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Long-Term Impact of Dirty and Clean Energy on Indonesia's Economic Growth: Before and During the COVID-19 Pandemic

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Abstract

Dirty (non-renewable) energy, considered environmentally harmful due to greenhouse gas emissions, is contrasted with clean (renewable) energy, which is believed to have positive ecological impacts that can boost economic growth in the long term. This study analyzes the long-term effects of electricity generation from both dirty and clean energy sources on economic growth in Indonesia, using data from two periods: before the COVID-19 pandemic (2000–2019) and the full period including the COVID-19 pandemic (2000–2022). Empirical findings from Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) methods reveal that dirty energy significantly impacts long-term economic growth in both periods, while clean energy does not have a substantial effect. A robustness check conducted using the Canonical Cointegrating Regression (CCR) method confirms that dirty energy continues to play a crucial role in Indonesia's long-term economic growth. A key finding is that the positive impact of dirty energy generation on economic growth was stronger in the full period including the COVID-19 pandemic compared to before. This suggests that dirty energy contributed more to economic growth during the pandemic. The study recommends a balanced approach to economic growth by prioritizing the transition to clean energy while recognizing the importance of dirty energy in Indonesia's economy. This transition should be gradual, using the current role of dirty energy to support economic development while investing in clean energy alternatives for sustainable growth.

Introduction

Generating electricity encompasses the process from various sources, broadly categorized as dirty and clean energy. Dirty sources like coal, oil, and natural gas rely on burning fossil fuels releasing greenhouse gases and pollutants. In contrast, clean sources such as solar, wind, hydro, biomass, and geothermal harness natural processes like water flow, wind blows, sunlight, and heat from the Earth without significant emissions [1–6]. While clean energy options are generally more sustainable, with lower environmental impacts, reduced resource depletion, and a shift toward cost competitiveness as technology advances, dirty energy remains the primary driver of today's world economic activity [7–14].

Balancing economic interests with environmental and climate concerns regarding electricity generation is a complex challenge for governments, industries, and communities worldwide [15–17]. Dirty energy has historically provided relatively cheap energy compared to alternative sources, making it attractive for businesses and consumers [18–20]. Additionally, some clean energy technologies are still in the early stages of development, necessitating ongoing research and development efforts [21–23]. Resistance from established energy industries and concerns about job losses, often supported by corruption and less democratic governments in some countries, make it hard to raise public awareness and support, further complicating the transition [24–29].

As one of the world's most densely populated countries, Indonesia still heavily relies on dirty energy sources for its electric generation. In 2019, before the COVID-19 pandemic, approximately 91.15% of the country's total electric generation came from dirty energy, while clean energy accounted for only 8.85%. In 2022, following the COVID-19 pandemic, the dependency on dirty energy decreased slightly to 89.13%, with clean energy making up 10.87%. A noteworthy finding from the data is that, despite the government's growing effort to diversify the energy mix towards cleaner and more sustainable sources, the portion of dirty energy has remained high compared to the year 2000, comprising 88.89% of the total electric generation, while clean energy constitutes 11.11% [30].

The impact of electric generation from dirty and clean energy sources on economic growth is quite complex [31]. Dirty energy sources can initially stimulate economic activity through job creation and industry growth, but over time, they entail significant long-term costs related to environmental degradation and health consequences, potentially even leading to disasters [32,33]. On the other hand, clean energy technologies can drive economic growth by fostering innovation and reducing long-term external costs associated with pollution and climate change. Additionally, investing in clean energy enhances energy independence, reduces price volatility, and opens up opportunities for market expansion and export potential in the growing global renewable energy sector [34,35]. It can be concluded that electric generation from both dirty and clean energy is expected to have a positive relationship with economic growth [36–38].

A prior research investigation, analyzing the influence of electricity generation on economic growth and drawing from data spanning 1980 to 2012 across 174 nations, reveals a robust and statistically significant correlation between electric generation from dirty and clean energy sources and economic growth [39]. Furthermore, an examination utilizing panel data encompassing 47 U.S. states from 1999 to 2017 demonstrates that generating electricity from clean energy sources has a beneficial effect, whereas relying on dirty energy sources may impede economic growth quality [40]. Moreover, a study that examined the connection between clean energy-based electricity generation and economic growth in OECD nations from 1980 to 2007 suggests a mutually reinforcing, positive correlation over the long term [41].

Previous studies conducted in Indonesia have also addressed the topics covered in this paper, with most focusing on electricity consumption rather than electricity generation. However, a gap in the research still exists. One study, which utilized data from 1971–2002, indicates a unidirectional causality running from economic growth to electricity generation. However, this study didn't specify the sources of electricity generation, was unable to establish the influence of electricity generation on economic growth, and didn't examine the dynamic long-term impact [42]. A review study provides a detailed explanation for the pattern of the capacity of power generation installed and electricity generation from both dirty and clean energy in Indonesia for the period 1987-2009, but it didn't analyze their impact on national economic growth [43]. Another review study in Indonesia also didn’t examine the effects of electric generation from clean energy sources on economic growth and only analyzed one type of clean energy, which is geothermal [44].

Given the existing research gap in the literature on Indonesian economic growth, this study distinguishes itself by investigating the influence of electricity generation derived from dirty and clean energy sources on Indonesia's economic growth. The novelty of this study lies in its potential to offer more extensive empirical evidence by utilizing data from both before and during the COVID-19 pandemic period concerning the repercussions of both dirty and clean energy on the nation's goals toward a sustainable economy.

Materials and Methods

Data and Variable

This study employs yearly time-series data, incorporating two distinct periods, both commencing in the year 2000. The first period spans from 2000 to 2019, denoted as the period preceding the COVID-19 pandemic. The second period covers the entire duration, including the COVID-19 pandemic, and spans from 2000 to 2022. This study labels these periods as 'before the COVID-19 pandemic' and 'during the COVID-19 pandemic,' respectively. The data utilized is sourced from two main databases: World Development Indicators (WDI) [45] and Ember Climate (EMBER) [30]. Detailed information regarding the data employed is outlined in Table 1.

Table 1. Variable synopsis.

Variable	Description	Units (Sources)	Definition
GDP	Gross Domestic Product	Constant LCU (WDI)	The sum of gross value added by all resident producers in the economy [45].
DE	Dirty Energy	TerraWatt (EMBER)	Refers to the generation of electricity using non-renewable energy sources such as coal, oil, and natural gas [30].
CE	Clean Energy	TerraWatt (EMBER)	Refers to the generation of electricity using renewable energy sources such as solar, wind, hydro, biomass, and geothermal [30].
K	Gross Fixed Capital Formation	Constant LCU (WDI)	The sum of gross value added by land improvements; plant, machinery, and equipment purchases; and the construction of public goods [45].
L	Labor Force	Person (WDI)	Comprises people ages 15 and older who supply labor for the production of goods and services during a specified period [45].

Econometric Model

It's important to emphasize that in order to establish a robust correlation between dirty and clean energy and economic growth, a model accounting for economic conditions, referring to the state of macroeconomic variables, is necessary. In this context, the Solow growth model has been selected to explore the connection between gross domestic product (GDP) and explanatory factors. What distinguishes the Solow model from other models is its incorporation of a practical Cobb-Douglas production function, which acknowledges the significant contributions of capital and labor to production. This model emphasizes the role of saving and investment in propelling economic growth. Augmenting savings and investment results in an expansion of the capital stock, ultimately leading to higher national income and products when the economy is operating at full capacity. Consequently, the Solow growth model is advantageous in examining the fundamental factors that influence economic growth [46,47].

To measure the relationship between GDP and the main explanatory variables, this paper describes GDP as a function of dirty energy, clean energy, gross fixed capital formation and labor force. Therefore, the GDP function is expressed in Equation 1.

$$GDP_t = f(DE_t, CE_t, K_t, L_t) \tag{1}$$

Where GDP refers to the gross domestic product, DE denotes dirty energy, CE signifies clean energy, K represents gross fixed capital formation, and L stands for labor.

Hence, Equation 2 displays the econometric model that portrays the variable relationship.

$$GDP_t = \beta_0 + \beta_1 DE_t + \beta_2 CE_t + \beta_3 K_t + \beta_4 L_t + \varepsilon_t \quad (2)$$

Furthermore, this study transforms Equation 2 into natural logarithmic (ln) form to facilitate interpretation in percentage terms, resulting in the final model presented in Equation 3.

$$lnGDP_t = \beta_0 + \beta_1 lnDE_t + \beta_2 lnCE_t + \beta_3 lnK_t + \beta_4 lnL_t + \varepsilon_t \quad (3)$$

Where t is the study period, β_0 is an intercept, β_1 - β_4 are the coefficients, and ε represents the error term.

Fully-Modified Ordinary Least Squares (FMOLS)

FMOLS represents a more sophisticated regression method in contrast to the conventional OLS, employed to handle endogeneity in econometric models. Endogeneity occurs when the independent variables in a regression model are correlated with the error term, resulting in distorted and unreliable coefficient estimates. FMOLS is specifically engineered to address this problem by concurrently incorporating instrumental variables and conducting a generalized instrumental variable regression. Through this integration of instrumental variables and adjustments to the structural equation, FMOLS can furnish reliable and impartial estimates of the regression coefficients, even when endogeneity is present [48,49].

Dynamic Ordinary Least Squares (DOLS)

DOLS is an extension of the conventional OLS, specifically tailored to address scenarios where variables exhibit non-stationarity. Standard OLS regression assumes that the variables are stationary, meaning their mean and variance remain constant over time. However, in economic datasets, numerous variables demonstrate non-stationary behavior, which can lead to misleading regression outcomes and misinterpretations. The central concept behind DOLS involves converting the original non-stationary time series into stationary ones while preserving the underlying long-term relationships between the variables [50,51].

Canonical Cointegrating Regression (CCR)

CCR is a widely utilized approach for investigating whether a group of integrated variables exhibit cointegration. This method is commonly applied in examining enduring connections between macroeconomic variables, scrutinizing economic indicators, and developing predictive models rooted in cointegrated relationships. It stands as a potent tool, offering valuable insights into the underlying structure of the data and the enduring relationships between variables over the long-term [52,53].

Workflow of the Study

The workflow in Figure 1 presents a structured approach to time series econometric analysis. It begins with Descriptive Statistics, followed by a Unit Root Test to assess stationarity. A Cointegration Test is then performed to determine if a long-run equilibrium relationship exists between variables. FMOLS and DOLS are applied to estimate these relationships, with results verified through a Robustness Check using CCR. The process concludes with a Discussion of the findings and Conclusions and Policy Recommendations. The workflow starts with "Start" and ends with "End."

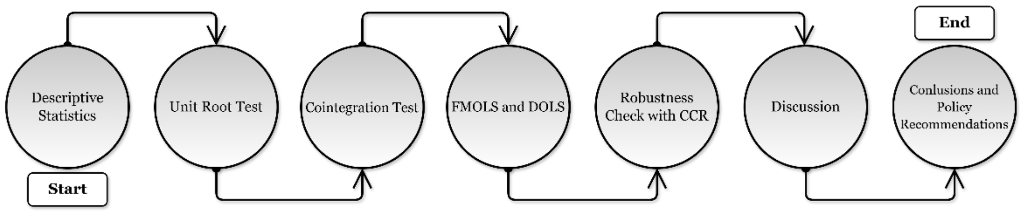

Figure 1. Workflow of the study.

Results and Discussion

Descriptive Statistics

The descriptive statistics in Table 1 summarize the variables ln(GDP), ln(DE), ln(CE), ln(K), and ln(L). The maximum and minimum values reveal the range for each variable: ln(GDP) ranges from 36.9993 to 35.9551, ln(DE) from 6.2846 to 5.0555, ln(CE) from 4.1810 to 2.9755, ln(K) from 35.8435 to 34.5979, and ln(L) from 18.7374 to 18.4272. Furthermore, the mean values indicate the central tendencies, with ln(GDP) having the highest mean (36.5045) and ln(CE) the lowest (3.4550). The median values are close to the means, indicating relatively symmetric distributions. The standard deviations highlight variability, with ln(K) showing the highest (0.4209) and ln(L) the lowest (0.1073).

Table 1. Descriptive statistics.

Variable	ln(GDP)	ln(DE)	ln(CE)	ln(K)	ln(L)
Mean	36.5045	5.7408	3.4550	35.3093	18.5864
Median	36.5250	5.7772	3.4375	35.3788	18.5995
Max.	36.9993	6.2846	4.1810	35.8435	18.7374
Min.	35.9551	5.0555	2.9755	34.5979	18.4272
Std. Dev.	0.3424	0.3921	0.3676	0.4209	0.1073

Unit Root Test

Furthermore, as indicated by the unit root test results presented in Table 2, all variables were found to be non-stationary at their levels (I(0)). However, upon taking their first differences (I(1)), all variables became stationary. This confirms that the data is stationary at the same order, with the mean, variance, and covariance demonstrating consistent behavior over time, which is suitable for dynamic estimation.

Table 2. Results of unit root test.

Variable	ADF – Fisher		PP – Fisher	
	(I(0))	(I(1))	(I(0))	(I(1))
ln(GDP)	0.6073	0.0177**	0.6073	0.0176**
ln(DE)	0.2547	0.0221**	0.2547	0.0221**
ln(CE)	0.9989	0.0001*	1.0000	0.0001*
ln(K)	0.3407	0.0069*	0.2220	0.0070*
ln(L)	0.8768	0.0012*	0.8771	0.0068*

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

Cointegration Test

The cointegration test is crucial for all methods that adopt a dynamic approach, as it implies a long-term relationship between the variables. This study employs one of the most reliable tests for determining cointegration: the Johansen cointegration test. As shown in Table 3, both before and during the COVID-19 pandemic, the model indicates a strong cointegration, where the actual number of CE units attained aligns with the anticipated number in most cases—3 hypothesized for the model before COVID-19 and 2 hypothesized for the model during the

COVID-19. It can be concluded that the estimation results of FMOLS, DOLS, and CCR are reliable, demonstrating a stable long-term relationship.

Table 3. Results of Johansen cointegration test.

Model	Hypothesized No. of CE(s)	Trace Statistic	0.05 Critical Value	Prob.
Before COVID-19	None *	107.1967	60.0614	0.0000
	At most 1 *	58.0051	40.1749	0.0003
	At most 2 *	29.8448	24.2759	0.0090
	At most 3 **	13.2833	12.3209	0.0344
	At most 4	1.3263	4.1299	0.2916
During COVID-19	None *	115.9427	60.0614	0.0000
	At most 1 *	54.8231	40.1749	0.0009
	At most 2 *	29.8146	24.2759	0.0091
	At most 3	8.1848	12.3209	0.2227

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

Econometric Results of FMOLS and DOLS

FMOLS and DOLS are advanced econometric techniques that surpass traditional OLS by estimating long-term relationships between time-series data through a broader set of lagged variables and instruments, while correcting for issues such as outliers, endogeneity, and variable biases. This study demonstrates a positive correlation between electricity generation from both dirty and clean energy sources and economic growth, as shown in Table 4. While the coefficients for both types of energy indicate a positive long-term impact, clean energy remains statistically insignificant in either period, with a probability value greater than 0.05.

Table 4. Results of FMOLS and DOLS.

Dependent: ln(GDP)						
Variable	Before COVID-19			During COVID-19		
	Coeff.	**t-Stat.**	**Prob.**	**Coeff.**	**t-Stat.**	**Prob.**
FMOLS						
ln(DE)	0.1514*	3.5979	0.0032	0.2679*	3.4879	0.0030
ln(CE)	0.0269	1.5164	0.1534	0.0221	0.6934	0.4980
ln(K)	0.0886**	2.6505	0.0200	0.1405**	2.3791	0.0301
ln(L)	0.4023*	3.3692	0.0050	0.7023*	3.4276	0.0035
C	24.609*	11.926	0.0000	16.720*	5.4951	0.0000
@TREND	0.0300*	10.489	0.0000	0.0141*	3.6247	0.0023
R^2	0.9998			0.9992		
Adj. R^2	0.9997			0.9991		
DOLS						
ln(DE)	0.1224***	2.0121	0.0639	0.2174**	2.1533	0.0459
ln(CE)	0.0240	0.9250	0.3706	0.0157	0.3711	0.7152
ln(K)	0.0716	1.4605	0.1662	0.1837**	2.3462	0.0314
ln(L)	0.4626**	2.8701	0.0124	0.5740**	2.2326	0.0393
C	24.249*	8.6283	0.0000	17.861*	4.6725	0.0002
@TREND	0.0319*	7.6525	0.0000	0.0168*	3.2391	0.0048
R^2	0.9997			0.9994		
Adj. R^2	0.9996			0.9992		

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

Based on Table 4, the FMOLS results reveal that a 1.0% increase in DE contributes to long-term GDP growth of 0.1514% in the period before the COVID-19 pandemic, and 0.2679% during the pandemic. Similarly, DOLS estimates suggest that a 1.0% rise in DE results in long-term GDP growth of 0.1224% before the COVID-19 pandemic and 0.2174% during the pandemic.

The findings also highlight a notable positive impact of K and L on GDP in both the FMOLS and DOLS models, particularly when considering dirty and clean energy generation during the COVID-19 pandemic. In the FMOLS model, a 1.0% increase in K and L raises GDP by 0.1405%

and 0.7023%, respectively. Furthermore, in the DOLS model, a 1.0% increase in K can boost GDP by 0.1837%, while a similar 1.0% increase in L could raise GDP by up to 0.5740%.

Both methods consistently show a significant trend, with probability values below 0.05, confirming the presence of a long-term relationship among the model variables. Additionally, the R-squared values of 99% across both periods underscore the strong fit of the models, suggesting that DE, CE, K, and L are key drivers explaining variations in GDP.

Robustness Check with CCR

CCR has the advantage of directly estimating the cointegrating vector without the need for differencing the data. Therefore, it is an excellent method for robustness checks of FMOLS and DOLS results. As shown in Table 5, the empirical findings of FMOLS and DOLS are consistent. CCR also confirms that electricity generation from dirty energy is significant, while clean energy is not substantial for economic growth.

Specifically, a 1.0% increase in DE can lead to a 0.1973% boost in long-term GDP in the period before COVID-19 and a 0.2599% increase during the COVID-19 period. Additionally, in both periods, both methods demonstrate a significant trend with a probability value of <0.05. This affirms that all variables in the model have a long-term relationship and exhibit an R-squared value of 99%, indicating the model's goodness of fit.

Table 5. Results of CCR.

Dependent: ln(GDP)						
Variable	Before COVID-19			During COVID-19		
	Coeff.	**t-Stat.**	**Prob.**	**Coeff.**	**t-Stat.**	**Prob.**
ln(DE)	0.1973*	3.5936	0.0033	0.2599*	3.2505	0.0050
ln(CE)	0.0728***	1.9289	0.0759	0.0095	0.1583	0.8762
ln(K)	0.1558**	2.8879	0.0127	0.1330***	1.8821	0.0781
ln(L)	0.2281	1.2581	0.2305	0.7601**	2.6580	0.0172
C	25.1280*	11.1607	0.0000	15.9916*	4.2805	0.0006
@TREND	0.0231*	4.3269	0.0008	0.0147**	2.8321	0.0120
R^2	0.9996			0.9993		
Adj. R^2	0.9995			0.9991		

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

The Summary of the Findings

Based on the FMOLS and DOLS approaches, we obtained results that are further validated using the CCR method. These findings are presented in Figure 2 to enhance clarity and facilitate easier understanding through visualization.

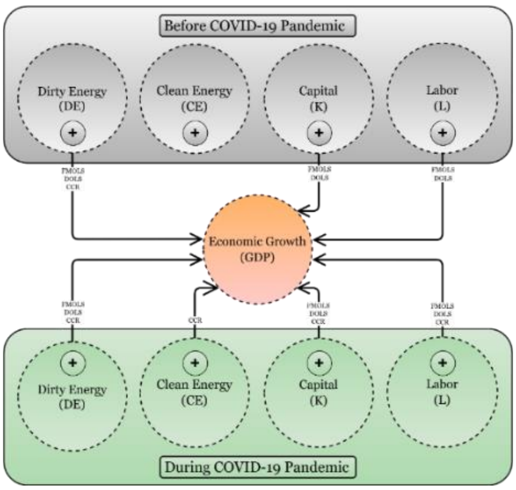

Figure 2. Graphical representation of the results.

Discussion

A sustainable electric generation system from dirty and clean energy sources is a cornerstone of economic growth in modern societies. It directly bolsters industrial output, powers essential services, and fosters technological advancements, enhancing overall productivity and quality of life. Moreover, reliable electricity access facilitates rural development, alleviates poverty, and supports diversification of industries, leading to a more resilient and adaptable economy.

This study's empirical findings emphasize the critical role of electricity generation from dirty energy sources in driving Indonesia's long-term economic growth. The evidence indicates that dirty energy sources have a positive impact on economic growth. This underscores the importance of optimizing the efficiency and sustainability of existing dirty energy infrastructure while simultaneously advancing the transition to cleaner and more sustainable energy alternatives.

In theoretical form, supported by numerous previous studies, the connection between electricity generation from energy sources and economic growth is marked as a positive relationship [1,2,7,39–41]. Similarly, this study also proved that electricity generation from energy sources significantly impacts economic growth. However, when energy sources are split into dirty and clean categories, this study found that dirty energy significantly affects, while clean energy doesn't have a long-term effect on Indonesia's economic growth.

This study also highlights the significant impact of dirty energy on economic growth across two distinct periods: before and during the COVID-19 pandemic. The findings reveal that the positive effect of electricity generation from dirty energy on Indonesia's economic growth was greater during the pandemic than before, as evidenced by the results from FMOLS, DOLS, and CCR analyses. Despite the suspension of many economic activities, such as factory operations, the study hypothesizes that this increase was driven by a higher demand for electricity as more people worked from home throughout the day. This shift required greater electricity generation to meet the rising demand. The pandemic fundamentally altered work patterns, with more individuals working remotely and households consuming more energy [54–56]. In contrast, clean energy had a significant and positive impact on economic growth only before the COVID-19 pandemic, and this was observed exclusively in the CCR method.

Furthermore, the results indicate that both capital and labor had a similar impact on economic growth in Indonesia before and during the COVID-19 pandemic. In both periods, these factors contributed positively to the country's economic growth, highlighting their consistent and significant role in driving development despite the challenges posed by the pandemic. This finding underscores the resilience of Indonesia's economic structure, particularly in leveraging its capital and labor resources for sustained growth. Moreover, these results align with the findings of several researchers worldwide, who have similarly identified capital and labor as critical drivers of economic growth [4,27,33].

Conclusions

This study investigates the impact of dirty energy and clean energy on driving Indonesia's economic growth before and during the COVID-19 pandemic. Electricity generation from dirty energy had a consistently positive impact, with its effect increasing during the pandemic due to higher residential energy demand from remote work, as validated by FMOLS, DOLS, and CCR models. In contrast, clean energy contributed positively to economic growth only before the COVID-19 pandemic, based on the CCR model. These findings highlight the need to optimize existing dirty energy infrastructure while accelerating the transition to cleaner energy to ensure long-term economic and environmental sustainability. Furthermore, both capital and labor contributed to increasing economic growth before and during the COVID-19 pandemic.

The study's policy recommendation includes implementing energy efficiency measures across industries, businesses, and households. This should be a priority, allowing for increased electricity demand without over-relying on dirty energy sources. Economic diversification should also be promoted, with investments in sectors like sustainable agriculture, eco-tourism, and green technology. Additionally, robust monitoring and reporting mechanisms, alongside international collaboration, will further bolster progress towards reducing reliance on dirty energy sources and achieving a more sustainable energy future for better growth of Indonesia's economy.

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