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Forecasting Carbon Emission Reductions: The Role of Solar Energy in Substituting Coal for Sustainable Development Goals

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ABSTRACT

This research aligns with the Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action), by introducing a comprehensive model for carbon emissions reduction through the substitution of clean energy to achieve the SDGs. The analysis begins with panel regression using historical data from 2008 to 2023, focusing on selected countries in the Asia-Pacific region, including coal-exporting countries like Indonesia and Australia, as well as coal-importing countries like China. The analysis is then extended with an ARIMA approach to forecast coal and solar energy consumption for the period 2024-2030. Subsequently, the forecast for carbon emissions reduction is conducted on average, analyzed using the previous panel regression equation by introducing values from the ARIMA analysis into pessimistic, moderate, and optimistic categories. The findings of this study indicate that solar energy consumption plays a crucial role in reducing carbon emissions, while coal consumption increases carbon emissions. On the other hand, the optimistic approach can facilitate the dominance of solar energy in the overall energy mix, resulting in significantly lower carbon emissions growth rates. Therefore, this research emphasizes the need to implement an optimistic model to drive the achievement of SDG 7 and SDG 13 by 2030.

Keywords: Carbon Emissions, Forecasting, Coal Energy Consumption, SDGs, Solar Energy Consumption
JEL Classifications: Q20, Q30, Q48, Q54

1. INTRODUCTION

Carbon emissions are a significant issue in global development, particularly due to their substantial impact on the ability to support the environment (Waheed et al., 2019). As carbon emissions rise, phenomena such as weather anomalies, increasing global temperatures, melting polar ice caps, and rising sea levels occur, highlighting the magnitude of this problem (Adams and Acheampong, 2019). This situation illustrates how human actions, especially those related to the use of fossil fuels like coal, contribute to global warming and exacerbate climate change (Raihan and Tuspekova, 2022). Since 1990, carbon emissions have increased by more than 50%, leading to long-term and irreversible changes in climate systems (He et al., 2023). Each country must take immediate action to adopt sustainable development practices. In this context, SDG 13, which focuses on climate action, calls upon countries worldwide to reduce their carbon emissions as a collective effort to prevent further environmental damage (Li et al., 2023).

In this context, energy is a crucial component in addressing climate change. SDG 7 emphasizes the importance of transitioning to clean and affordable energy (He et al., 2022). The use of renewable energy, such as solar energy, can reduce dependence on coal, which is a major source of carbon emissions (Aimon et al., 2023a; Kurniadi et al., 2024). The goal of low-carbon development is to sustain economic and social growth through activities that produce low emissions (Kabeyi et al., 2022; Kurniadi et al., 2022). This

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is a vital solution for achieving both SDG 7 and SDG 13. Each country must urgently adopt low-carbon development policies, which are part of sustainable development practices (Aimon et al., 2021). Additionally, the transition to renewable energy accelerates progress toward SDG 7, which focuses on universal access to affordable, reliable, and modern energy. Countries can promote the use of renewable energy technologies and improve energy efficiency, which will ultimately reduce greenhouse gas emission levels (Aimon et al., 2022). To ensure that the world remains on track to achieve SDG 7 and SDG 13 by 2030, implementing these strategies will be crucial (D'Adamo, 2022; Swain and Karimu, 2020).

Controlling carbon emissions is a crucial issue in the context of sustainable global development, primarily due to coal's significant contribution to the accumulation of carbon emissions (Adebayo et al., 2023). Among non-renewable energy sources such as natural gas and oil, coal is the largest contributor to carbon emissions (Paraschiv and Paraschiv, 2020; Zhang et al., 2019). This is because coal remains the primary source for nearly 40% of electricity generation worldwide (Oberschelp et al., 2019). In addition to playing a critical role in industries such as steel, cement, chemicals, and pharmaceuticals, coal is also an important commodity for exporting countries like Indonesia and Australia, as well as major importing nations like China. Dependence on coal is highly detrimental to the environment. Global warming is caused by carbon emissions from coal combustion, exacerbating climate change (Liu et al., 2020).

In this context, SDG 13, which focuses on climate action, emphasizes reducing carbon emissions to prevent further environmental degradation (Franco et al., 2020). Coal-producing countries like Indonesia and Australia face significant challenges in balancing their economic needs with the global responsibility to reduce emissions (Edwards, 2019). To meet the SDG 13 targets, Indonesia, Australia, and China must reduce their reliance on coal. Additionally, SDG 7 promotes the use of renewable energy to achieve the goal of affordable and clean energy access (Abbasi et al., 2024). Renewable resources like solar energy offer a crucial solution to reducing global reliance on coal (Creutzig et al., 2017). Countries like Indonesia and Australia can develop their solar industries by leveraging abundant renewable energy resources, which would support a more environmentally friendly economic diversification. For China, transitioning to renewable energy can accelerate the achievement of SDG 7 and significantly reduce carbon emissions from coal use.

Previous literature has emphasized the significant negative impact of coal energy, particularly its environmental effects. Numerous studies have highlighted the detrimental impacts of coal use, especially due to its contribution to air pollution and greenhouse gas emissions. For instance, Schmidt et al. (2021) explain that coal combustion releases carbon dioxide and nitrogen oxides into the atmosphere, leading to global warming and worsening environmental crises. Xu et al. (2017) state that, compared to other non-renewable energy sources, coal-fired power plants emit higher levels of pollutants. Therefore, coal is considered a major driver of global warming. These emissions accelerate global warming and disrupt climate patterns, hindering efforts towards sustainable development. Additionally, Zhang et al. (2021) stated that long-term reliance on coal energy without strict regulation could significantly hinder global efforts to reduce carbon emissions and mitigate the impacts of climate change. Zhao et al. (2019) found that approximately 41% of anthropogenic mercury emissions are caused by coal-fired power plants. Mercury is a highly toxic substance that contaminates soil and water, posing risks to human health and biodiversity. Moreover, coal mining poses significant risks to air quality. Moreno et al. (2019) found that coal mining produces fine particles such as PM10 and PM2.5, which can easily enter the lungs and cause additional environmental damage. Coal waste also presents a major threat to the environment. Feng et al. (2019) found that coal waste left in the soil degrades soil quality, which can have long-term impacts on agriculture and food security. Poor soil quality limits land's ability to support agricultural production, threatening local ecosystems and global efforts to achieve sustainable food systems.

Based on the findings from these studies, it is crucial for countries to consider the negative effects of coal use as a commodity, as this can significantly diminish their ability to support the environment. As highlighted by Aimon et al. (2023b), several countries have transitioned to more environmentally friendly renewable energy sources. The adoption of solar energy as a substitute for coal is a key step in this transformation. Solar energy, one of the cleanest energy sources, offers an efficient and sustainable way to meet national energy needs. Countries can lower energy costs while reducing carbon emissions by decreasing their reliance on limited resources like coal and transitioning to abundant and free resources such as solar energy. This shift not only leads to a more stable and resilient energy future but also enhances environmental sustainability and improves the quality of life for communities. Therefore, achieving the goals of SDG 7 and 13 in support of sustainable development is a strategic step. This study focuses on the analysis of several countries in the Asia-Pacific region, as this area hosts some of the world's largest carbon emitters. Experts suggest that Asian countries must reduce their reliance on coal to support the global campaign against climate change (Clark et al., 2020).

In this context, special attention is given to the carbon emissions contributions from countries such as Indonesia, Australia, and China, which play a significant role in global energy consumption patterns. According to the latest data from the Statistical Review of World Energy published by BP, the Asia-Pacific region accounted for 52% of global carbon emissions last year. This highlights the need to intensify efforts to mitigate the impact of climate change (Shi et al., 2021). Therefore, countries in this region must transition from high-polluting energy sources like coal to cleaner and more sustainable energy sources. Reducing carbon emissions in these countries will have a significant impact on the successful achievement of the SDGs 7 and 13. Overall, the aim of this study is to provide a deep understanding of the importance of energy transition in several Asia-Pacific countries and the strategic role that coal-exporting and importing nations can play in the global effort to tackle climate change. Consequently, this study is expected to serve as a reference for policymakers in developing effective strategies to achieve both energy and environmental sustainability.

2. LITERATURE REVIEW

On September 25, 2015, the United Nations officially established the SDGs. SDG 7 emphasizes the importance of access to clean, affordable, and sustainable energy, while SDG 13 focuses on concrete actions to address climate change, including carbon emissions control (Kulkarni et al., 2022). Implementing the SDGs, particularly in the context of reducing carbon emissions, is a crucial step toward sustainable transformation that requires planned and comprehensive cross-sector collaboration (Huisingh et al., 2015). In this context, development is not only about economic growth; it also reflects a nation's efforts to progress while considering social and environmental aspects through the use of clean energy (Jaiswal et al., 2022).

This paradigm shift is becoming increasingly relevant, given that growth-oriented development often exploits natural resources without considering long-term environmental impacts (Zhou and Park, 2020). As a result, environmental degradation and carbon emissions continue to rise, ultimately harming human quality of life. Within the framework of the SDGs, the increase in carbon emissions is an urgent issue that requires serious attention and a deep understanding (Christensen, 2023). Uncontrolled carbon emissions can hinder the achievement of long-term goals and the SDGs. Therefore, it is essential for countries to plan development in accordance with SDG principles, including gathering information through scenarios and simulations that can help control carbon emissions by focusing on key indicators such as coal consumption and solar energy consumption.

2.1. Hypothesis on the Impact of Coal Consumption on Carbon Emissions

In recent years, many researchers have focused on the relationship between coal consumption and carbon emissions. According to several studies, increased coal consumption directly leads to an increase in greenhouse gas emissions such as carbon dioxide. According to Farquharson et al. (2017), every ton of coal burned releases a significant amount of carbon into the atmosphere, contributing to global warming. A similar study conducted by Wang et al. (2018) emphasizes that carbon emissions and overall environmental health are influenced by the use of coal as a primary energy source. Therefore, it can be concluded that high coal consumption challenges sustainable energy and environmental policies. In an economic context, coal is considered an important commodity that drives the economic growth of many countries. Many nations, especially developing ones, rely on coal to meet their energy needs, which is expected to stimulate economic growth. Zhao and Alexandroff (2019) explain how increased production and investment are often associated with rising coal consumption, potentially leading to job creation and increased national revenue. Furthermore, there is a global shift towards the use of more environmentally friendly renewable energy sources, although coal remains a primary energy source. As stated by Hof et al. (2016), this transition is crucial for achieving greenhouse gas reduction targets set by various international agreements. Countries will face significant challenges in reaching SDGs, particularly related to climate change mitigation, if they continue to rely on coal as their main energy source. Consequently, it is important for policymakers to consider other, more environmentally friendly energy sources as alternatives to coal. By understanding the relationship between coal consumption and environmental impact, countries can weigh the existing benefits and risks. This will not only help protect the environment but also promote fair and sustainable economic growth for future generations.

H_1: Coal energy consumption has a significant impact on carbon emissions.

2.2. Hypothesis on the Impact of Solar Energy Consumption on Carbon Emissions

Many recent studies have focused on the relationship between solar energy consumption and carbon emissions. Research by Shahsavari and Akbari (2018) shows that solar energy consumption can significantly reduce emissions. Unlike non-renewable energy sources such as coal, solar energy is considered a clean and environmentally friendly source because it does not produce greenhouse gases or harmful pollutants in the atmosphere. These findings are particularly important for countries striving to reduce carbon emissions while pursuing sustainable economic growth (Raihan et al., 2022). The spread of solar energy indicates that a country has achieved a level of success in the use of clean energy. Solar energy has begun to replace non-renewable sources, particularly coal, in energy consumption in many countries (Opeyemi, 2021). Due to its abundance and low production costs, coal has long been a primary energy source in many nations (Gasparotto and Martinello, 2021). However, the transition from coal to solar energy is becoming increasingly important as global awareness of the threats posed by climate change and environmental degradation rises. This shift reflects environmental concern and is a crucial part of the global effort to achieve the SDGs. Additionally, research by Altassan (2023; Kuşkaya et al. (2023) shows that solar energy consumption supports environmental sustainability and reduces carbon emissions. The ability of nature to sustain life and human activities without causing irreversible damage is referred to as environmental capacity. With the increasing use of solar energy, there are no negative impacts on the environment comparable to those of coal or other fossil fuels. This indicates that countries that enhance their solar energy consumption can maintain or even improve environmental quality without sacrificing economic growth. Efforts to combat climate change are also directly linked to the increased consumption of solar energy (Zhang et al., 2022). Overall, various studies indicate that, as a primary energy source, the use of solar energy leads to a significant reduction in carbon emissions. The increasing consumption of solar energy will play a crucial role in protecting the environment and building a cleaner, more sustainable energy future.

H_2: Solar energy consumption has a significant impact on carbon emissions.

3. METHODOLOGY

3.1. Data and Variables

Secondary data is the type of data used in this study, sourced from the BP Statistical Review of World Energy. This study analyzes a combination of cross-sectional and time series data, known as panel data. The cross-sectional data focuses on Asia-Pacific countries selected based on specific criteria. The first criterion is the largest coal-producing countries, which include Indonesia and Australia. The second criterion is the largest coal-importing country, which is China. The time series data covers the historical period from 2008 to 2023, with forecast data extending from 2024 to 2030.

Additionally, the variables in this study are categorized into two groups: the dependent variable (carbon emissions) and the independent variables (coal energy consumption and solar energy consumption). It is also important to define and measure data for each variable used in this study. This explanation is essential to provide a clear understanding of the context and relevance of the analyzed variables. Details regarding the definitions, measurements, and data sources for these variables can be found in Table 1, which presents information systematically to facilitate the reader's understanding of each element involved in the research.

3.2. Analysis Model

3.2.1. Panel regression

Panel regression is used to examine the impact of coal and solar energy consumption on carbon emissions. Panel regression was chosen because it accommodates both cross-sectional data (Indonesia, Australia, and China) and time series data (2008 to 2023). This approach enables a deeper analysis of the dynamics between variables across different time spans and countries. The data used in this panel regression is longitudinal, capturing both temporal and spatial variations that influence carbon emissions in each country. Specifically, this study adopts the common effects model (CEM) as the panel regression model to be interpreted, as CEM assumes that the estimated parameters are consistent across the three countries. Furthermore, CEM disregards individual country characteristics and focuses on identifying general trends that affect the relationship between energy consumption and carbon emissions. In this context, CEM is considered suitable as this study aims to reveal common patterns in the energy-emission relationship among countries with similar energy characteristics, particularly regarding coal consumption and renewable energy use such as solar power, as shown in Equation (1).

$$Y_{it} = \alpha_0+\alpha_1 X_{1it}+\alpha_2 X_{2it}+\varepsilon_{it} \quad (1)$$

Table 1: Research variable information

Variable	Explanation
Carbon Emission (Y)	The carbon emission rate from burning coal energy, expressed as a percentage, is sourced from the BP Statistical Review of World Energy
Coal Energy Consumption (X_1)	Total energy consumption of coal for 1 year, measured in exajoules, is sourced from the BP Statistical Review of World Energy
Solar Energy Consumption (X_2)	Total energy consumption of solar energy for 1 year, measured in exajoules, is sourced from the BP Statistical Review of World Energy

Where, α represents parameters, i denotes cross-sectional, t indicates time-series, and ε is the error term.

Equation (1) represents the CEM panel regression approach, the most basic estimation method in panel data regression. Furthermore, Equation (1) forms the basis for forecasting a carbon emission control model for the upcoming period, 2024–2030.

3.2.2. Autoregressive integrated moving average (ARIMA)

The use of the ARIMA method is a primary focus in forecasting the projected consumption of coal and solar energy for the 2024–2030 period. This method was chosen for its reliability in utilizing historical data patterns to predict future trends, which is highly relevant in the context of energy consumption that exhibits seasonal characteristics and specific trends over time. In this study, historical data on coal and solar energy consumption from 2008 to 2023 will serve as the foundation for the forecasting analysis. This 16-year data range provides a robust view of consumption patterns that may influence forecast outcomes. The results from this ARIMA analysis are designed to guide predictions for carbon emissions reduction models by substituting coal energy consumption with solar energy during the 2024–2030 period. Thus, the ARIMA model will be trained to recognize these patterns, enabling it to deliver more accurate and relevant projections.

The ARIMA process in this study is conducted for each country, namely Indonesia, Australia, and China, and consists of five main steps. First, a stationarity test is performed to ensure that the data is stationary, which is a prerequisite for the ARIMA model. Second, the correlogram test is used to identify autocorrelation patterns and select initial model parameters. Third, automatic ARIMA is applied to automatically determine the best model. Next, a diagnostic test is conducted to verify the adequacy of the model by analyzing residuals. Finally, forecasting results are generated, providing future value predictions based on the validated ARIMA model.

3.2.3. Forecasting carbon emission reductions

The carbon emissions reduction forecast in this study is conducted using a projection technique that integrates two complementary analytical methods: panel regression and ARIMA models. The first step in this forecasting approach is to obtain the coefficient and constant values (parameters) from the previously analyzed panel regression model. These parameters measure the impact of the main independent variables, coal energy consumption and solar energy consumption, on carbon emissions. With these parameters, it is possible to introduce projected values for coal and solar energy consumption for the years 2024 through 2030, obtained from previous ARIMA analysis. This combined approach enables a more accurate estimation of carbon emissions reduction based on projected energy consumption variations.

The calculations are then grouped into three distinct models, each aimed at offering a different perspective on the impact of coal consumption reduction and increased solar energy use on carbon emission forecasts. The first, the pessimistic model, assumes a 10% substitution from coal to solar energy. The second, the moderate model, assumes a 20% substitution from coal to solar energy. Finally, the optimistic model assumes a 30% substitution from coal to solar energy.

The purpose of the calculations above is to analyze the impact of reducing coal energy consumption and increasing solar energy use on carbon emission forecasts. By dividing the analysis into three distinct models, it can provide various perspectives on how variations in energy substitution may influence future carbon emissions. Through this approach, it is expected to yield more accurate estimates of the potential for carbon emissions reduction, thus assisting policymakers in formulating more effective strategies to address climate change.

4. RESULTS AND DISCUSSION

4.1. Panel Regression Results

The study's results begin with a fundamental interpretation, aiming to apply a carbon emission forecasting model for the 2024–2030 period. This model is designed by substituting coal energy with solar energy, a process detailed in the previous sections. The interpretation of the CEM derived from the panel regression analysis for this study is summarized in Equation (2). This equation includes key variables that influence carbon emissions, which are essential to understanding the impact of energy consumption on climate change. By incorporating these variables, this study aligns with SDG 7, which emphasizes the importance of ensuring access to clean, affordable, and sustainable energy for all. Additionally, this analysis is directly relevant to SDG 13, which focuses on urgent action to combat climate change and its impacts.

$$Y_{it} = 0.222135^{**}+0.340471X_{1it}^{***}-0.186611X_{2it}^{**}+\varepsilon_{it} \quad (2)$$

***Significant at α=1%; **significant at α=5%

The main information from Equation (2) is that each independent variable, including coal energy consumption and solar energy consumption, has a significant impact on carbon emissions. Specifically, coal energy consumption has a positive effect, while solar energy consumption and green economic growth have negative effects.

4.1.1. The impact of coal consumption on carbon emissions

The first hypothesis in this study is confirmed, indicating that coal consumption has a significant impact on carbon emissions. Coal has a positive and significant effect on carbon emissions in Indonesia, Australia, and China, as these three countries play key roles in the global coal supply chain. Indonesia and Australia, as major coal exporters, rely heavily on coal production and exports to support their economies. The extraction, processing, and combustion of coal in these two countries result in significant carbon emissions. In Australia, despite having more advanced energy policies that promote renewable energy, the country remains one of the largest coal exporters in the world. Substantial domestic coal usage, particularly in heavy industries and power generation, continues to contribute to high carbon emissions. Similarly, in Indonesia, coal is the primary source of electricity, and coal exports are a mainstay of the national economy. This heavy reliance on coal is directly linked to a significant rise in carbon emissions, as coal is one of the most carbon-intensive fossil fuels when burned. Furthermore, any increase in coal consumption in the international market, driven by high demand from importing countries such as China, leads to a spike in carbon emissions. China, as the world's largest coal importer, uses this fuel to meet its vast energy needs. The country's manufacturing and energy sectors are heavily dependent on coal as a primary resource, which significantly increases carbon emissions. This dependency on coal in China contributes to high levels of carbon emissions, considering that coal combustion produces more carbon dioxide compared to other energy sources. The environmental impact of China's high coal consumption is considerable, contributing substantially to global climate change issues.

Thus, the interaction between coal-exporting and coal-importing countries highlights that coal consumption directly drives the increase in carbon emissions, from production in exporting countries to combustion in importing countries. This study's findings are also supported by several related studies, including Pata (2018), who found that coal energy produces 66% more carbon dioxide per unit of energy compared to gas, which is primarily composed of methane and other carbon compounds. These results are further reinforced by the findings of Kartal et al. (2024), who identified global warming as one of the most significant impacts of coal energy use due to its release of heat-trapping greenhouse gases such as carbon dioxide and methane. Additionally, Li and Cheng (2020) found that carbon emissions from coal combustion generate toxic particles containing sulfur dioxide, nitrogen oxides, lead, and other heavy metals, all of which deteriorate air quality.

4.1.2. The impact of solar energy consumption on carbon emissions

The second hypothesis in this study is confirmed, showing that solar energy consumption has a significant impact on carbon emissions. Solar energy consumption has a negative effect on carbon emissions, meaning that the more solar energy is used, the lower the carbon emissions produced. This is relevant for Indonesia and Australia, both of which are coal exporters, as well as China, the main coal importer. The shift to solar energy in these countries helps reduce reliance on coal, a non-renewable energy source with a significant impact on carbon emissions. Solar energy, as a clean and renewable energy source, produces no carbon emissions during the energy conversion process, so increasing its use directly contributes to carbon emissions reduction. In Indonesia and Australia, although both have large coal sectors, solar energy development is a strategic step toward reducing their carbon footprints. Solar energy can partially replace energy generated from coal, especially in sectors less reliant on coal. In Indonesia, solar energy use is still in its early stages, but the government has shown a commitment to increasing solar power usage to reduce coal dependence. In Australia, with its high solar potential due to intense sunlight, solar adoption has significantly contributed to lowering carbon emissions, aligning with the country's efforts to accelerate the transition to clean energy. By integrating more renewable energy, such as solar, into their national energy grids, both countries can balance their roles as coal exporters with global efforts to reduce carbon emissions. Meanwhile, in China, despite being the largest coal importer, substantial investments in solar energy have reduced the demand for coal and the associated emissions. China has become a global leader in solar panel installations, directly helping to reduce carbon emissions in the energy sector. By replacing part of its energy demand with solar power, China can significantly curb carbon emissions resulting from coal combustion, demonstrating its commitment to global carbon reduction goals.

Overall, solar energy consumption in these three countries plays an important role in lowering carbon emissions levels. As solar energy use continues to grow, these countries can slow down the pace of climate change and meet the emission reduction targets set within the SDGs. This study's findings are also supported by related research, including Saidi and Omri (2020), who found that renewable energy use is a key solution for reducing the increase in carbon emissions. Similarly, Akram et al. (2020) emphasized the need to develop alternative energy sources from non-renewable resources to slow climate change. Furthermore, a study by Nguyen and Kakinaka (2019), also found that an energy mix dominated by renewable energy will help preserve environmental quality.

4.2 ARIMA Results

4.2.1. Stationarity

To apply the ARIMA model, a stationarity test is required as a prerequisite to ensure that the data have constant mean, variance, and covariance. The Augmented Dickey-Fuller (ADF) test is used with a P-value criterion of < 0.05 to indicate stationarity at the level (I(0)), first difference (I(1)), and second difference (I(2)), as shown in Table 2.

Based on the information in Table 2, for Indonesia, variable X1 is stationary at I(1) with a P-value of 0.0074, and X2 is stationary at I(2) with a P-value of 0.0111. For Australia, variable X1 is stationary at I(1) with a p-value of 0.0048, and X2 is stationary at I(2) with a P-value of 0.0005. Finally, for China, both variables X1 and X2 are stationary at I(2) with P-values of 0.0006 and 0.0061, respectively. Based on these results, the integration order of each variable in each country can be determined as a requirement for the ARIMA modeling to be applied.

4.2.2. Correlogram

The correlogram shows the pattern of correlation between values across different time lags. In ARIMA analysis, this test is essential for determining data stationarity based on autocorrelation (ACF) and partial autocorrelation (PACF), as shown in Table 3.

Based on the information in Table 3, the ACF and PACF diagrams for each variable in each country are displayed. First, in Indonesia, the ACF for variable X1 cuts off at lag 3, while for variable X2, the cutoff occurs at lag 2. Meanwhile, the PACF for both variables X1 and X2 cuts off at lag 2. Second, in Australia, the ACF and PACF for both variables X1 and X2 cut off at lag 2. Lastly, in China, the ACF and PACF for variables X1 and X2 also cut off at lag 2.

4.2.3. Automatic ARIMA

Automatic ARIMA is a method used to automatically identify the best ARIMA model for a time series dataset. The ARIMA model itself is a forecasting technique that combines autoregressive (AR), differencing (I), and moving average (MA) components to address trends, cycles, and seasonal patterns in time series data. At this stage, the AR and MA components for each variable in each country will be determined, as shown in Table 4.

Based on the results of the automatic ARIMA test in Table 4, it can be seen that in Indonesia, variable X1 has an AR component of 0 and an MA component of 2, while variable X2 has both AR and MA components of 1. In Australia, variable X1 shows an AR component of 2 and an MA component of 1, while variable X2 has an AR component of 0 and an MA component of 1. Meanwhile, in China, variable X1 has an AR component of 1 and an MA component of 0, differing from variable X2, which has an AR component of 0 and an MA component of 1.

4.2.4. Diagnostic

Diagnostic testing in the ARIMA method is crucial to ensure that the resulting model meets the necessary assumptions for accurate and reliable forecasting, as shown in Table 5.

According to the diagnostic test results presented in Table 5, the residual correlogram for all variables in each analyzed country is randomly distributed. The ACF and PACF values, which do not exceed the established limits, have validated the previous test series. Thus, this condition indicates that the recommended model specification falls within a good category.

4.2.5. Forecasting

The forecasting results in this study involved several important steps, starting with the stationarity test aimed at ensuring that the data does not exhibit significant trends or seasonality, followed by correlogram analysis to help determine the appropriate model parameters. Furthermore, the use of Automatic ARIMA allows for the automatic selection of the optimal model based on information criteria. The results of the forecasting tests provide valuable insights into the patterns and trends in the data, as well as the accuracy of the predictions, as shown in Table 6.

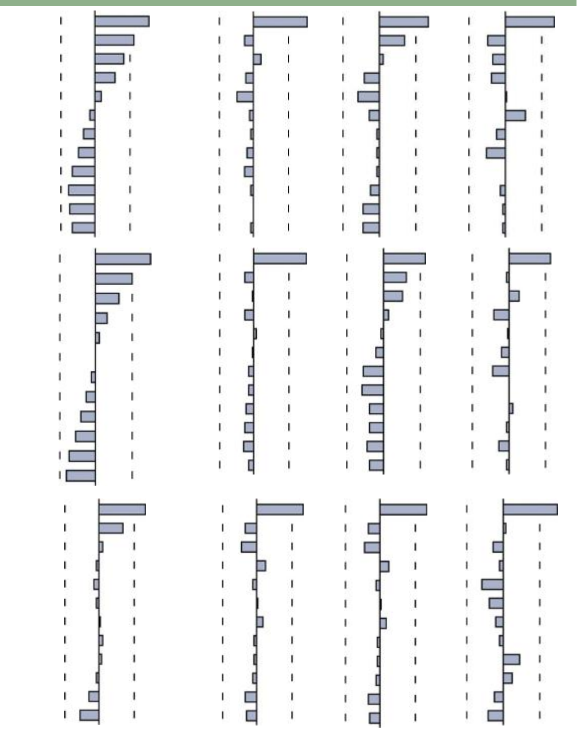
Based on the information in Table 6, the results of the forecasting tests conducted across all analyzed countries indicate that the forecast for coal consumption (X1F) tends to follow a

Table 2: Stationarity results

Country	Variable					
	X1			X2		
	I (0)	I (1)	I (2)	I (0)	I (1)	I (2)
Indonesia	0.9874	0.0074***	-	0.7414	0.7033	0.0111**
Australia	0.2379	0.0048***	-	0.9969	0.2709	0.0005***
China	0.3451	0.1514	0.0006***	0.9775	0.6726	0.0061***

Table 3: Correlogram results

Country	Variable			
	X1		X2	
	ACF	PACF	ACF	PACF
Indonesia				
Australia				
China				



ACF: Autocorrelation function, PACF: Partial autocorrelation function

Table 4: Automatic ARIMA results

Country	Variable	
	X1	X2
Indonesia	(0,2)(0,0)	(1,1)(0,0)
Australia	(2,1)(0,0)	(0,1)(0,0)
China	(1,0)(0,0)	(0,1)(0,0)

quadratic pattern. This suggests that the relationship between coal consumption and time is not only linear but also involves more complex changes. The quadratic curve can be interpreted to mean that, in the early period, coal consumption may increase rapidly; however, over time, the growth rate may decline or even reverse, reflecting the influence of factors such as environmental policies, energy transitions, or changes in societal preferences. In contrast, for the forecast of solar energy consumption (X2F), the identified pattern is exponential. This indicates that solar energy consumption is increasing very rapidly over time. The exponential curve reflects the significant growth potential in the use of solar energy, especially in a global context that increasingly supports the transition to sustainable energy.

4.3. Carbon Emission Reduction Model Results

4.3.1. Pessimistic model

Carbon emission forecasting in the pessimistic model is conducted by reducing coal energy consumption by 10%. This reduction is then substituted with solar energy. Based on the assumptions outlined in this study's pessimistic model, the projected average conditions for reducing carbon emissions in Indonesia, Australia, and China are determined for the period 2024–2030 (Figure 1).

Table 5: Diagnostic results

Country	Variable			
	X1		X2	
	ACF	PACF	ACF	PACF
Indonesia				
Australia				
China				

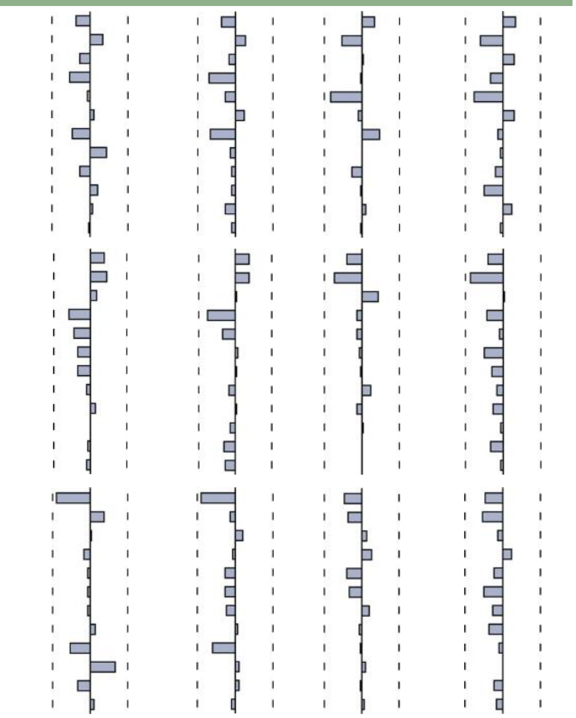


Figure 1: Forecasted carbon emission reduction in the pessimistic model

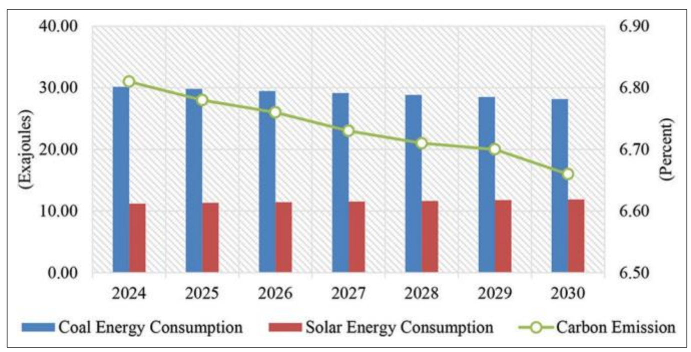
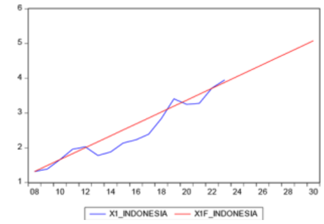
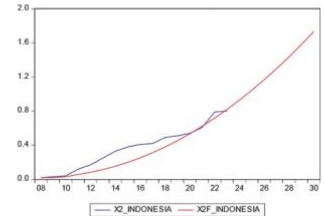
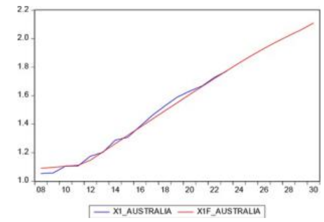
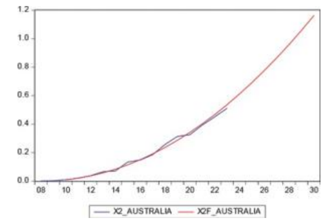
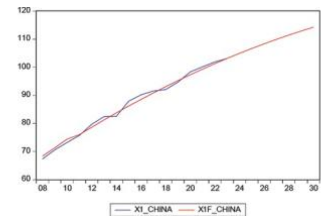
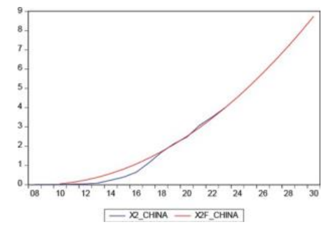


Figure 1 illustrates a 10% annual reduction in coal energy consumption, replaced by solar energy. This reduction is a primary factor driving the downward trend in carbon emission growth each year during the estimation period. According to the pessimistic model, coal consumption is projected to significantly decrease from 30.13 exajoules in 2024 to 28.16 exajoules in 2030. Although coal consumption declines, solar energy consumption only experiences a modest increase from 11.21 exajoules in 2024 to 11.87 exajoules in 2030. This suggests that while there is a shift towards renewable energy, the transition pace still requires further attention.

The gradual reduction in carbon emissions also follows a stepwise pattern, with projected decreases from 6.81% in 2024 to 6.66% in 2030. Despite this reduction, the annual average growth rate of carbon emissions from 2023 to 2030 across all countries

Table 6: Forecasting results

Country	Variable	
	X1	X2
Indonesia		
Australia		
China		

analyzed in this study remains at 6.73%/year. The average coal energy consumption over this period reaches 29.14 exajoules per year, while average solar energy consumption is only 11.60 exajoules per year. This data underscores that renewable energy consumption, particularly solar energy, is still in its early stages of development and needs further enhancement.

The trends observed in this pessimistic model reveal that energy consumption through 2030 remains predominantly coal-based, with coal contributing 71.54% to the energy mix, while solar energy contributes only 28.46%. This indicates that solar energy usage in this pessimistic model remains suboptimal despite efforts to shift energy consumption towards cleaner sources. The heavy reliance on coal could hinder more aggressive and sustainable carbon emission reduction targets.

In the context of SDG 7, this transition appears minimal. Although renewable energy usage has increased, the dependency on coal remains significant and may impede progress towards clean and affordable energy access for all. This situation is closely related to SDG 13, which stresses the need for urgent action to address climate change. The limited reduction in carbon emissions suggests that more aggressive and planned measures are essential for effectively tackling climate change. Efforts to increase the proportion of renewable energy, including solar energy, in the national energy mix are critical for minimizing environmental impacts and achieving long-term goals in carbon emission reduction.

4.3.2. Moderate model

Carbon emission forecasting in the moderate model involves reducing coal energy consumption by 20% and substituting it with solar energy. Based on the assumptions outlined in this study's moderate model, the projected average conditions for reducing carbon emissions in Indonesia, Australia, and China are determined for 2024–2030 (Figure 2).

Figure 2 illustrates a 20% annual reduction in coal energy consumption, replaced by solar energy. Consequently, the growth trend of carbon emissions declines each year over the estimated period. In the moderate model, coal consumption decreases more rapidly, from 26.78 exajoules in 2024 to 24.74 exajoules in 2030. At the same time, solar energy consumption shows a significant increase, from 17.30 exajoules in 2024 to 18.20 exajoules in 2030. The reduction in carbon emissions is also evident, with emissions decreasing from 4.22% in 2024 to 4.01% in 2030.

Additionally, the average carbon emission growth rate for the 2024–2030 period across all countries analyzed in this study is recorded at 4.16%/year. This figure represents a significant reduction of 2.57% compared to the pessimistic model. In this context, the average coal energy consumption reaches 25.76 exajoules per year, decreasing by 3.38 exajoules compared to the pessimistic model. On the other hand, average solar energy consumption increases to 17.82 exajoules per year, reflecting a rise of 6.22 exajoules from the pessimistic model.

The moderate model highlights that, by 2030, the energy mix will still be dominated by coal consumption. Coal's contribution remains significant at 59.11%, despite a 12.43% reduction compared to the pessimistic model. Conversely, solar energy's contribution reaches 40.89%, reflecting an identical 12.43% increase from the pessimistic model. This indicates that the increased use of solar energy has contributed to a reduction in

Figure 2: Forecasted carbon emission reduction in the moderate model

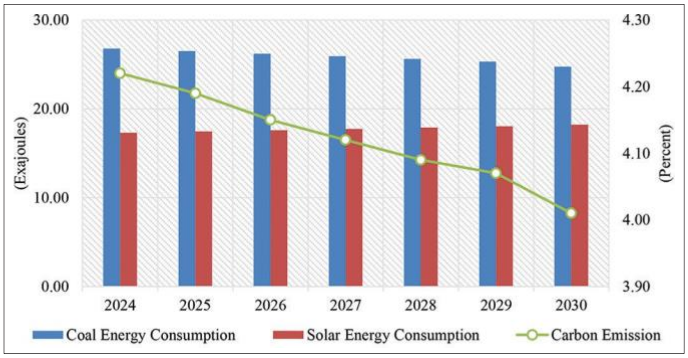
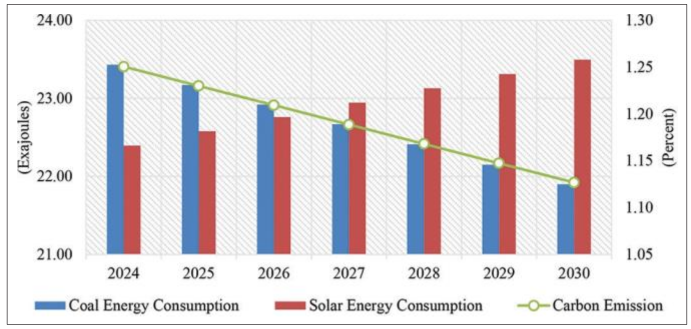


Figure 3: Forecasted carbon emission reduction in the optimistic model



carbon emission growth in the moderate model compared to the pessimistic model.

It is important to note that while the moderate model shows significant progress in carbon emission reduction, challenges remain. One of the most notable achievements of this model is the clearer shift toward renewable energy use, particularly solar energy. Thus, this model aligns more closely with SDG 7, which focuses on improving access to sustainable and environmentally friendly energy. However, despite the rise in renewable energy use, a key challenge in the moderate model is the relatively high level of carbon emissions compared to the desired targets.

The increased contribution of solar energy in the moderate model indeed demonstrates progress in the transition to clean energy, but the still-high carbon emissions indicate that this shift is insufficient to meet SDG 13, which targets significant carbon emission reductions to combat climate change. This suggests that although positive steps have been made toward decarbonization, these efforts must be intensified for a more aggressive transition with a greater impact. Without more decisive policies and accelerated adoption of renewable energy, it will be challenging for the countries analyzed to meet global climate commitments. In other words, although progress has been made in renewable energy use, the continued significant reliance on fossil fuels, particularly coal, indicates a need for further efforts. Coal, as one of the most polluting energy sources, still holds a dominant role in the energy mix of these countries.

4.3.3. Optimistic model

Carbon emission forecasting in the optimistic model is conducted by reducing coal energy consumption by 30%. This reduction is then replaced by solar energy. Based on the assumptions outlined in this study's optimistic model, the projected average conditions for reducing carbon emissions in Indonesia, Australia, and China are determined for 2024–2030 (Figure 3).

Figure 3 illustrates a 30% annual reduction in coal energy consumption, replaced by solar energy, resulting in a yearly decrease in carbon emission growth throughout the estimated period. In the optimistic model, coal consumption sees a sharp decline from 23.43 exajoules in 2024 to 21.90 exajoules in 2030, alongside a significant increase in solar energy consumption from 22.39 exajoules in 2024 to 23.49 exajoules in 2030. Carbon emissions drop substantially, from 1.25% in 2024 to 1.13% in 2030. Additionally, the average annual carbon emission growth rate for the 2024–2030 period across all countries analyzed is 1.18%, representing a reduction of 5.55% compared to the pessimistic model and 2.98% compared to the moderate model. The average coal energy consumption is 22.54 exajoules per year, a decrease of 6.60 exajoules from the pessimistic model and 3.22 exajoules from the moderate model. Meanwhile, average solar energy consumption is 23.04 exajoules per year, an increase of 11.44 exajoules compared to the pessimistic model and 5.22 exajoules compared to the moderate model.

In the optimistic model, the energy mix is dominated by coal consumption only until 2026. From 2027 to 2030, solar energy becomes the dominant source. This indicates that coal's contribution is 49.45%, a reduction of 22.09% from the pessimistic model and 9.66% from the moderate model. Conversely, solar energy's contribution reaches 50.55%, reflecting an identical 22.09% increase from the pessimistic model and 9.66% from the moderate model. This demonstrates that the optimistic model has reached an optimal level in developing and utilizing solar energy to support economic activities, achieving a higher reduction in carbon emissions compared to the previous models.

The optimistic model is the most supportive of achieving SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. In this model, there is a sharp reduction in fossil fuel use, particularly coal, replaced by renewable energy such as solar. This shift signifies a substantial transition from dependence on environmentally harmful energy sources to cleaner and more eco-friendly energy. This transition allows countries like Indonesia, Australia, and China not only to reduce their carbon footprints but also to accelerate the development of renewable energy infrastructure. This aligns with global efforts to mitigate the negative impacts of fossil fuel use, such as air pollution and ecosystem degradation.

Furthermore, the optimistic model strongly supports achieving SDG 13, which calls for urgent action to combat climate change and its impacts. The drastic reduction in carbon emissions in this model reflects a strong commitment to climate change mitigation, with more ambitious emission reduction measures compared to the moderate and pessimistic models. This significant reduction in carbon emissions is essential not only for meeting national climate targets but also for contributing to the global goal of limiting global temperature rise to below 2 degrees Celsius, in line with the Paris Agreement.

Additionally, the substantial shift toward renewable energy in the optimistic model reflects robust support for long-term sustainability, indicating that the involved countries are building a cleaner energy future. Higher renewable energy use will help prevent future emission growth risks and reduce dependence on finite and increasingly costly fossil fuels. Thus, this optimistic model not only creates an immediate positive impact in reducing carbon emissions but also establishes a sustainable path to achieving more ambitious long-term climate goals.

5. CONCLUSION

This study concludes that solar energy consumption plays a key role in reducing carbon emissions, while coal-based energy consumption significantly contributes to carbon emission increases. Among the pessimistic, moderate, and optimistic models, the optimistic model proves to be the most effective approach for facilitating the dominance of solar energy in the national energy mix. With a more aggressive substitution of coal energy by solar energy, carbon emission growth rates can be drastically suppressed. These findings are highly relevant in the context of achieving SDGs 7 and 13. The optimistic model supports SDG 7, which focuses on access to clean and affordable energy, by facilitating a significant shift toward renewable energy. Simultaneously, greater carbon emission reductions in the optimistic model also support SDG 13, which calls for urgent action to combat climate change. Thus, this study affirms that a more ambitious transition toward renewable energy, especially solar energy, is crucial for achieving these SDG targets and for global climate change mitigation.

The policy implications of this study’s findings are highly significant for supporting the achievement of SDGs 7 and 13 in Indonesia, Australia, and China. To achieve SDG 7, which underscores the importance of access to affordable and clean energy, governments in these three countries need to develop policies that encourage large-scale investment in renewable energy infrastructure, with a primary focus on solar energy. This approach requires enhanced incentives for the development and adoption of solar technology, including subsidies, tax reductions, and technical support for companies investing in renewable energy projects. Additionally, the creation of a clear and transparent regulatory framework would be highly beneficial in facilitating the transition from coal to solar energy, thereby providing greater certainty for investors and industry stakeholders.

Additionally, reducing coal subsidies is crucial for accelerating the transition to solar energy. In Indonesia, this policy could be implemented by reallocating coal subsidies to support solar energy projects in remote areas where electricity access remains limited. Australia and China could also consider restructuring existing subsidies to boost solar energy’s competitiveness. By shifting support from coal to solar energy, these three countries can reduce their reliance on coal, a source that contributes to carbon emissions and climate change.

From the perspective of SDG 13, which focuses on climate action, stronger and more sustainable policies are needed to significantly reduce carbon emissions. This includes setting more ambitious emission reduction targets in line with international climate commitments. In Indonesia, Australia, and China, concrete steps such as implementing a carbon tax can serve as an effective strategy to encourage industrial sectors to transition to more environmentally friendly energy sources, such as solar energy. Such a tax would create financial incentives for companies to lower their emissions, drive innovation in solar energy technology, and contribute to overall emission reduction targets.

Finally, strengthening international cooperation on renewable energy technology, particularly solar energy, is a crucial component in supporting global carbon reduction efforts. Through international partnerships, these three countries can share knowledge, technology, and best practices in solar energy development. This cooperation would not only accelerate the adoption of solar technology in each country but also bolster their standing in global climate discussions. By integrating these policies, Indonesia, Australia, and China can effectively contribute to achieving SDGs 7 and 13 while fostering a more sustainable and environmentally friendly future.

However, this study has some limitations that should be noted. First, the model used in this study assumes of linearity in the transition from coal to solar energy, which may not fully capture the complex dynamics of the global energy market. Second, this study only analyzes three countries, namely Indonesia, Australia, and China which, although representing some major trends in energy consumption, do not fully reflect global conditions. Therefore, these results may not be entirely generalizable to other countries with different economic structures and energy policies. Another limitation is the availability of historical data and limited long-term projections. In some cases, significant technological or policy changes in the energy sector could alter the trends projected in this study. Hence, further research is needed to integrate more dynamic and adaptive policy scenarios and to include more countries to provide a more comprehensive view of the global energy transition and its impact on carbon emissions. Overall, despite these limitations, this study provides strong evidence that the transition to renewable energy, particularly solar energy, is a crucial step to achieving significant carbon emission reductions and supporting global efforts in achieving SDGs.

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