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Renewable Energy, Trade Openness, and CO_2 Emissions in G20 Economies: Evidence from Dynamic Panel GMM

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Abstract

The widening gap between domestic soybean demand and local production has raised concerns over the economic sustainability of soybean farming in Indonesia. This study examines the determinants of production cost, cost efficiency, and cost inefficiency in soybean farming in Central Java Province, focusing on Grobogan and Blora Regencies. Using farm-level data from 200 soybean farmers, the study applies a stochastic cost frontier model and a second-stage regression of predicted cost inefficiency. The results show that output and labor wage significantly increase total production cost, while fertilizer price is weakly significant and seed price is not statistically significant. The mean cost efficiency score is 0.8904, indicating that farmers could reduce production costs by approximately 10.96 percent while maintaining the same output and input-price conditions. The second-stage results show that planting frequency and irrigation access are significantly associated with lower cost inefficiency, while age, farming experience, and education are not statistically significant. These findings suggest that cost inefficiency in soybean farming is more closely related to production routines and water access than to general farmer characteristics. Policy support should therefore focus on improving input timing, labor management, irrigation access, and repeated production learning among smallholder soybean farmers.

Keywords: Renewable Energy, Trade Openness, CO_2 Emissions, Panel GMM

JEL Classification: Q53, Q54, Q56

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1. INTRODUCTION

The environmental issue that is currently of concern to the world is global warming. Increasing climate change is caused by an increase in greenhouse gas emissions In addition, economic growth factors are the cause of increasing total carbon emissions, giving rise to global warming (Acheampong, 2018). Since the industrial revolution, the world has experienced rapid development through technological advances that have encouraged economic and social development and growth where the massive use of energy has caused greenhouse gas emissions to increase, especially carbon dioxide (CO2) emissions. Environmental pollution and economic growth are related to each other, every time environmental pollution increases, economic productivity increases (Hussein et al., 2023). Using of conventional energy is an important component and engine of economic growth (Warsame, 2022). Additionally, anthropogenic greenhouse gas emissions, generated by economic practices and activities such as the use of fossil fuels and industrial waste disposal, are estimated to have caused a 1°C increase in global warming above pre-industrial levels (Koshta et al., 2021).

Specifically, carbon dioxide emissions have increased drastically, especially after the industrial revolution as a result of globalization (Aslam et al., 2022). A number of countries agreed in 2015 to sign the Paris Climate Conference. The conference is a global action plan in which 196 participating countries contribute to reducing global warming by trying to pressure countries to prevent the earth's temperature from exceeding the threshold of 2°C. Therefore, participating countries are asked to reduce national emission levels so that the environment can continue to be protected. Data shows that global energy demand has increased every year by 2.5% since the 1850s, but until now there has been no relevant evidence to suggest a decline in the next few years (Sorrell, 2015). Global carbon emissions have increased from 35.38 Gt in 2016, rising to 36.81 Gt in 2019. Although in 2020 there was a decline caused by the Covid-19 pandemic, resulting in a decline in economic activity.

Responding to this issue, the G20 consists of 20 countries (1 is the European Union) where G20 member countries represent 80% of global investment, 60% of the world's population, 75% of global trade and 85% of the world economy. The G20 is also a global emitter responsible for more than 80% of greenhouse gas emissions. This is due to the massive use of energy in economic activities as an effort to increase economic growth. According to reportsBrown to Green stated that in 2018, there was an increase in carbon dioxide emissions by 1.8% according to energy utilization in G20 countries. Conventional energy sources are very limited in number, but their energy availability is very necessary to increase productivity and encourage economic growth, even though they have negative externalities on the environment (Zhao et al., 2022). The effect of energy on economic growth is still inconclusive. There is an energy-led economic growth hypothesis where high economic growth plays a role in energy consumption (Mohsin et al., 2021). According to Magazzino & Brady (2018) there is an inverse relationship when using renewable energy, where the use of renewable energy has a negative relationship to economic growth. So the two studies still have contradictions in the research results.

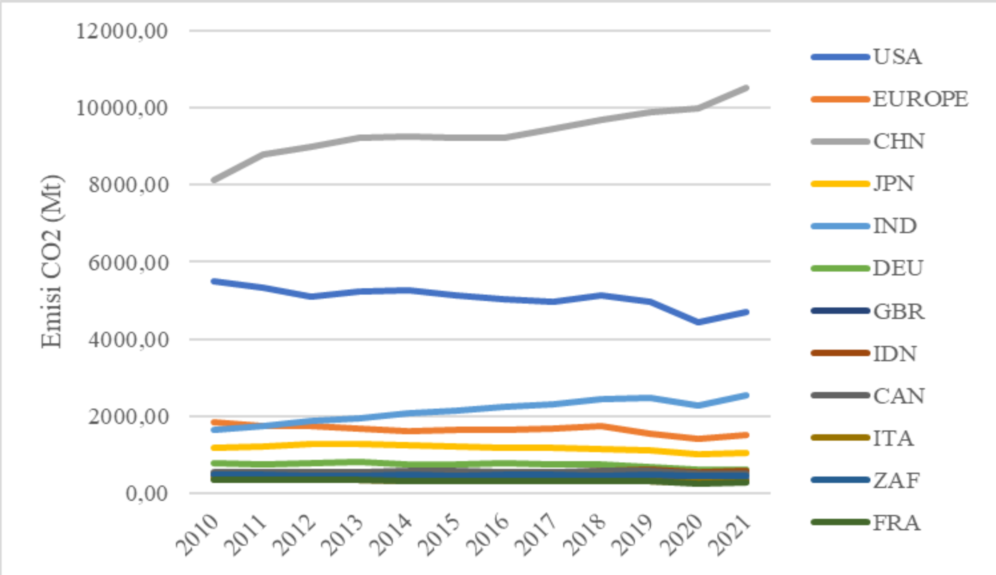

Figure 1. Carbon Dioxide Emissions from G20 Countries, 2010-2021
Notes: The data contain from South Africa (ZAF), United States (USA), Saudi Arabia (SAU), Argentina (ARG), Australia (AUS), Brazil (BRA), China (CHN), England (GBR), India (IND), Indonesia (IDN), Italy (ITA), Japan (JPN), Germany (DEU), Canada (CAN), South Korea (KOR), Mexico (MEX), Franch (FRA), Russia (RUS), Turkye (TUR) and Uni Eropa. Source: World Indicator Development 2022.

Figure 1 shows the movement of carbon dioxide emissions pollution in the G20 countries in 2010-2021. An extreme increase in carbon dioxide emissions occurred in China at a level that exceeds the carbon dioxide emissions of the United States and European Union countries. In the graph above, it can be seen that carbon dioxide emissions have generally increased significantly in all countries except the United States and Europe, where the trend has tended to decrease in recent years. In order to carry out development and accelerate economic growth, this is often the reason why a country ignores environmental quality. Economic development by encouraging economic growth is closely related to the exploitation of natural resources and the environment (Zhu et al., 2019). Research from Dong et al., (2018) using the ARDL method and Granger causality shows thatGross Domestic Product has a positive effect on carbon dioxide emissions in the long term. Other research from Hasnisah et al., (2019) strengthens previous research and states that with different methods whereGross Domestic Product has a positive effect on carbon dioxide emissions. This shows that the environment is used as 1) provider of facilities 2) provider of raw materials 3) recipient of residue (waste). Therefore, the environment is capital and an important part of economic activities. However, the use of fossil energy resources is a major contributor to global climate change. Climate change is not only caused by natural activities, but also caused by human activities such as urbanization, deforestation, transportation, industrialization and household activities, causing an increase in the greenhouse effect in the last few decades.

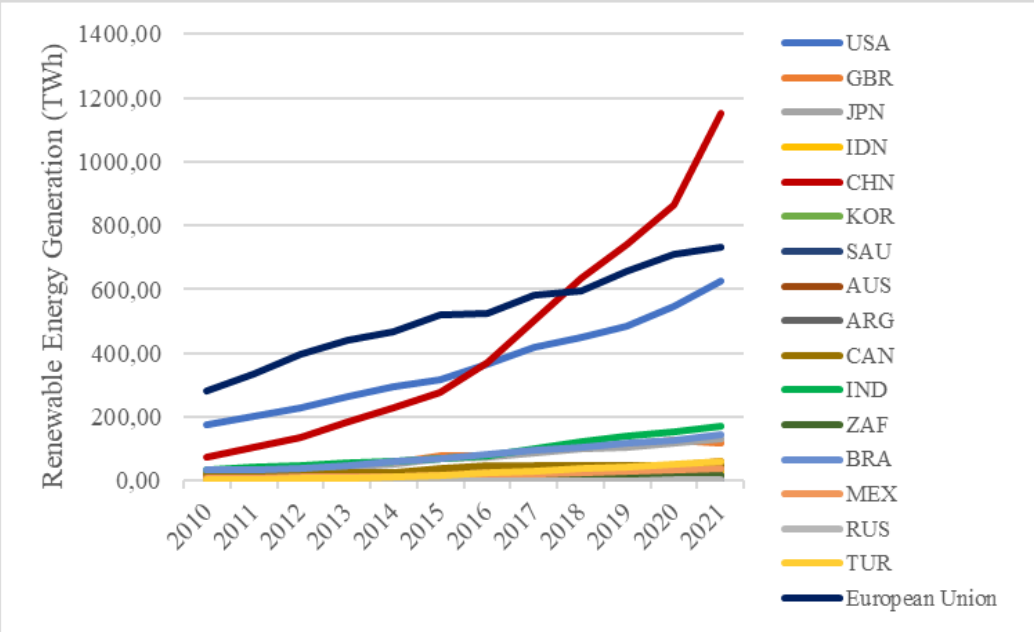

Figure 2. Renewable Energy (TWh) of G20 Countries, 2010-2021

Notes: The data contain from South Africa (ZAF), United States (USA), Saudi Arabia (SAU), Argentina (ARG), Australia (AUS), Brazil (BRA), China (CHN), England (GBR), India (IND), Indonesia (IDN), Italy (ITA), Japan (JPN), Germany (DEU), Canada (CAN), South Korea (KOR), Mexico (MEX), Franch (FRA), Russia (RUS), Turkye (TUR) and Uni Eropa. Source: World Indicator Development 2022.

Figure 2 shows the development of gross renewable energy generation sourced from wind, geothermal, solar, biomass and recycled waste (excluding hydroelectric power plants) calculated in Terawatt-Hour (TWh) units in G20 member countries. Based on this figure, it can be seen that the highest development of renewable energy generation is China, the United States and the European Union, which continues to experience significant increases from year to year. Meanwhile, other member countries have lower total renewable energy generation but still experience an increase every year, which is the impact of the Paris Climate Agreement to achieve targets. Net Zero Emission in this century (Obobisa, 2022). to achieve this target, most countries make the development of renewable energy one of the main routes. Countries that have a high total renewable energy generation value are countries with advanced economies. As written in the reportInternational Energy Agency (IEA) shows that China accounted for 40% of the global increase in renewable energy production, including the construction of wind turbines in 2015 and that by 2020 renewable power generation will be increased by almost 200 GW, accounting for approximately 90% of all installed capacity in world . The United States continues to contribute to developing renewable energy, thus showing an increasing trend (Gaies et al., 2022). In addition, countries in the European Union are starting to gradually abandon coal as an energy source and develop production with environmentally friendly and sustainable renewable energy . So that European Union member countries focus on renewable energy in running a green economy (Grodzicki & Jankiewicz, 2022).

Renewable energy is generally viewed as a crucial tool for reducing carbon dioxide emissions because it can replace fossil fuels in production and consumption. Most studies have found that increased renewable energy consumption is associated with reduced CO_2 emissions. However, this relationship is not always linear and consistent across countries. Some studies have found threshold effects (Koc & Bulus, 2020), non-linear relationships (Ben Jebli et al., 2016), and weaker long-term effects compared to short-term effects (Q. Wang et al., 2023). These differences may be due to variations in the energy mix structure (Mata et al., 2024), the level of technological development, green investment capacity, and a country's dependence on fossil fuels (Nguyen, 2026). On the other hand, the effect of trade openness on CO_2 emissions remains mixed. Trade openness can reduce emissions through the transfer of clean technology, increased production efficiency, and access to more environmentally friendly capital goods (Shahbaz et al., 2017). However, trade can also increase emissions through expanding production activities, increasing energy consumption, exploiting natural resources, and increasing cross-border transportation activities (Ahmed et al., 2016). Furthermore, Granger causality findings indicate that trade and renewable energy often influence CO_2 emissions, but inverse and reciprocal relationships are also found (S. Zhang et al., 2017). This suggests that the relationship between renewable energy, trade openness, and carbon emissions is dynamic and strongly influenced by the economic characteristics and environmental policies of each country.

Studies on the relationship between renewable energy and CO_2 emissions are growing as global attention grows on the energy transition and efforts to mitigate the impacts of climate change. The primary transmission channel between renewable energy and CO_2 emissions occurs through the substitution effect in the energy mix (Koc & Bulus, 2020; Ben Jebli et al., 2016). Increasing the use of renewable energy, such as solar, wind, hydro, biomass, and geothermal, can reduce dependence on coal, oil, and natural gas. When renewable energy replaces fossil fuels in electricity production, industrial activities, transportation, and household consumption, the carbon intensity of economic activity decreases (Destek & Sinha, 2020). Therefore, shifting the composition of energy use to a more environmentally friendly one is the primary mechanism linking the increase in renewable energy to reduced CO_2 emissions. This mechanism also works through increased efficiency and modernization of production technology. Renewable energy development is generally accompanied by investments in low-carbon technologies, energy infrastructure upgrades, and improvements in energy efficiency. The use of cleaner technologies allows a country to produce economic output with lower emissions (Dogan & Seker, 2016). Therefore, renewable energy not only reduces the direct use of fossil fuels but also drives changes in technology and production processes toward a lower-carbon-intensive economic system.

Various cross-country studies and panel data studies generally find that renewable energy consumption is negatively related to CO_2 emissions (Koc & Bulus, 2020; Wang et al., 2023; Mata et al., 2024). These findings suggest that the greater the contribution of renewable energy to total energy consumption or production, the lower the resulting carbon emissions. However, the magnitude of the emission reduction effect can vary across countries. In countries with a still-dominant proportion of fossil fuels, small increases in renewable energy may not be enough to significantly reduce emissions (Dogan & Seker, 2016). Conversely, in countries with established clean energy infrastructure and robust energy transition policies, increases in renewable energy can result in larger emission reductions (Vo et al., 2020). Furthermore, the relationship between renewable energy and CO_2 emissions is not always linear or constant. The impact of renewable energy may depend on reaching a certain level or threshold before it can have a significant impact on emissions. In the early stages of the energy transition, infrastructure development, equipment production, and the integration of renewable energy technologies may still require fossil fuels, so the benefits of emission reductions may not be immediately visible (Q. Wang et al., 2023). The effect may also be weaker when increased renewable energy merely increases energy supply without actually replacing fossil fuel consumption. Therefore, the effectiveness of renewable energy transmission channels on CO_2 emissions is strongly influenced by the structure of the energy mix, income levels, technological capacity, institutional quality, environmental policies, and dependence on fossil fuels (Nguyen, 2026). Renewable energy will have a stronger emission reduction impact if its increase is truly accompanied by a cessation or reduction in fossil fuel use. Conversely, if renewable energy only serves as a supplement to growing energy needs, its impact on emission reductions may be limited.

In addition to changes in the energy mix, CO_2 emissions are also influenced by trade openness, which alters a country's scale of production, specialization patterns, technology use, and economic structure. Unlike renewable energy, which generally has a negative impact on emissions, the transmission of trade openness to environmental quality tends to be more complex. Its impact can increase or decrease emissions, depending on the relative strength of scale effects, composition effects, and technical effects arising from international trade activities (Dou et al., 2020). Initially, increased trade openness can drive emissions up through scale effects. Access to international markets expands demand, increases production, expands industrial activity, and increases energy use. If additional energy needs are still met by coal, oil, and gas, trade expansion will increase fossil fuel consumption and CO_2 emissions (Ho & Iyke, 2019). Furthermore, trade can create composition effects when a country shifts its resources to sectors where it has a comparative advantage. If such specialization occurs in heavy manufacturing, mining, or energy-intensive sectors, trade openness will worsen environmental quality (Bakri et al., 2025).

Trade openness also indirectly affects emissions through changes in energy intensity, energy consumption structure, and economic transformation. Increased imports of capital goods and clean technologies can reduce the energy required to produce each unit of output. Conversely, growing exports of raw commodities or energy-intensive manufactured products can increase dependence on fossil fuels. Therefore, the direction and magnitude of the effect of trade openness on CO_2 emissions are not uniform, but are determined by the production structure, trade composition, energy mix, income level, technological capacity, and the strength of environmental policies in each country (Dou et al., 2023). Based on these findings, the relationship between renewable energy, trade openness, and CO_2 emissions shows a complex pattern and has not yet yielded a unified conclusion. Renewable energy generally contributes to emission reductions through fossil fuel substitution and improvements in technological efficiency, while trade openness can increase or decrease emissions through scale, composition, and technical effects. Differences in previous research indicate that the influence of these two variables is highly dependent on each country's structural characteristics, level of development, energy mix, technological capacity, and the quality of environmental policies. Therefore, this study analyzes the impact of renewable energy and trade openness on CO_2 emissions, taking into account the heterogeneity between EU and non-EU countries within the G20. This approach is expected to provide a more comprehensive understanding of the differences in transmission channels and the effectiveness of energy and trade policies in supporting carbon emission reductions.

However, after reaching a certain level of openness and development, trade can reduce emissions through technical effects and technological spillovers. Integration into global markets allows countries to gain access to more efficient machinery, clean energy technologies, production know-how, and higher environmental standards (Q. Wang et al., 2024). International competition can also encourage companies to improve energy efficiency and adopt low-carbon production methods. Under these conditions, the benefits of technology and productivity gains can offset or even exceed the increase in emissions resulting from expanding production scales. The emission-reducing effects tend to be stronger in developed or high-income countries because these countries have better technological capacity, environmental regulations, institutional quality, and financing capabilities. Conversely, in some developing countries, trade openness can increase emissions through the mechanism of*pollution haven* (Khan & Safdar, 2023). Relatively weak environmental regulations and lower compliance costs can attract the migration of pollution-intensive industries from countries with stricter environmental regulations. As a result, trade actually reinforces specialization in carbon-intensive sectors and increases domestic emissions (Sulaiman et al., 2023). Based on these inconsistencies, there remains a research gap regarding how renewable energy and trade openness simultaneously affect CO_2 emissions in groups of countries with different economic characteristics and energy systems. Most previous studies analyze this relationship in aggregate, thus failing to fully capture cross-country heterogeneity. Therefore, the novelty of this study lies in the use of a dynamic panel model to compare the effects of renewable energy and trade openness on CO_2 emissions between EU and non-EU countries within the G20 group. This separation allows the study to identify whether the effectiveness of renewable energy and the environmental consequences of trade openness differ between countries relatively advanced in the energy transition and those still dependent on fossil fuels.

2. RESEARCH METHOD

This study uses a panel data approach because the data analyzed encompasses both inter-country and inter-temporal dimensions. The use of panel data allows the study to observe changes in CO_2 emissions, renewable energy consumption, and trade openness in each country over the observation period while simultaneously comparing differences in characteristics between countries. This approach is relevant because the relationship between renewable energy, trade openness, and CO_2 emissions is not always uniform but can vary based on each country's income level, economic structure, energy mix, technological capacity, and environmental policies. To explore the relationship between renewable energy, trade openness, and CO_2 emissions, this study combines time-series and cross-section data. The time-series data covers the period 2010–2021, and the cross-section covers 46 countries, members of the G-20. The study presents panel data results from the CEM, FEM, and REM models. The study also applies the GMM method due to its large period and cross-section. Furthermore, the application of GMM is used to eliminate endogeneity problems in the variables renewable energy, GDP, urbanization, energy consumption, trade openness, and FDI. According to Szetela et al., (2022) panel GMM estimation is more beneficial in dealing with bias problems in the model. The equation for the model as follows:

$$\mathrm{lnco2}_{it} = \beta_0 + \beta_1 \mathrm{lnco2}_{it-1} + \beta_2 \mathrm{lngdp}_{it} + \beta_3 \mathrm{lnre}_{it} + \beta_4 \mathrm{lnce}_{it} + \beta_5 \mathrm{lnup}_{it} + \beta_6 \mathrm{lntrd}_{it} + \beta_7 \mathrm{FDI}_{it} + \varepsilon_{it}$$

Where the notations i and t are for the time-series and cross section of the model.β_0 is a constant; β_1-b_7 is the coefficient value of the independent variable in the model. Lnco2 is CO2 emissions, lngdp is gross domestic product, lnre is renewable energy, lnce is conventional energy consumption, lnup is the number of urban residents, lntrd is trade openness, and fdi is foreign direct investment. The ln notation indicates that the data is in logarithmic form. e is the disturbance error value. Data sourced from the World Bank and British Proteleum. The research developed three models: the full model for all 46 countries as members of the G-20, model 2 for non-EU countries, and model 3 for the EU countries as members of the G-20. The main advantage of using panel data is its ability to control for individual heterogeneity that cannot be observed directly but remains relatively constant over time. Panel data also provides a larger number of observations, increases data variation, reduces collinearity problems between variables, and produces more efficient estimates than using time series data or cross-regional data separately. This approach also allows research to capture possible differences in the effects of renewable energy and trade openness on CO_2 emissions across country groups, including effects that are non-linear, dependent on certain thresholds, or differ according to economic development characteristics (Koc & Bulus, 2020). Next, the study applied the Generalized Method of Moments (GMM) to dynamic panel data. The use of GMM is necessary because CO_2 emissions tend to be persistent, so that emission levels in previous periods can influence emissions in the current period. Furthermore, there is a potential for a two-way causal relationship between CO_2 emissions, renewable energy, trade openness, economic growth, and energy consumption. For example, increasing renewable energy can reduce emissions, but pressure to reduce emissions can also encourage renewable energy development. This condition can give rise to endogeneity problems, causing conventional panel estimators to be biased and inconsistent (Zafar et al., 2019). The panel GMM method can overcome endogeneity by using lagged values of variables as internal instruments, while controlling for unobserved individual country effects. This approach is also suitable for analyzing dynamic relationships and estimating the short- and long-term impacts of renewable energy and trade openness on CO_2 emissions. Thus, the use of panel GMM is expected to produce more consistent estimates and be able to describe the heterogeneity and dynamics of the relationships between variables more comprehensively (Baltagi, 2005).

3. RESULTS AND DISCUSSIONS

The estimation results show differences in the direction and significance level of the coefficients between the Common Effect Model (CEM), Fixed Effect Model (FEM), Random Effect Model (REM), and Generalized Method of Moments (GMM). These differences are particularly evident in the variables GDP, urban population, and trade openness. This indicates that ignoring cross-country heterogeneity, emission dynamics, and potential endogeneity can produce different estimates. Because the GMM model incorporates lagged CO_2 emissions and uses internal instruments to address endogeneity, the primary interpretation of the study should focus on the GMM results, as long as all model specification tests have been met. According to Arellano and Bond (1991) dynamic panel data requires specification tests on model consistency using the Arellano-Bond test approach and testing model validity using the Sargan test approach. The probability value in the Arellano-Bond and Sargan tests shows a probability value above 5 percent, thus rejecting $H1._0$ which means that the model is consistent and valid on GMM dynamic panel data. Koefisien lag emisi CO_2 atau ($lnCO_{2i,t-1}$) is 0.379 and is significant at the 1 percent level. These results indicate that CO_2 emissions are persistent or dynamic. A 1 percent increase in CO_2 emissions in the previous period is associated with a 0.379 percent increase in current period emissions, assuming other variables remain constant. Although emissions show persistence, a coefficient value below one indicates that the effect of emission shocks will gradually diminish and the model does not exhibit an explosive process. The value (1 - 0.379 = 0.621) can also be interpreted to mean that approximately 62.1 percent of the adjustment to equilibrium occurs in one period (Koc & Bulus, 2020; Wang et al., 2023).

Table 1 shows that GDP has a coefficient of -0.120 and is significant at the 1 percent level in the GMM model. A 1 percent increase in GDP is estimated to reduce CO_2 emissions by 0.120 percent in the short run, all other things being equal. This result may indicate a decoupling process or *decoupling* between economic growth and carbon emissions. Countries in the sample may have experienced increased energy efficiency, a shift in economic structure toward lower-carbon sectors, the implementation of environmental regulations, or the adoption of cleaner production technologies (Wang et al., 2023; Zafar et al., 2019; Lestari et al., 2024). Renewable energy has a coefficient of -0.019 and is significant at the 5 percent level. This means that a 1 percent increase in renewable energy use is associated with a 0.019 percent reduction in CO_2 emissions in the short term. The direction of this coefficient is consistent across all models, although it is not significant in the CEM. These results support the energy substitution mechanism, namely that renewable energy can reduce emissions when replacing coal, oil, and natural gas in the energy mix. However, the coefficient is relatively small, which may indicate that the share of renewable energy is not yet large enough to completely replace fossil fuel use or that renewable energy still functions as a supplementary energy supply (Dogan & Seker, 2016; Vo et al., 2020).

Table 1. Estimation Result of Panel Data

Variabel	CEM	FEM	REM	GMM
lnco2(-1)				0.379
				(21.82)***
lngdp	0.124	-0.100	-0.124	-0.120
	(4.53)***	(-2.36)**	(-3.02)***	(-9.19)***
lnre	-0.012	-0.022	-0.028	-0.019
	(-0.69)	(-4.05)***	(-5.35)***	(-2.51)**
lnce	0.283	0.928	0.890	0.968
	(07.81)***	(16.89)***	(18.33)***	(33.87)***
lnup	0.599	-0.139	0.175	-0.019
	(14.52)***	(-1.35)	(2.70)***	(-0.15)
lntrd	0.280	-0.213	-0.206	0.042
	(3.80)	(-5.92)***	(-5.54)***	(3.86)***
fdi	0.002	-0.0002	-0.0001	0.00003
	(1.48)	(-1.17)	(-0.83)	(0.60)
Cons	-12.162	9.931	5.379	5.429
	(-10.33)***	(6.54)***	(4.73)***	(2.85)***
Diagnostic Tools				
Sargan Test				0.9495
Abond Test				0.9925

Source: data processed

In contrast, conventional energy consumption has a positive coefficient of 0.968 and is significant at the 1 percent level. A 1 percent increase in conventional energy consumption is estimated to increase CO_2 emissions by 0.968 percent in the short term. This variable produces a positive and significant coefficient across all models, thus representing the most consistent finding. The coefficient's magnitude, close to one, indicates that dependence on fossil fuels is a major factor driving carbon emissions. This finding also suggests that renewable energy development needs to be accompanied by a reduction in conventional energy use for the energy transition to truly result in emission reductions (Horobet et al., 2024). Urban population has a coefficient of -0.019, but it is not statistically significant. These results indicate that changes in urban population have not been proven to have a direct effect on CO_2 emissions after economic factors, energy use, trade, and emission dynamics are controlled. The direction and significance of this variable are also unstable in the static model. CEM produces a positive and significant effect, FEM produces a negative but insignificant effect, and REM produces a positive and significant effect. This instability suggests that the impact of urbanization likely depends on country characteristics, such as urban density, transportation systems, infrastructure quality, energy use, and spatial planning policies (N. Zhang et al., 2017; Xu et al., 2020; A'yun et al., 2026).

Trade openness has a coefficient of 0.042 and is significant at the 1 percent level in the GMM model. A 1 percent increase in trade openness is estimated to increase CO_2 emissions by 0.042 percent in the short run. This result suggests that scale effects and trade composition effects likely outweigh technical effects. Trade expansion can increase production activity, international transportation, energy consumption, and specialization in carbon-intensive sectors. However, the results for trade openness are highly sensitive to the estimation method (Dou et al., 2020). FEM and REM yield negative coefficients, while CEM and GMM yield positive coefficients. This difference reinforces the suspicion of heterogeneity and a simultaneous relationship between trade and emissions. FDI has a coefficient of 0.00003 and is not statistically significant. This result indicates that there is no empirical evidence that foreign investment flows directly affect CO_2 emissions. This insignificance is consistent across CEM, FEM, REM, and GMM. The environmental impact of FDI may depend on the type of investment. Investment in energy-intensive industries can increase emissions through a number of mechanisms. *pollution haven*, while investment in green technology and more efficient production can reduce emissions through *pollution halo effect* (Ling et al., 2015).

Table 2. Estimation Result of Dynamic Panel Data

Variabel	Full Model	Non-Uni Europe	Uni Europe
lnco2(-1)	0.379	0.343	0.149
	(21.82)***	(2.45)**	(9.97)***
lngdp	-0.120	0.737	0.071
	(-9.19)***	(2.68)***	(0.83)
lnre	-0.019	-0.002	-0.133
	(-2.51)**	(-0.87)	(-17.85)***
lnce	0.968	0.398	0.960
	(33.87)***	(2.25)**	(19.80)***
lnup	-0.019	-1.494	-0.457
	(-0.15)	(-3.29)***	(-0.96)
lntrd	0.042	0.041	0.209
	(3.86)***	(1.13)	(7.17)***
fdi	0.00003	0.002	5.486
	(0.60)	(0.44)	(0.13)
Cons	5.429	9.673	7.138
	(2.85)***	(3.39)***	(1.28)

Source: data processed

Table 2 shows the estimation results indicating that the lag coefficient of CO_2 emissions, namely ($lnCO_{2i,t-1}$), is positive and significant across all models. The coefficient is 0.379 in the overall model, 0.343 in the non-EU group, and 0.149 in the EU group. These results indicate that CO_2 emissions are persistent, meaning that the level of emissions in the previous period influences the level of emissions in the current period. Emission persistence appears stronger in non-EU countries than in EU countries. The lower lag coefficient in the

EU group also indicates that emission shocks tend to dissipate more quickly, possibly related to stronger environmental regulations, energy transitions, and technological capacity (Wang et al., 2023; Shahbaz et al., 2017). All lag coefficients are below one, so the model does not indicate an explosive emission process. Different results were found in the non-EU group. The GDP coefficient is 0.737 and is significant at the 1 percent level, indicating that a 1 percent increase in GDP increases CO_2 emissions by approximately 0.737 percent. This indicates that economic growth in the non-EU group is still largely supported by production activities, industrialization, and fossil fuel consumption. In the long term, the impact is estimated to reach around 1.122 percent, obtained from (0.737 / (1 - 0.343)). In the EU group, GDP has a positive coefficient of 0.071, but it is not significant. This means that changes in GDP have not been statistically proven to affect CO_2 emissions. These results may reflect that economic growth and emissions in the EU have become relatively decoupled due to increased efficiency, a shift towards the service and technology sectors, the implementation of carbon pricing, and the increased use of low-carbon energy (Zafar et al., 2019). This heterogeneity is quite relevant to actual developments. IEA data shows that by 2024, energy emissions in developed countries will decline, while emissions in developing and emerging economies will increase due to growing energy demand, industrialization, and dependence on fossil fuels.

Renewable energy has a negative coefficient of -0.019 and is significant at the 5 percent level in the overall model. This result means that a 1 percent increase in renewable energy reduces CO_2 emissions by approximately 0.019 percent in the short term. The long-term impact is estimated at -0.019 / (1 - 0.379) = 0.031. A 1 percent increase in renewable energy is estimated to reduce emissions by approximately 0.031 percent in the long term. This negative trend supports the substitution mechanism, namely that renewable energy reduces emissions when its use replaces coal, oil, and natural gas (Dogan & Seker, 2016). In the non-EU group, renewable energy has a coefficient of -0.002 and is not significant. This result indicates that the increase in renewable energy is not strong enough to significantly reduce emissions. This condition can occur if the addition of renewable energy only meets the growth in energy demand without being accompanied by a reduction in fossil fuel use. In other words, renewable energy still plays a role as a supplementary energy source, not as a substitute for conventional energy (Destek & Sinha, 2020). Conversely, renewable energy in the European Union has a coefficient of -0.133 and is significant at the 1 percent level. A 1 percent increase in renewable energy reduces CO_2 emissions by approximately 0.133 percent in the short term and by approximately 0.156 percent in the long term. This significant effect indicates that the energy substitution channel is more effective in the European Union because renewable energy development has been accompanied by a reduction in coal use, strengthening of energy networks, storage technologies, environmental regulations, and carbon pricing policies (Vo et al., 2020; Lestari et al., 2024).

Conventional energy consumption has a positive and significant impact across all models. The coefficient is 0.968 in the overall model, 0.398 in the non-EU group, and 0.960 in the EU group. These results indicate that the use of coal, oil, and gas is the main factor increasing CO_2 emissions. In the overall model, a 1 percent increase in conventional energy consumption increases emissions by approximately 0.968 percent in the short term. The long-term impact is approximately 1.559 percent. In the non-EU group, the long-term impact is approximately 0.606 percent, while in the EU it is approximately 1.128 percent. The large conventional energy coefficient in the EU does not necessarily imply that the EU is more dependent on fossil fuels than the non-EU group. The coefficient indicates that each marginal change in fossil fuel use results in a large emission response after other factors are controlled. These results also confirm that increasing renewable energy is insufficient if fossil fuel use is not reduced (Q. Wang et al., 2023).

Trade openness has a positive coefficient of 0.042 and is significant in the overall model. This means that a 1 percent increase in trade openness increases emissions by approximately 0.042 percent in the short run and 0.068 percent in the long run. These results indicate that the scale and composition effects of trade are more dominant than the technical effects. Increased trade increases production, transportation, and energy use and can encourage specialization in carbon-intensive sectors. In the non-EU group, the coefficient of trade openness is 0.041, but it is not significant. Therefore, there is no evidence that increased trade directly affects emissions in that group. The impact of trade may differ across countries due to differences in export composition, industrial structure, energy use, and the quality of environmental regulations. In the EU group, the coefficient of trade openness is 0.209 and is significant at the 1 percent level. A 1 percent increase in trade openness increases emissions by approximately 0.209 percent in the short run and 0.246 percent in the long run. These findings suggest that increased production, movement of goods, involvement in global value chains, and the possible displacement of carbon-intensive activities may still offset the benefits of clean technology transfer (Koc & Bulus, 2020; Mu'min et al., 2023).

FDI has no significant effect on emissions in any of the three models. The statistical values are only 0.600 in the overall model, 0.440 in the non-EU group, and 0.130 in the EU group, respectively. Therefore, there is insufficient evidence to conclude that FDI increases or decreases CO_2 emissions. This insignificance may occur because FDI has two opposing effects. FDI in the mining, fossil fuel, and heavy industry sectors can increase emissions through *pollution haven effect*. Conversely, foreign investment that brings clean technology, production efficiency, and higher environmental standards can reduce emissions through *pollution halo effect* When both types of investment are combined, the net effect of FDI may be insignificant. Overall, research shows that renewable energy tends to reduce emissions, but the strength of the effect varies across countries. Dependence on conventional energy remains the main driver of emissions (W.-Z. Wang et al., 2021) and the impact of economic growth, urbanization, trade, and FDI depends heavily on economic structure, energy mix, technology, income levels, and institutional quality (Poumanyvong & Kaneko, 2010).

4. CONCLUSIONS

This study investigates the effects of renewable energy, trade openness, and other economic and energy-related factors on CO_2 emissions using a dynamic panel GMM approach. The positive and significant coefficient of lagged CO_2 emissions across all specifications demonstrates that emissions are persistent and that current environmental conditions are partly determined by past emission levels. The findings also confirm that the relationship between economic activity, energy consumption, international trade, and environmental degradation is heterogeneous across European Union and non-European Union economies. Renewable energy is found to reduce CO_2 emissions in the full sample and the European Union group, while its effect is statistically insignificant in non-European Union economies. This difference suggests that renewable energy produces a stronger environmental benefit when it effectively substitutes fossil-based energy rather than merely supplementing growing energy demand. The stronger effect in European Union economies may reflect more advanced renewable-energy infrastructure, stricter environmental regulations, greater technological capacity, and stronger policy support for the energy transition. Conventional energy consumption, however, consistently increases emissions in all models, indicating that fossil-fuel dependence remains the principal driver of carbon emissions.

Trade openness increases CO_2 emissions in the full sample and the European Union group but has no significant effect in non-European Union economies. These results suggest that the scale and composition effects of trade, including expanded production, transportation, and specialization in energy-intensive activities, may outweigh the benefits of cleaner-technology transfer. Economic growth also produces different environmental consequences across groups: it increases emissions in non-European Union economies, has no significant effect in European Union economies, and reduces emissions in the full model. Meanwhile, foreign direct investment does not significantly affect emissions, possibly because pollution-intensive and environmentally friendly investments generate opposing effects. The policy implications are that renewable-energy development should be accompanied by a measurable reduction in fossil-energy consumption. Governments should strengthen investment in clean-energy infrastructure, energy storage, grid integration, and low-carbon technologies while gradually limiting carbon-intensive production. Trade policies should also incorporate environmental standards, carbon-efficiency requirements, and incentives for environmentally friendly goods and technologies. Future research should test non-linear and threshold effects, distinguish trade and FDI by sector, account for cross-sectional dependence, and formally examine whether the estimated coefficients differ between European Union and non-European Union economies.

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6. REFERENCES

A'yun, I. Q., Nguyen, T. T. H., Darsono, S. N. A. C., Pho, T. V, Khoirudin, R., & Lubis, F. R. A. (2026). Economic development and inequality in human development: The mediating roles of urbanisation, non-renewable energy consumption, economic complexity, and globalisation. *Sustainable*, 100220. https://doi.org/10.1016/j.scowo.2026.100220

Acheampong, A. O. (2018). Economic growth, CO2 emissions and energy consumption: What causes what and where? *Energy Economics*, *74*, 677–692. https://doi.org/10.1016/j.eneco.2018.07.022

Ahmed, K., Shahbaz, M., & Kyophilavong, P. (2016). Revisiting the emissions-energy-trade nexus: Evidence from the newly industrializing countries. *Environmental Science and Pollution Research*, *23*, 7676–7691. https://doi.org/10.1007/s11356-015-6018-x

Arellano, M., & Bond, S. (1991). Some test of specification for panel data: Monte carlo evidence and an application to employment equations. *The Review of Economic Studies*, *58*(2), 277–297. https://doi.org/10.2307/2297968

Aslam, B., Hu, J., Ali, S., AlGarni, T. S., & Abdullah, M. A. (2022). Malaysia's economic growth, consumption of oil, industry and CO_2 emissions: Evidence from the ARDL model. *International Journal of Environmental Science and Technology*, *19*(4), 3189–3200. https://doi.org/10.1007/s13762-021-03279-1

Bakri, M. A., Chia, Y.-E., & Chia, R. C.-J. (2025). Trade openness and carbon emissions using threshold approach: Evidence from selected Asian countries. *Carbon Research*, *4*. https://doi.org/10.1007/s44246-025-00211-x

Baltagi, B. H. (2005). *Econometric Analysis of Panel Data* (3rd ed.). John Wiley & Sons.

Ben Jebli, M., Ben Youssef, S., & Ozturk, I. (2016). Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. *Ecological Indicators*, *60*, 824–831. https://doi.org/10.1016/j.ecolind.2015.08.031

Destek, M. A., & Sinha, A. (2020). Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries. *Journal of Cleaner Production*, *242*, 118537. https://doi.org/10.1016/j.jclepro.2019.118537

Dogan, E., & Seker, F. (2016). Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy. *Renewable Energy*, *94*, 429–439. https://doi.org/10.1016/j.renene.2016.03.078

Dong, K., Sun, R., Jiang, H., & Zeng, X. (2018). CO_2 emissions, economic growth and the environmental Kuznets curve in China: What roles can nuclear energy and renewable energy play? *Journal of Cleaner Production*, *196*, 51–63. https://doi.org/10.1016/j.jclepro.2018.05.271

Dou, Y., Chen, F., Kong, Z., & Dong, K. (2023). Re-estimating the trade openness–carbon emissions nexus: A global analysis considering nonlinear, mediation, and heterogeneous effects. *Applied Economics*, *55*(57), 6793–6808. https://doi.org/10.1080/00036846.2023.2166659

Dou, Y., Dong, K., Jiang, Q., & Dong, X. (2020). How does trade openness affect carbon emission? New international evidence. *Journal of Environmental Assessment Policy and Management*, *22*(03–04), 225005. https://doi.org/10.1142/S1464333222500053

Gaies, B., Nakhli, M. S., & Sahut, J. M. (2022). What are the effects of economic globalization on CO_2 emissions in MENA countries? *Economic Modelling*, *116*. https://doi.org/10.1016/j.econmod.2022.106022

Grodzicki, T., & Jankiewicz, M. (2022). The impact of renewable energy and urbanization on

CO_2 emissions in Europe – Spatio-temporal approach. *Environmental Development*, *44*, 100755. https://doi.org/10.1016/j.envdev.2022.100755

Hasnisah, A., Azlina, A. A., & Taib, C. M. I. C. (2019). The impact of renewable energy consumption on carbon dioxide emissions: Empirical evidence from developing countries in Asia. *International Journal of Energy Economics*, *9*(3), 135–143. https://www.econjournals.com/index.php/ijeep/article/view/7535

Ho, S.-Y., & Iyke, B. N. (2019). Trade openness and carbon emissions: Evidence from Central and Eastern European countries. *Review of Economics*, *70*(1). https://doi.org/10.1515/roe-2018-0001

Horobet, A., Belascu, L., Radulescu, M., Balsalobre-Lorente, D., Botoroga, C.-A., & Negreanu, C.-C. (2024). Exploring the nexus between greenhouse emissions, environmental degradation and green energy in Europe: A critique of the environmental Kuznets curve. *Energies*, *17*(20), 5109–5120. https://doi.org/10.3390/en17205109

Hussein, H. A., Warsame, A. A., Barre, G. M., & Salad, M. A. (2023). The nexus between economic growth, energy consumption, and environmental degradation in Kenya. *International Journal of Energy Economics and Policy*, *13*(6), 220–226. https://doi.org/10.32479/ijeep.14293

Khan, A., & Safdar, S. (2023). Symmetric and asymmetric analysis of trade and environment in Pakistan. *Environmental Science and Pollution Research*, *30*, 11399–11416. https://doi.org/10.1007/s11356-022-22669-7

Koc, S., & Bulus, G. C. (2020). Testing validity of the EKC hypothesis in South Korea: Role of renewable energy and trade openness. *Environmental Science and Pollution Research*, *27*, 29043–29054. https://doi.org/10.1007/s11356-020-09172-7

Koshta, N., Bashir, H. A., & Samad, T. A. (2021). Foreign trade, financial development, agriculture, energy consumption and CO2 emission: Testing EKC among emerging economies. *Indian Growth and Development Review*, *14*(1), 50–80. https://doi.org/10.1108/IGDR-10-2019-0117

Lestari, Y. T., Kurniawan, M. L. A., & Khan, Z. (2024). Dynamic Analysis of Environmental Degradation and Economic Activities in the Asia-Pacific Region. *Journal of Management Studies and Development*, *3*(2), 69–80. https://doi.org/10.56741/jmsd.v3i02.503

Ling, C. H., Ahmed, K., Muhamad, R. B., & Shahbaz, M. (2015). Decomposing the trade-environment nexus for Malaysia: What do the technique, scale, composition, and comparative advantage effect indicate? *Environmental Science and Pollution Research*, *22*, 20131–20142. https://doi.org/10.1007/s11356-015-5217-9

Magazzino, C., & Brady, G. L. (2018). The relationship among renewable energy, economic growth, labor and capital formation in Italy. *Rivista Di Studi Sulla Sostenibilita*, *6*, 35–48. https://doi.org/10.3280/riss2018-001005

Mata, J. P. V, Bautista, M. G. G., Granda, L. E. S., & Moreano, E. G. Z. (2024). Evaluating the environmental Kuznets curve: The role of renewable energy, economic growth, urban density and trade openness on CO_2 emissions. An analysis for high-income countries using the CS-ARDL model. *International Journal of Energy Economics and Policy*, *14*(6), 580–596. https://doi.org/10.32479/ijeep.16740

Mu'min, M. S., Susilowati, I., Qudsyina, H., Wahyuni, H. A., Rismawati, S., Kusumawardhani, H. A., & Miah, M. R. (2023). Nexus between economic growth, renewable energy, industry value added and CO_2 emissions in ASEAN. *Jurnal Ekonomi Pembangunan: Kajian Masalah Ekonomi Dan Pembangunan*, *24*(2), 265–281. https://doi.org/10.23917/jep.v24i2.23165

Mohsin, M., Kamran, H. W., Nawaz, M. A., Hussain, M. S., & Dahri, A. S. (2021). Assesing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. *Journal of Environmental Management*, *284*. https://doi.org/10.1016/j.jenvman.2021.111999

Nguyen, Q. K. (2026). Green energy is not always green: An analysis of renewable energy, economic growth, and CO_2 emissions in developing countries. *Sustainable Development*, *Early View*. https://doi.org/10.1002/sd.70970

Obobisa, E. S. (2022). Achieving 1.5°C and net-zero emissions target: The role of renewable energy and financial development. *Renewable Energy*, *188*, 967–985. https://doi.org/10.1016/j.renene.2022.02.056

Poumanyvong, P., & Kaneko, S. (2010). Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis. *Ecological Economics*, *70*(2), 434–444. https://doi.org/10.1016/j.ecolecon.2010.09.029

Shahbaz, M., Nasreen, S., Ahmed, K., & Hammoudeh, S. (2017). Trade openness–carbon emissions nexus: The importance of turning points of trade openness for country panels. *Energy Economics*, *61*, 221–232. https://doi.org/10.1016/j.eneco.2016.11.008

Sulaiman, C., Leng, N. S., Abdul-Rahim, A. S., Muhammad-Jawad, I., & Samad, N. S. A. (2023). Fresh evidence on the influence of trading activities on CO_2 emissions in developed and developing high CO_2 emitting countries: Long panel data modelling. *International Journal of Sustainable Economy*, *15*(4). https://doi.org/10.1504/IJSE.2023.134186

Sorrell, S. (2015). Reducing energy demand: A review of issues challenges and approaches. *Renewable and Sustainable Energy Reviews*, *47*, 74–82. https://doi.org/10.1016/j.rser.2015.03.002

Szetela, B., Majewska, A., Jamroz, P., Djalilov, B., & Salahodjaev, R. (2022). Renewable energy and CO_2 emissions in top natural resource rents depending countries: The role of governance. *Frontiers in Energy Research*, *10*(March), 1–7. https://doi.org/10.3389/fenrg.2022.872941

Vo, D. H., Vo, A. T., Ho, C. M., & Nguyen, H. M. (2020). The role of renewable energy, alternative and nuclear energy in mitigating carbon emissions in the CPTPP countries. *Renewable Energy*, *161*, 278–292. https://doi.org/10.1016/j.renene.2020.07.093

Wang, Q., Wang, L., & Li, R. (2024). Trade openness helps move towards carbon neutrality-insight from 114 countries. *Sustainable Development*, *32*(1), 1081–1095. https://doi.org/10.1002/sd.2720

Wang, Q., Zhang, F., & Li, R. (2023). Revisiting the environmental Kuznets curve hypothesis in 208 counties: The roles of trade openness, human capital, renewable energy and natural resource rent. *Environmental Research*, *216*(Part 3), 114637. https://doi.org/10.1016/j.envres.2022.114637

Wang, W.-Z., Liu, L.-C., Liao, H., & Wei, Y.-M. (2021). Impacts of urbanization on carbon emissions: An empirical analysis from OECD countries. *Energy Policy*, *151*, 112171. https://doi.org/10.1016/j.enpol.2021.112171

Warsame, A. A. (2022). Does oil price affect the economic growth in Somalia asymmetrically? *International Journal of Energy Economics and Policy*, *12*(5), 47–54. https://doi.org/10.32479/ijeep.13210

Xu, G., Zhou, Z., Jiao, L., & Zhao, R. (2020). Compact urban form and expansion pattern slow down the decline in urban densities: A global perspective. *Land Use Policy*, *94*, 104563. https://doi.org/10.1016/j.landusepol.2020.104563

Zafar, M. W., Mirza, F. M., Zaidi, S. A. H., & Hou, F. (2019). The nexus of renewable and nonrenewable energy consumption, trade openness, and CO_2 emissions in the framework of EKC: Evidence from emerging economies. *Environmental Science and Pollution Research*, *26*, 15162–15173. https://doi.org/10.1007/s11356-019-04912-w

Zhang, N., Yu, K., & Chen, Z. (2017). How does urbanization affect carbon dioxide emissions? A cross-country panel data analysis. *Energy Policy*, *107*, 678–687. https://doi.org/10.1016/j.enpol.2017.03.072

Zhang, S., Liu, X., & Bae, J. (2017). Does trade openness affect CO_2 emissions: Evidence from ten newly industrialized countries? *Environmental Science and Pollution Research*, *24*, 17616–17625. https://doi.org/10.1007/s11356-017-9392-8

Zhao, X., Ramzan, M., Sengupta, T., Sharma, D. G., Shahzad, U., & Cui, L. (2022). Impact of bilateral trade on energy affordability and accessibility across Europe: Does economic globalization reduce energy poverty? *Energy Build*, *262*. https://doi.org/10.1016/j.enbuild.2022.112023

Zhu, L., Hao, Y., Lu, Z. N., Wu, H., & Ran, Q. (2019). Do economic activities cause air pollution? Evidence from China's major cities. *Sustainable Cities and Society*, *49*, 1–10. https://doi.org/10.1016/j.scs.2019.101593