Obs.	31	31	31	31	31

Table 3. Unit root test results.

Variable	ADF				P-P			
	Level		*1st Diff.*		*Level*		*1st Diff.*	
	t-stat.	**Prob.**	**t-stat.**	**Prob.**	**t-stat.**	**Prob.**	**t-stat.**	**Prob.**
lnCO2	-2.3944	0.1517	-3.9981*	0.0047	-7.0877*	0.0000	-5.0186*	0.0003
lnHYDRO	0.6598	0.9889	-8.0741*	0.0000	-1.0456	0.7236	-10.414*	0.0000
lnGDP	-0.4728	0.8832	-3.7886*	0.0077	-0.4728	0.8832	-3.6966*	0.0096
lnGFCF	-0.5354	0.8705	-4.4969*	0.0014	-0.5515	0.8670	-3.5449**	0.0138
lnLF	-2.0656	0.2591	-3.7987*	0.0077	-2.6456	0.0954	-4.4231*	0.0016

Note: * indicates the significance level at the 1% level.

Table 4. ARDL bounds test results.

F-bounds test		Null Hypothesis: No levels relationship		
Test Statistic	**Value**	**Sig.**	**I(0)**	**I(1)**
F-stat.	13.6340	At 10%	2.2	3.09
K	4	At 5%	2.56	3.49
		At 2.5%	2.88	3.87
		At 1%	3.29	4.37

illustrates the comprehensive journey of the research process.

3. Results and Discussion

3.1. Descriptive Statistics

The descriptive statistics presented in Table 2 for a set of logged economic and environmental variables span a period of 31 observations. The proximity of mean and median values across all variables suggests relatively symmetrical distributions. CO_2 emissions and hydropower energy consumption exhibit similar variability, with standard deviations of approximately 0.40, indicating a consistent data spread. In comparison, economic growth and capital show slightly higher standard deviations, around 0.41 and 0.46, suggesting a bit more fluctuation in these economic indicators. Furthermore, labor has the lowest standard deviation, at 0.17, demonstrating the least variability among the variables studied. Examining the maximum and minimum values for each variable reveals a range of data without extreme outliers, further supporting the overall consistency and reliability of the dataset.

3.2. Unit Root Test

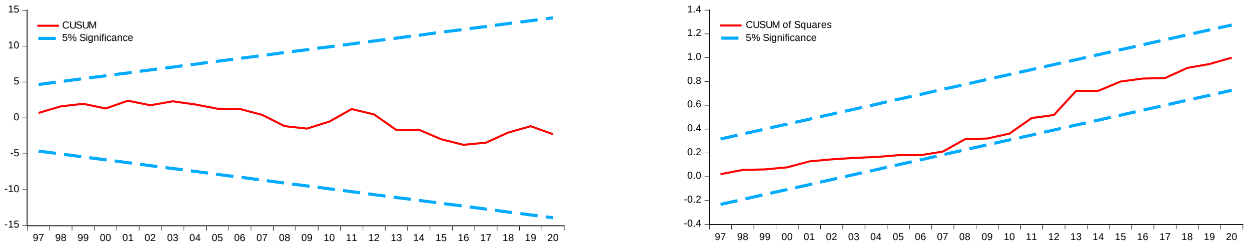
As shown in Table 3, unit root and stationarity tests were performed for each series using Augmented Dickey-Fuller (ADF) and Phillips-Perron (P-P) tests. Initially, the tests were conducted at levels I(0), followed by the first difference I(1). The outcomes of the ADF test indicate that all variables are stationary at first difference I(1). Specifically, CO2, HYDRO, GDP, GFCF, and LF variables exhibit stationarity at a confidence level of 99%. Conversely, the results of the P-P test suggest that the CO_2 variable is stationary both at levels and at the first difference I(1). In contrast, all other variables also achieve stationarity at the first difference I(1) with a confidence level of 99%, except for GFCF. The GFCF variable attains stationarity at the first difference I(1) with a confidence level of 95%. These findings suggest that the data exhibit stationarity in the first difference. Consequently, we can confidently employ the ARDL approach to examine the short-term and long-term impacts.

3.3. Cointegration Test

The cointegration test results, as detailed in Table 4, provide strong evidence of cointegration through the ARDL bounds test. This test assesses the long-term equilibrium relationship among variables within an ARDL model. The null hypothesis, which posits the absence of cointegration, is strongly challenged by an F-statistic of 13.63, exceeding the I(1) critical values across all specified significance levels. Considering four independent variables in the model, the findings robustly reject the null hypothesis, confirming the presence of a cointegration relationship within the dataset.

3.4. Diagnostic Test

Table 5 presents the outcomes of diagnostic tests for a statistical regression model, indicating a robust and well-specified model. The Adjusted R-squared value surpasses 0.9903, indicating that a significant proportion of the



(a) **(b)**

Figure 3. The parameters stability test with CUSUM (a) and CUSUMQ (b).

Table 5. The results of the diagnostic test.

Diagnostic tests	**Coeff.**	**Prob.**	**Decision**
R^2	> 0.9917	-	The model is well-fitted
R^2 Adjusted	> 0.9903	-	The model is well-fitted
Jarque-Bera	1.0164	0.6016	Residuals are normally distributed
CUSUM & CUSUMQ	-	< 0.05	The model is stable
Breusch-Godfrey LM test	1.2008	0.3199	No serial correlation exists
Breusch-Pagan-Godfrey test	0.8174	0.5492	No heteroscedasticity exists
Harvey test	0.2665	0.9269	No heteroscedasticity exists
Glejser test	0.6309	0.6780	No heteroscedasticity exists
ARCH test	2.7615	0.1081	No heteroscedasticity exists
Ramsey test	1.1368	0.2673	The model is properly specified

variance in the dependent variable is accounted for by the model, signifying an exceptional fit. The CUSUM and CUSUMQ assessments yield probabilities below 0.05, affirming the stability of the model's coefficients over time. The Jarque-Bera test outcome, with a value of 1.0164 and a probability of 0.6016, suggests that the residuals follow a normal distribution, as the p-value exceeds the conventional significance threshold. Additionally, the Breusch-Godfrey LM test exhibits a high p-value of 0.3199, indicating the absence of serial correlation in the residuals. The Ramsey test produces a p-value of 0.2673, indicating that the model is appropriately specified without any bias in linear predictions. Finally, the Breusch-Pagan-Godfrey, Harvey, Glejser, and ARCH tests yield p-values of 0.5492, 0.9269, 0.6780, and 0.1081, respectively, indicating that the residuals exhibit constant variance, thus revealing no heteroscedasticity. These results suggest that the model is statistically sound, with well-fitted parameters and assumptions that hold true, which is conducive to predictive accuracy and analytical reliability.

Furthermore, the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) stability diagnostic tests are utilized to assess the long-term stability of the ARDL model. The plots in Figure 3 demonstrate that CO2 emissions in Indonesia remained consistently within the 95% threshold limit from 1990 to 2020, fluctuating by no more than 5% during this period. Moreover, the CO_2 emissions function showcases the effectiveness and coherence of the parameters employed in both the short and long term, a validation supported by CUSUM and CUSUMSQ.

3.5. Short-Term and Long-Term Analysis of the ARDL Test

The ARDL estimation results, as shown in Table 6, reveal that only the HYDRO and LF have a significant impact on CO_2 emissions in the long term. Both are statistically strong and significant at the 1% level. HYDRO has a significant negative impact on CO_2 emissions, indicating that a 1% increase in HYDRO will result in a 0.18% reduction in CO_2 emissions. In contrast, LF has a significant positive impact on CO_2 emissions, suggesting that a 1% increase in LF will lead to a 2.61% increase in CO_2 emissions. This suggests that hydropower energy enhances the environment in the future by reducing the level of emissions. At the same time, labor plays a significant role in promoting CO_2 emissions, possibly due to increased labor leading to higher consumption levels. This can drive up demand for goods and services, producing more CO_2 emissions from production and consumption.

Additionally, the Error Correction Term (ECT) exhibits a noteworthy and negative coefficient in the short term, suggesting a long-term equilibrium within this model. Moreover, the short-term analysis aligns with the long-term results, with only the HYDRO and LF displaying statistical significance. Specifically, a 1% increase in HYDRO corresponds to a 0.13% reduction in CO_2 emissions, while a similar increase in LF results in a 1.96% rise in CO_2 emissions in the short-term.

3.6. Robustness Test

As indicated in Table 7, only the HYDRO and LF variables demonstrate a considerable influence on CO_2 emissions over the long term. We utilize FMOLS, DOLS, and CCR

Table 6. The results of ARDL estimation.

Variable	Coeff.	t-stat.	Prob.
Long-term			
lnHYDRO	-0.1788*	-2.8878	0.0081
lnGDP	0.0887	0.2137	0.8326
lnGFCF	-0.0580	-0.2923	0.7725
lnLF	2.6053*	5.3508	0.0000
Short-term			
ECT(-1)	-0.7516*	-9.9422	0.0000
ΔlnHYDRO	-0.1344*	-2.9922	0.0063
ΔlnGDP	0.0667	0.2161	0.8308
ΔlnGFCF	-0.0436	-0.2952	0.7703
ΔlnLF	1.9582*	3.0594	0.0054
C	-34.6435	-10.6161	0.0000

Note: ***, **, and * indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 7. The results of robustness test estimations.

Variable	FMOLS		DOLS		CCR	
	Coeff.	**t-stat.**	**Coeff.**	**t-stat.**	**Coeff.**	**t-stat.**
lnHYDRO	-0.1546*	-3.5377	-0.1515*	-3.1817	-0.1604**	-2.3100
lnGDP	-0.0452	-0.1483	-0.0767	-0.2315	-0.0166	-0.0405
lnGFCF	-0.0415	-0.2800	-0.0045	-0.0276	-0.0545	-0.2778
lnLF	2.8833*	8.1642	2.8740*	7.5405	2.8617*	6.7568
C	-36.8318	-15.5609	-36.7972	-14.5785	-36.8154	-14.4447
R^2	0.9917		0.9919		0.9916	
R^2 adjusted	0.9903		0.9906		0.9903	

Note: ***, **, and * indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 8. The results of pairwise Granger causality test.

Null Hypothesis	F-stat.	Prob.	Direction
lnHYDRO ≠ lnCO2	5.8108**	0.0230	HYDRO ↔ CO2
lnCO2 ≠ lnHYDRO	12.5132*	0.0015	
lnGDP ≠ lnCO2	2.1355	0.1555	-
lnCO2 ≠ lnGDP	0.0692	0.7944	
lnGFCF ≠ lnCO2	1.1476	0.2935	-
lnCO2 ≠ lnGFCF	0.7853	0.3833	
lnLF ≠ lnCO2	5.1246**	0.0318	LF → CO2
lnCO2 ≠ lnLF	1.0617	0.3120	
lnGDP ≠ lnHYDRO	17.3801*	0.0003	GDP ↔ HYDRO
lnHYDRO ≠ lnGDP	6.7697**	0.0149	
lnGFCF ≠ lnHYDRO	9.2861*	0.0051	GFCF ↔ HYDRO
lnHYDRO ≠ lnGFCF	5.0209**	0.0335	
lnLF ≠ lnHYDRO	18.0348*	0.0002	LF → HYDRO
lnHYDRO ≠ lnLF	0.1995	0.6587	
lnGFCF ≠ lnGDP	2.1663	0.1526	GDP → GFCF
lnGDP ≠ lnGFCF	3.6797***	0.0657	
lnLF ≠ lnGDP	0.3015	0.5875	-
lnGDP ≠ lnLF	2.5562	0.1215	
lnLF ≠ lnGFCF	1.6845	0.2053	-
lnGFCF ≠ lnLF	1.2023	0.2825	

Note: ***, **, and * indicate significance at the 10%, 5%, and 1% levels, respectively.

estimation as robustness tests to confirm the ARDL findings. LF exhibits notable significance, reaching a 1% probability level in both FMOLS and DOLS estimations and in the CCR results. Similarly, HYDRO shows a 1% significance level in both FMOLS and DOLS analyses, while the CCR test indicates a 5% significance level for its impact on CO_2 emissions. Therefore, we can infer that LF and HYDRO exert a strong and significant influence on CO_2 emissions over the long term.

The estimation results of the CO_2 emissions model demonstrate that the LF variable exhibits a positive long-term impact, while the HYDRO variable exhibits a negative long-term impact on CO_2 emissions. Specifically, a 1% increase in LF is associated with an increase in CO_2 emissions of 2.88% according to the FMOLS method, 2.87% based on DOLS, and 2.86% according to the CCR method. Furthermore, a 1% increase in HYDRO demonstrates a negative impact on CO_2 emissions, resulting in a reduction of 0.15% according to FMOLS and DOLS, and 0.16% according to CCR.

3.7. Pairwise Granger Causality Test

To broaden the scope of the empirical findings, this study additionally employed pairwise Granger causality analysis to determine the causal relationships among the variables, as illustrated in Table 8. In summary, the research identified three unidirectional and three bidirectional causalities. Specifically, unidirectional causality was detected from LF to CO2, LF to HYDRO, and GDP to GFCF, while CO2, GDP, and GFCF variables all exhibited bidirectional causality with HYDRO. Figure 4 illustrates both unidirectional and bidirectional causality in this study, aiding understanding of variable relationships.

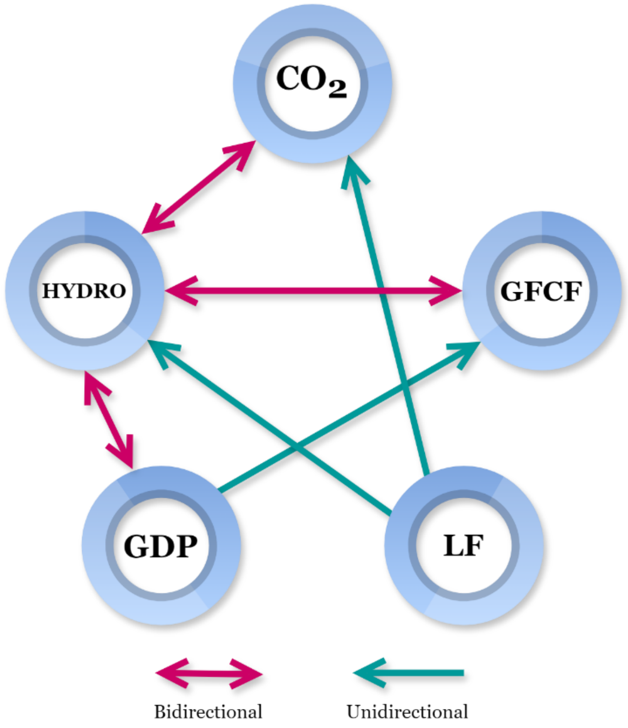


Figure 4. Overview of Granger causality

3.8. Discussion

The empirical findings of this study reveal that, among the variables considered, only hydropower energy consumption and labor have a significant dynamic impact on CO_2 emissions in Indonesia. The long-term effects of hydropower energy consumption, economic growth, capital, and labor on CO_2 emissions are summarized and visually represented in Figure 5, which provides a graphical representation of the results.

Hydropower has a negative impact on CO_2 emissions, which means it reduces CO_2 emissions both in the short term and long term. This finding is similar to studies conducted by Alsaleh & Abdul-Rahim [26], Xia & Wang [21], Ummalla et al. [11], Wolde-Rufael & Weldemeskel [63], Bilgili et al. [64], Khanna [65], and Ope Olabiwonnu et al. [20], which explain the widespread consumption of renewable energy sources, particularly hydropower, providing energy without increasing CO_2 emissions.

Hydropower emerges as a sustainable energy solution, harnessing the natural water cycle to generate electricity without reliance on fossil fuels or GHG emissions. Its environmental compatibility underscores its pivotal role in fostering a greener energy landscape. The causality between hydropower energy consumption and CO_2 emissions suggests that transitioning to renewable sources like hydropower is crucial to achieving the necessary reduction in CO_2 emissions. Hydropower is a clean source of renewable energy; unlike fossil fuels, it does not produce CO_2 emissions when generating electricity [13].

Furthermore, labor in this study shows a positive impact, increasing the CO_2 emissions both in the short and long term. These results align with Idroes et al. [3]. One might interpret this finding within the framework of economic development and environmental policies. In developing nations, where industrialization and economic growth may be priorities, the positive relationship suggests that efforts to boost labor productivity or economic activities might come with an environmental cost. Similarly, Maulidar et al. [54] show that increased labor leads to increased CO_2 emissions in Indonesia.

The pairwise Granger causality analysis revealed relationships among key variables. There was a bidirectional causal relationship between hydropower energy consumption and economic growth, suggesting that increased hydropower usage contributes to economic growth, while economic growth drives further investment in hydropower infrastructure. A bidirectional causal relationship also existed between hydropower energy consumption and capital, implying a symbiotic relationship where investment in hydropower infrastructure leads to capital accumulation, and increased capital allows for the development and expansion of hydropower projects. Economic growth had a unidirectional causal effect on capital, highlighting that economic expansion facilitates capital, which is essential for sustained growth and development. Additionally, labor had a unidirectional causal effect on hydropower energy consumption and CO_2 emissions. This suggests that policies to enhance labor participation and employment levels may inadvertently impact energy consumption patterns and CO_2 emissions.

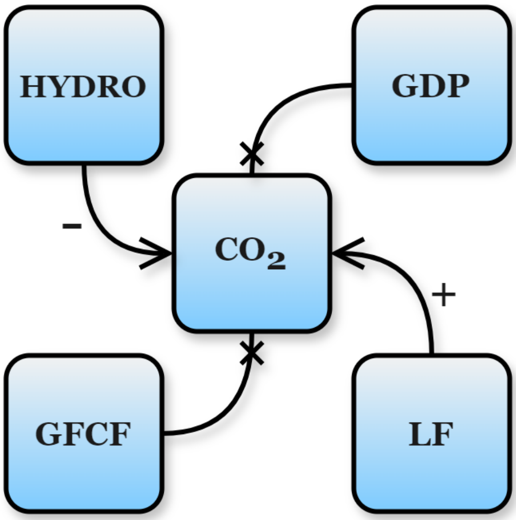


Figure 5. Graphical representation of the results.

4. Conclusions and Policy Recommendations

This study investigates the dynamic impact of hydropower energy consumption, economic growth, capital, and labor on CO_2 emissions in Indonesia from 1990 to 2022 using the ARDL approach. The findings reveal that hydropower energy consumption reduces CO_2 emissions in Indonesia in both the short and long term. At the same time, an increase in labor leads to a rise in CO_2 emissions in both the short and long term. These ARDL results are further validated by FMOLS, DOLS, and CCR approaches, confirming the robustness of the findings. Moreover, the pairwise Granger causality test highlights the presence of a bidirectional causal relationship between hydropower energy consumption and CO_2 emissions in Indonesia. This implies that not only does hydropower energy consumption influence CO_2 emissions, but CO_2 emissions also affect the consumption of hydropower energy in Indonesia.

Based on the findings of this study, which revealed that hydropower energy consumption reduces CO_2 emissions. At the same time, labor increases CO_2 emissions in Indonesia, policymakers should adopt a two-pronged approach to address environmental concerns and promote sustainable economic growth. Firstly, the government should prioritize investment in sustainable hydropower infrastructure, as it has been shown to have a consistent negative impact on CO_2 emissions. This involves constructing new hydropower plants and refurbishing existing ones to optimize efficiency. Secondly, to counter the positive correlation between labor force participation and CO_2 emissions, policymakers must focus on skill development and educational initiatives to equate the workforce with sustainable practices and green technologies. This may involve collaborating with industries to provide training programs that promote eco-friendly practices and encourage the adoption of cleaner production methods. Additionally, implementing policies that incentivize companies to invest in energy-efficient technologies and adopt sustainable labor practices can further reduce the environmental impact of economic activities. Despite the study's limitations, such as data constraints and methodological considerations, future research could employ longitudinal analyses, cross-country comparisons, and comprehensive policy evaluations to deepen our understanding of the relationships between hydropower energy consumption, economic growth, capital, labor, and CO_2 emissions, ultimately guiding policymakers in developing effective strategies for a more sustainable future.

Author Contributions: Conceptualization, P.M. and G.M.I.; methodology, G.M.I. and I.H.; software, P.M and N.Z.; validation, G.M.I.; formal analysis, P.M., S.F., I.H., N.Z. and G.M.I.; investigation, P.M. and G.M.I.; resources, G.M.I.; data curation, S.F., I.H. and N.Z.; writing—original draft preparation, P.M., I.H. and G.M.I.; writing—review and editing, S.F. and N.Z.; visualization, P.M., S.F. and N.Z.; supervision, G.M.I.; project administration, P.M. and G.M.I.; All authors have read and agreed to the published version of the manuscript.

Funding: This study does not receive external funding.

Data Availability Statement: The data is available by request.

Acknowledgments: The authors express their gratitude to their institutions and universities.

Conflicts of Interest: All the authors declare that there are no conflicts of interest.

References

1. Usman, M., Khalid, K., and Mehdi, M. A. (2021). What Determines Environmental Deficit in Asia? Embossing the Role of Renewable and Non-renewable Energy Utilization, *Renewable Energy*, Vol. 168, 1165–1176. doi:10.1016/j.renene.2021.01.012.
2. Wahab, S., Imran, M., Ahmed, B., Rahim, S., and Hassan, T. (2024). Navigating Environmental Concerns: Unveiling the Role of Economic Growth, Trade, Resources and Institutional Quality on Greenhouse Gas Emissions in OECD Countries, *Journal of Cleaner Production*, Vol. 434, 139851. doi:10.1016/j.jclepro.2023.139851.
3. Idroes, G. M., Hardi, I., Hilal, I. S., Utami, R. T., Noviandy, T. R., and Idroes, R. (2024). Economic Growth and Environmental Impact: Assessing the Role of Geothermal Energy in Developing and Developed Countries, *Innovation and Green Development*, Vol. 3, No. 3, 100144. doi:10.1016/j.igd.2024.100144.
4. Wang, J., and Dong, K. (2019). What Drives Environmental Degradation? Evidence from 14 Sub-Saharan African Countries, *Science of The Total Environment*, Vol. 656, 165–173. doi:10.1016/j.scitotenv.2018.11.354.
5. Hardi, I., Idroes, G. M., Zulham, T., Suriani, S., and Saputra, J. (2023). Economic Growth, Agriculture, Capital Formation and Greenhouse Gas Emissions in Indonesia: FMOLS, DOLS and CCR Applications, *Ekonomikalia Journal of Economics*, Vol. 1, No. 2, 82–91. doi:10.60084/eje.v1i2.109.
6. Gemechu, E., and Kumar, A. (2022). A Review of How Life Cycle Assessment Has Been Used to Assess the Environmental Impacts of Hydropower Energy, *Renewable and Sustainable Energy Reviews*, Vol. 167, 112684. doi:10.1016/j.rser.2022.112684.
7. Idroes, G. M., Hardi, I., Rahman, M. H., Afjal, M., Noviandy, T. R., and Idroes, R. (2024). The Dynamic Impact of Non-renewable and Renewable Energy on Carbon Dioxide Emissions and Ecological Footprint in Indonesia, *Carbon Research*, Vol. 3, No. 1, 35. doi:10.1007/s44246-024-00117-0.
8. Leal Filho, W., Tripathi, S. K., Andrade Guerra, J. B. S. O. D., Giné-Garriga, R., Orlovic Lovren, V., and Willats, J. (2019). Using the Sustainable Development Goals towards a Better Understanding of Sustainability Challenges, *International Journal of Sustainable Development & World Ecology*, Vol. 26, No. 2, 179–190. doi:10.1080/13504509.2018.1505674.
9. Henderson, K., and Loreau, M. (2023). A Model of Sustainable Development Goals: Challenges and Opportunities in Promoting Human Well-Being and Environmental Sustainability, *Ecological Modelling*, Vol. 475, 110164. doi:10.1016/j.ecolmodel.2022.110164.
10. Berga, L. (2016). The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review, *Engineering*, Vol. 2, No. 3, 313–318. doi:10.1016/J.ENG.2016.03.004.

11. Ummalla, M., Samal, A., and Goyari, P. (2019). Nexus among the Hydropower Energy Consumption, Economic Growth, and CO2 Emissions: Evidence from BRICS Countries, *Environmental Science and Pollution Research*, Vol. 26, No. 34, 35010–35022. doi:10.1007/s11356-019-06638-1.
12. van Ledden, A., Can, M., and Brusselaers, J. (2024). Toward a Greener Future: Investigating the Environmental Quality of Non-Green Trading in OECD Countries, *Ekonomikalia Journal of Economics*, Vol. 2, No. 1, 15–28. doi:10.60084/eje.v2i1.149.
13. Danmaraya, I. A., and Danlami, A. H. (2022). Impact of Hydropower Consumption, Foreign Direct Investment and Manufacturing Performance on CO2 Emissions in the ASEAN-4 Countries, *International Journal of Energy Sector Management*, Vol. 16, No. 5, 856–875. doi:10.1108/IJESM-06-2021-0019.
14. Hardi, I., Ray, S., Attari, M. U. Q., Ali, N., and Idroes, G. M. (2024). Innovation and Economic Growth in the Top Five Southeast Asian Economies: A Decomposition Analysis, *Ekonomikalia Journal of Economics*, Vol. 2, No. 1, 1–14. doi:10.60084/eje.v2i1.145.
15. Idroes, G. M., Syahnur, S., Majid, S. A., Sasmita, N. R., and Idroes, R. (2021). Provincial Economic Level Analysis in Indonesia Based on the Geothermal Energy Potential and Growth Regional Domestic Products Using Cluster Analysis, *IOP Conference Series: Materials Science and Engineering*, Vol. 1087, No. 1, 012079. doi:10.1088/1757-899X/1087/1/012079.
16. Wang, J., and Azam, W. (2024). Natural Resource Scarcity, Fossil Fuel Energy Consumption, and Total Greenhouse Gas Emissions in Top Emitting Countries, *Geoscience Frontiers*, Vol. 15, No. 2, 101757. doi:10.1016/j.gsf.2023.101757.
17. Sasmita, N. R., Phonna, R. A., Fikri, M. K., Khairul, M., Apriliansyah, F., Idroes, G. M., Puspitasari, A., and Saputra, F. E. (2023). Statistical Assessment of Human Development Index Variations and Their Correlates: A Case Study of Aceh Province, Indonesia, *Grimsa Journal of Business and Economics Studies*, Vol. 1, No. 1, 12–24. doi:10.61975/gjbes.v1i1.14.
18. Hardi, I., Ringga, E. S., Fijay, A. H., Maulana, A. R. R., Hadiyani, R., and Idroes, G. M. (2023). Decomposed Impact of Democracy on Indonesia's Economic Growth, *Ekonomikalia Journal of Economics*, Vol. 1, No. 2, 51–60. doi:10.60084/eje.v1i2.80.
19. Noviandy, T. R., Idroes, G. M., and Hardi, I. (2024). Enhancing Loan Approval Decision-Making: An Interpretable Machine Learning Approach Using LightGBM for Digital Economy Development, *Malaysian Journal of Computing (MJOC)*, Vol. 9, No. 1, 1734–1745. doi:10.24191/mjoc.v9i1.25691.
20. Ope Olabiwonnu, F., Haakon Bakken, T., and Anthony Jnr, B. (2022). The Role of Hydropower in Renewable Energy Sector toward CO2 Emission Reduction during the COVID-19 Pandemic, *International Journal of Green Energy*, Vol. 19, No. 1, 52–61. doi:10.1080/15435075.2021.1930005.
21. Xia, C., and Wang, Z. (2020). The Effect of Fossil Fuel and Hydropower on Carbon Dioxide Emissions: EKC Validation with Structural Breaks, *Journal of Environmental Engineering and Landscape Management*, Vol. 28, No. 1, 36–47. doi:10.3846/jeelm.2020.11832.
22. Bildirici, M. E., and Gökmenoğlu, S. M. (2017). Environmental Pollution, Hydropower Energy Consumption and Economic Growth: Evidence from G7 Countries, *Renewable and Sustainable Energy Reviews*, Vol. 75, 68–85. doi:10.1016/j.rser.2016.10.052.
23. Lu, S., Dai, W., Tang, Y., and Guo, M. (2020). A Review of the Impact of Hydropower Reservoirs on Global Climate Change, *Science of The Total Environment*, Vol. 711, 134996. doi:10.1016/j.scitotenv.2019.134996.
24. Wang, Q., Guo, J., and Li, R. (2023). Better Renewable with Economic Growth without Carbon Growth: A Comparative Study of Impact of Turbine, Photovoltaics, and Hydropower on Economy and Carbon Emission, *Journal of Cleaner Production*, Vol. 426, 139046. doi:10.1016/j.jclepro.2023.139046.
25. Idroes, G. M., Syahnur, S., Majid, M. S. A., Idroes, R., Kusumo, F., and Hardi, I. (2023). Unveiling the Carbon Footprint: Biomass vs. Geothermal Energy in Indonesia, *Ekonomikalia Journal of Economics*, Vol. 1, No. 1, 10–18. doi:10.60084/eje.v1i1.47.
26. Alsaleh, M., and Abdul-Rahim, A. S. (2022). The Pathway toward Pollution Mitigation in EU28 Region: Does Hydropower Growth Make a Difference?, *Renewable Energy*, Vol. 185, 291–301. doi:10.1016/j.renene.2021.12.045.
27. Mohsin, M., Orynbassarov, D., Anser, M. K., and Oskenbayev, Y. (2023). Does Hydropower Energy Help to Reduce CO2 Emissions in European Union Countries? Evidence from Quantile Estimation, *Environmental Development*, Vol. 45, 100794. doi:10.1016/j.envdev.2022.100794.
28. Chowdhury, A. F. M. K., Wild, T., Zhang, Y., Binsted, M., Iyer, G., Kim, S. H., and Lamontagne, J. (2024). Hydropower Expansion in Eco-Sensitive River Basins under Global Energy-Economic Change, *Nature Sustainability*, Vol. 7, No. 2, 213–222. doi:10.1038/s41893-023-01260-z.
29. International Hydropower Association. (2022). Hydropower Status Report: Sector trends and insights, from https://www.hydropower.org/publications/2022-hydropower-status-report.
30. Silalahi, D. F., Blakers, A., and Cheng, C. (2023). 100% Renewable Electricity in Indonesia, *Energies*, Vol. 17, No. 1, 3. doi:10.3390/en17010003.
31. Erinofiardi, Gokhale, P., Date, A., Akbarzadeh, A., Bismantolo, P., Suryono, A. F., Mainil, A. K., and Nuramal, A. (2017). A Review on Micro Hydropower in Indonesia, *Energy Procedia*, Vol. 110, 316–321. doi:10.1016/j.egypro.2017.03.146.
32. Maulidar, P., and Syathi, P. B. (2023). Analysis of Public Willingness to Pay (WTP) for Old-Age Security in Banda Aceh, *Jurnal Ekonomi Dan Kebijakan Publik Indonesia*, Vol. 10, No. 2, 110–124. doi:10.24815/ekapi.v10i2.36762.
33. Langer, J., Quist, J., and Blok, K. (2021). Review of Renewable Energy Potentials in Indonesia and Their Contribution to a 100% Renewable Electricity System, *Energies*, Vol. 14, No. 21, 7033. doi:10.3390/en14217033.
34. Kurniawan, V. A., Pradheksa, P. Y., and Saleh, R. (2024). The Failure of Micro-Hydro Technology: A Case Study of the Banyubiru Project in Central Java, Indonesia, *Renewable and Sustainable Energy Transition*, Vol. 5, 100081. doi:10.1016/j.rset.2024.100081.
35. IEA. (2023). Energy Statistics Data Browser, from https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser.
36. Maghfirra, D., Cohon, J. L., Jaramillo, P., and Morgan, M. G. (2022). Optimizing an Equitable Micro-Hydropower Deployment: Application of a Multi-Objective Method for Rural Indonesia, *Journal of Multi-Criteria Decision Analysis*, Vol. 29, Nos. 3–4, 218–229. doi:10.1002/mcda.1769.
37. Pandyaswargo, A. H., Wibowo, A. D., and Onoda, H. (2022). Socio-Techno-Economic Assessment to Design an Appropriate Renewable Energy System for Remote Agricultural Communities in Developing Countries, *Sustainable Production and Consumption*, Vol. 31, 492–511. doi:10.1016/j.spc.2022.03.009.
38. Blum, N. U., Sryantoro Wakeling, R., and Schmidt, T. S. (2013). Rural Electrification through Village Grids—Assessing the Cost Competitiveness of Isolated Renewable Energy Technologies in Indonesia, *Renewable and Sustainable Energy Reviews*, Vol. 22, 482–496. doi:10.1016/j.rser.2013.01.049.
39. Rospriandana, N., Burke, P. J., Suryani, A., Mubarok, M. H., and Pangestu, M. A. (2023). Over a Century of Small Hydropower Projects in Indonesia: A Historical Review, *Energy, Sustainability and Society*, Vol. 13, No. 1, 30. doi:10.1186/s13705-023-00408-1.
40. Didik, H., Bambang, P. N., Asep, S., and Purwanto, Y. A. (2018). Sustainability Challenge of Micro Hydro Power Development in

Indonesia, *IOP Conference Series: Earth and Environmental Science*, Vol. 147, 012031. doi:10.1088/1755-1315/147/1/012031.

41. WDI. (2023). WorldBank Development Indicator Databased, from https://databank.worldbank.org/source/world-development-indicators.
42. Sinaga, O., Alaeddin, O., and Jabarullah, N. H. (2019). The Impact of Hydropower Energy on the Environmental Kuznets Curve in Malaysia, *International Journal of Energy Economics and Policy*, Vol. 9, No. 1, 308–315. doi:10.32479/ijeep.7328.
43. Bello, M. O., Solarin, S. A., and Yen, Y. Y. (2018). The Impact of Electricity Consumption on CO2 Emission, Carbon Footprint, Water Footprint and Ecological Footprint: The Role of Hydropower in an Emerging Economy, *Journal of Environmental Management*, Vol. 219, 218–230. doi:10.1016/j.jenvman.2018.04.101.
44. Solarin, S. A., Bello, M. O., and Bekun, F. V. (2021). Sustainable Electricity Generation: The Possibility of Substituting Fossil Fuels for Hydropower and Solar Energy in Italy, *International Journal of Sustainable Development & World Ecology*, Vol. 28, No. 5, 429–439. doi:10.1080/13504509.2020.1860152.
45. Pata, U. K. (2018). Renewable Energy Consumption, Urbanization, Financial Development, Income and CO2 Emissions in Turkey: Testing EKC Hypothesis with Structural Breaks, *Journal of Cleaner Production*, Vol. 187, 770–779. doi:10.1016/j.jclepro.2018.03.236.
46. Zou, G. L. (2012). The Long-Term Relationships among China's Energy Consumption Sources and Adjustments to Its Renewable Energy Policy, *Energy Policy*, Vol. 47, 456–467. doi:10.1016/j.enpol.2012.05.022.
47. Ridzuan, A. R., Albani, A., Latiff, A. R. A., Razak, M. I. M., and Murshidi, M. H. (2020). The Impact of Energy Consumption Based on Fossil Fuel and Hydroelectricity Generation towards Pollution in Malaysia, Indonesia and Thailand, *International Journal of Energy Economics and Policy*, Vol. 10, No. 1, 215–227. doi:10.32479/ijeep.8140.
48. Idroes, G. M., Hardi, I., Noviandy, T. R., Sasmita, N. R., Hilal, I. S., Kusumo, F., and Idroes, R. (2023). A Deep Dive into Indonesia's CO2 Emissions: The Role of Energy Consumption, Economic Growth and Natural Disasters, *Ekonomikalia Journal of Economics*, Vol. 1, No. 2, 69–81. doi:10.60084/eje.v1i2.115.
49. Brock, W. A., and Taylor, M. S. (2010). The Green Solow Model, *Journal of Economic Growth*, Vol. 15, No. 2, 127–153. doi:10.1007/s10887-010-9051-0.
50. Solow, R. M. (1956). A Contribution to the Theory of Economic Growth, *The Quarterly Journal of Economics*, Vol. 70, No. 1, 65. doi:10.2307/1884513.
51. Cobb, C. W., and Douglas, P. H. (1928). A Theory of Production, *The American Economic Review*, Vol. 18, No. 1, 139–165.
52. Pata, U. K., Dam, M. M., and Kaya, F. (2022). How Effective Are Renewable Energy, Tourism, Trade Openness, and Foreign Direct Investment on CO2 Emissions? An EKC Analysis for ASEAN Countries, *Environmental Science and Pollution Research*, Vol. 30, No. 6, 14821–14837. doi:10.1007/s11356-022-23160-z.
53. Wei, Z., and Lihua, H. (2022). Effects of Tourism and Eco-Innovation on Environmental Quality in Selected ASEAN Countries, *Environmental Science and Pollution Research*, Vol. 30, No. 15, 42889–42903. doi:10.1007/s11356-021-17541-z.
54. Maulidar, P., Fitriyani, F., Sasmita, N. R., Hardi, I., and Idroes, G. M. (2024). Exploring Indonesia's CO2 Emissions: The Impact of Agriculture, Economic Growth, Capital and Labor, *Grimsa Journal of Business and Economics Studies*, Vol. 1, No. 1, 43–55. doi:10.61975/gjbes.v1i1.22.
55. Adebayo, T. S., Akinsola, G. D., Kirikkaleli, D., Bekun, F. V., Umarbeyli, S., and Osemeahon, O. S. (2021). Economic Performance of Indonesia amidst CO2 Emissions and Agriculture: A Time Series Analysis, *Environmental Science and Pollution Research*, Vol. 28, No. 35, 47942–47956. doi:10.1007/s11356-021-13992-6.
56. Dickey, D. A., and Fuller, W. A. (1981). Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root, *Econometrica*, Vol. 49, No. 4, 1057. doi:10.2307/1912517.
57. Phillips, P. C. B., and Perron, P. (1988). Testing for a Unit Root in Time Series Regression, *Biometrika*, Vol. 75, No. 2, 335. doi:10.2307/2336182.
58. Phillips, P. C. B., and Hansen, B. E. (1990). Statistical Inference in Instrumental Variables Regression with I(1) Processes, *The Review of Economic Studies*, Vol. 57, No. 1, 99. doi:10.2307/2297545.
59. Stock, J. H., and Watson, M. W. (1993). A Simple Estimator of Cointegrating Vectors in Higher Order Integrated Systems, *Econometrica*, Vol. 61, No. 4, 783. doi:10.2307/2951763.
60. Park, J. Y. (1992). Canonical Cointegrating Regressions, *Econometrica*, Vol. 60, No. 1, 119. doi:10.2307/2951679.
61. Idroes, G. M., Hardi, I., Nasir, M., Gunawan, E., Maulidar, P., and Maulana, A. R. R. (2023). Natural Disasters and Economic Growth in Indonesia, *Ekonomikalia Journal of Economics*, Vol. 1, No. 1, 33–39. doi:10.60084/eje.v1i1.55.
62. Granger, C. W. J. (1969). Investigating Causal Relations by Econometric Models and Cross-spectral Methods, *Econometrica*, Vol. 37, No. 3, 424. doi:10.2307/1912791.
63. Wolde-Rufael, Y., and Weldemeskel, E. M. (2020). Environmental Policy Stringency, Renewable Energy Consumption and CO2 Emissions: Panel Cointegration Analysis for BRIICTS Countries, *International Journal of Green Energy*, Vol. 17, No. 10, 568–582. doi:10.1080/15435075.2020.1779073.
64. Bilgili, F., Lorente, D. B., Kuşkaya, S., Ünlü, F., Gençoğlu, P., and Rosha, P. (2021). The Role of Hydropower Energy in the Level of CO2 Emissions: An Application of Continuous Wavelet Transform, *Renewable Energy*, Vol. 178, 283–294. doi:10.1016/j.renene.2021.06.015.
65. Khanna, M. (2021). COVID-19: A Cloud with a Silver Lining for Renewable Energy?, *Applied Economic Perspectives and Policy*, Vol. 43, No. 1, 73–85. doi:10.1002/aepp.13102.