



The Dynamic Interactions of CO₂ Emissions and Renewable Energy Consumption on Economic Growth in G20 Countries: A Panel VAR Approach

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Abstract

The interactions among CO₂ emissions, renewable energy consumption, and economic growth are highly interconnected, especially among the G20 countries, and significantly impact global CO₂ emissions and the global economy. Therefore, we need a more comprehensive understanding to take action to harmonize economic growth with sustainable development. This research will examine the dynamic interaction between CO₂ emissions and renewable energy consumption on economic growth in G20 countries. In addition, this study uses Panel Vector Autoregression (VAR) methodology over the period 1990 to 2022 and includes several critical phases. This included unit root tests to assess the statistical validity of the data, cointegration tests to determine temporal changes among the variables, and impulse response function tests along with variance decomposition to determine the impact of shocks to one variable on another. The study findings show a correlation between emissions, renewable energy consumption, and economic growth in G20 countries. The results show that CO₂ emissions have a favorable short-term effect, boosting GDP growth and economic activity. In contrast, CO₂ emissions and GDP show negative consequences in the long run. In addition, we confirm that the short-term correlation between renewable energy consumption and GDP is negative. However, the utilization of renewable energy sources has a positive impact in the long run. Therefore, G20 countries should implement renewable energy policies to promote economic growth, achieve sustainable development goals, and mitigate CO₂ emissions in the short and long term.

Keywords: GDP, CO₂ Emissions, Renewable Energy Consumption, Panel VAR, G20 Countries

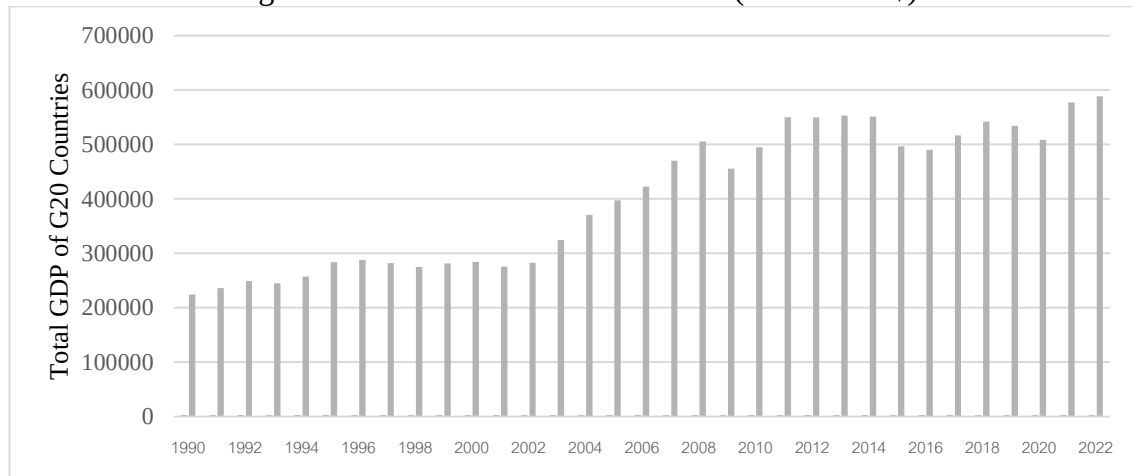
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1. Introduction

Economic growth is one of the main objectives of economic policy, and it is often associated with high levels of resource utilization (Alakbarov et al., 2024). On the other hand, an increase in carbon dioxide emissions will harm economic growth (Alyasari & Alzawbaee, 2020). Consequently, this suggests that the rise in carbon dioxide emissions is a consequence of an increase in the use of fossil fuels and the activity of industrial processes, both of which contribute to climate change, which might slow economic growth. During this decade, environmental degradation has markedly intensified, heightening global warming and climate change concerns (Mitić et al., 2022). For example, the G20 countries are predicted to contribute 85% of global GDP and are responsible for 80% of carbon emissions in the world's energy sector (Sucahyo & Arsala Rahmani, 2023). In addition, the Paris Agreement was made in 2015 due to the CO₂ emission problem. This agreement obliges countries worldwide to raise awareness of the onset of climate change problems (Adebayo et al., 2022). However, to address global climate challenges, change is required by switching to renewable energy sources; the G20 countries are a collection of nations with significant economic strength and substantial environmental influence, particularly on climate change. Wang & Zhang (2021) argued that the use of fossil fuels is the primary cause of environmental degradation and economic growth in many countries worldwide, and that climate change is recognized as a global issue by some countries. Figure 1 indicates the total GDP growth of G20 countries from 1990–2022.

Figure 1: Total GDP of G20 Countries (Current US\$)



Sources: World Bank Indicators (2024)

Figure 1 shows the volatility in economic growth, as measured by total GDP, across G20 nations from 1990 to 2022. As an additional point of interest, growth was inconsistent from 1990 to 2000. Subsequently, significant development was recorded from 2001 to 2008, before the 2008 global financial crisis. Therefore, G20 countries took concrete steps to take precautions to avoid a depression in 2008 (Bery et al., 2019). However, there are still concerns about economic growth in global trade growth following the 2008 crisis, when G20 countries began implementing fiscal and monetary policies to stimulate economic recovery. On the other hand, some concrete steps were taken by some G20 countries, including lowering interest rates, stabilizing the financial system, and making regulations according to the needs at that time. Furthermore,

economic growth was quite volatile in the G20 countries in 2018 and 2019, and a sharp decline in 2020 was driven by the impact of COVID-19, which affected almost all countries worldwide. It significantly affected economic growth and resulted in global economic disruption, including reduced economic activity and regional quarantine by several countries worldwide. Taylan et al. (2022) supposed that COVID-19 has various impacts on G20 countries, including inflation, GDP fluctuations, unemployment, and changes in government policies regarding emissions. In addition, the economies of G20 countries began to recover in 2021, with many countries reporting substantial GDP growth due to concrete steps to lift lockdown restrictions in several countries. As seen in Figure 1, the global economy expanded by around 1.93% from 2020 to 2021. The G20 nations made a significant contribution, increasing their GDP per capita from 577,332.012 to 588,474.4033 (U.S. dollars). In addition, if a nation's gross domestic product experiences considerable growth, this will immediately increase that country's carbon emissions, which will have an immediate and direct effect on the rise in carbon dioxide emissions.

This follows research from Aye & Edoja (2017) that economic growth positively correlates with CO₂ emissions. A stronger correlation will also increase economic growth. Therefore, the commitment of G20 countries to climate change is expected to reduce global emissions by 50% by 2030 and implement strategies to achieve net-zero emissions (UNDP, 2021). In conclusion, economic expansion is positively associated with CO₂ emissions and is accompanied by increased emissions. Consequently, the G20 countries responsible for the highest CO₂ emissions have to implement aggressive measures to reduce carbon emissions without disrupting their economic operations. However, the G20 countries have to implement strategies and initiatives prioritizing climate change mitigation and sustainable growth. This aligns with Alajlan & Alreshaidi (2022), who state that unidirectional causality positively influences the relationship between carbon dioxide emissions and economic development in the short- and medium-term. A one percent increase in economic growth would result in a three-point-three percent rise in carbon dioxide emissions, both now and over the long term. On the other hand, one of the economic policies is economic development, which is associated with increased resource consumption (Alakbarov et al., 2024). Furthermore, high economic growth and increasing population will indirectly increase fossil fuel energy consumption, increasing CO₂ emissions in a country. Therefore, there is a need for a concrete policy to encourage energy efficiency in order to reduce the increase in CO₂ emissions and prevent a worsening of economic growth (Aye & Edoja, 2017). Furthermore, renewable energy sources have the role of reducing CO₂ emissions by 60% of all greenhouse gases globally (Adebayo et al., 2022). This suggests that concrete measures are required to address climate change, as carbon dioxide emissions are the most significant contributor to global greenhouse gas emissions.

This is consistent with the research by Marinaş et al. (2018), which shows a direct correlation between long-term economic growth and renewable energy use. This demonstrates that countries implementing renewable energy sources will result in economic growth. This is because renewable energy can enhance energy independence and promote economic growth for sustainable development. This phenomenon is consistent with the EKC hypothesis, which posits that an increase in income will directly result in environmental degradation. However, once individuals reach a certain income level, they will place greater emphasis on environmental quality, leading in gradual environmental improvement, even as opinions continue to rise (Alakbarov et al., 2024). In addition, the transition to renewable energy takes time, as some countries still depend on fossil fuels. This is supported by research from Feriansyah et al. (2022a), which found that the impact of GDP in ASEAN countries on CO₂ emissions has a relatively high

elasticity of 0.0617%. This study's findings indicate a substantial correlation between GDP and CO₂ emissions in ASEAN countries. The elasticity level and economic development in ASEAN countries will result in a proportional increase in emissions. This demonstrates that economic growth can indirectly promote environmental degradation. Consequently, it is imperative to implement preventive measures to reduce carbon dioxide emissions and concurrently implement sustainable economic development.

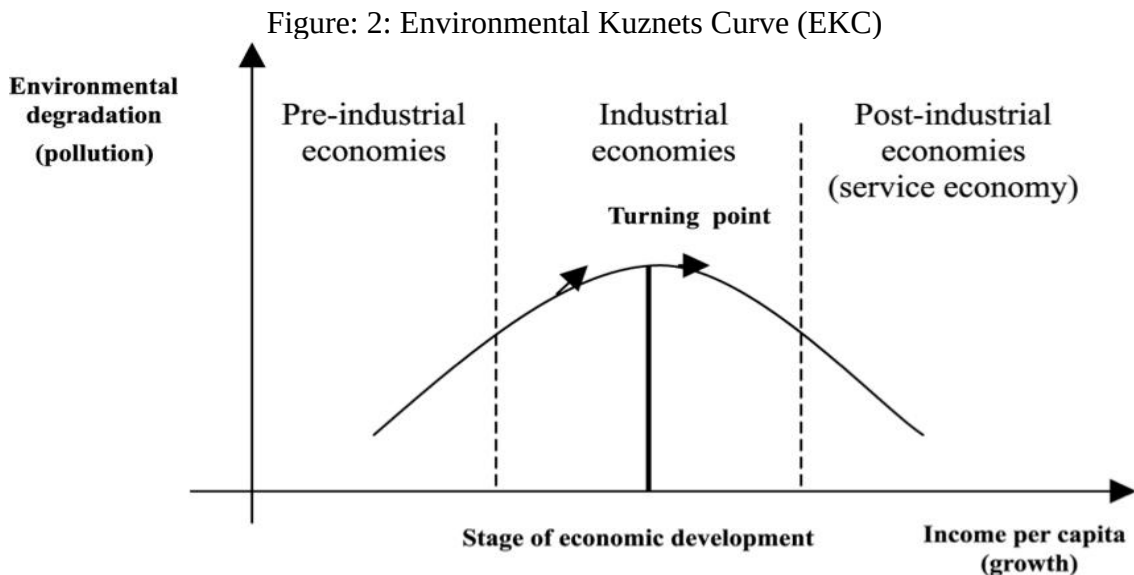
The research by Ntanos et al. (2018) shows a significant relationship between the consumption of renewable energy sources and economic growth. In particular, higher economic growth rates are associated with greater renewable energy consumption. In contrast, lower economic growth rates are generally associated with lower levels of renewable energy consumption. The study's findings show that nations experiencing high economic growth rates use more renewable energy than those experiencing low economic growth rates. Furthermore, energy consumption is crucial for economic growth, as the development of Germany, the UK, the USA, Canada, China, Egypt, Nigeria, South Africa, Kenya, and Rwanda is significantly reliant on energy (Niyonzima et al., 2022). Another fact is that renewable energy accounts for 58% of economic growth in countries such as Australia, Canada, Japan, Germany, the United Kingdom, the United States, Sweden, the Netherlands, Ireland, India, South Africa, and Spain (Shahbaz et al., 2020). Put another way, a country will likely see significant economic growth if it transitions to renewable energy. In addition, the government and other relevant stakeholders may benefit from the positive and substantial impact of the transition to renewable energy on the economy's expansion. This is supported by Zhao & Wang (2015), who stated that all countries should prioritize implementing a more efficient energy transition. In addition, renewable energy consumption is one of the potential factors that can reduce CO₂ emissions. This is, according to Islam et al. (2023), intended to show that renewable energy can reduce CO₂ emissions. Consequently, optimizing renewable energy consumption (REC) may mitigate CO₂ emissions, necessitating a thorough comprehension of renewable energy's impact on G20 nations.

Therefore, climate change is one of the issues often discussed in the G20 agenda, and it is very important to policymakers, who indirectly consider the relationship between climate and a country's performance. In addition, the impact of environmental degradation has become an major issue and one of the most debated topics in the current era, in both developed and developing countries (Osobajo et al., 2020). For example, G20 countries are estimated to account for 85% of global GDP and are responsible for 80% of carbon emissions in the energy sector worldwide (Sucahyo & Arsala Rahmani, 2023). On the other hand, there are two problems currently faced by G20 countries: a) Different policies and commitments among G20 countries, which have an impact on the lack of uniformity in efforts to reduce CO₂ emissions without reducing GDP, and b) The transition from fossil energy to renewable energy is still a big problem for G20 countries, although many G20 countries have committed to being a target of the Paris Agreement but often lag due to several obstacles, including inadequate infrastructure, still having dependence on fossil fuels, as well as investment and technological challenges. In addition, some developed countries in the G20 have entered the category of achieving net zero. In contrast, some developing countries still face challenges in meeting the net-zero target because their incomes still depend on fossil fuels. This disharmony can be an obstacle to accelerating renewable energy. Therefore, one way to reduce CO₂ emissions is to use renewable energy sources without reducing GDP. On the other hand, this policy still requires a comprehensive study of the impact of CO₂ emissions and renewable energy consumption on GDP in G20 countries, so it is necessary to examine the short- and long-term impacts of CO₂ emissions and renewable energy consumption on economic growth in G20 countries in the short term and long-term.

The importance of this study is that it examines the dynamic interactions between renewable energy consumption and carbon dioxide emissions in the context of economic growth in G20 countries, both in the short and long term. Furthermore, it aims to address a significant research gap in the current literature by examining the impact of G20 nations' GDP on renewable energy use and carbon dioxide emissions. Finally, researchers anticipate that the study will have significant ramifications for G20 countries and associated parties, providing a comprehensive understanding of the factors contributing to CO₂ emissions and proposing more impactful and efficient policies and actions. Consequently, the results of this study have the potential to enlighten decision-making processes and promote sustainable growth, not only within G20 countries but also in other developing countries that are confronted with comparable obstacles

2. Literature Review

In the literature review, we conducted a more comprehensive review of the literature on GDP, CO₂ emissions, renewable energy consumption, and three control variables: trade openness, urbanization, and foreign direct investment. Furthermore, we focus only on the dynamic interaction between CO₂ emissions and the REC on GDP. Research by Mendoza et al. (2021), Suproń & Myszczyzyn (2023), Vo et al. (2019), and Yan et al. (2022) shows that several studies have used the Environmental Kuznets Curve (EKC) hypothesis to examine the relationship between economic expansion and carbon emissions throughout growth phases. In addition, the EKC Curve Hypothesis examines the relationship between economic advancement and environmental deterioration. The concept is shown as an inverted U-shaped curve, indicating that when nations undergo economic expansion, there is an initial rise in environmental degradation, followed by a reduction as income levels rise and technological advancements occur considerably. It can be seen in Figure 2.1 below:



Sources: Grossman & Krueger, (1995)

2.1 The Nexus of CO₂ Emissions on Economic Growth

Over the last several decades, some studies by different scholars have looked at the connection between GDP emissions and CO₂ emissions. Previous research by Pertiwi et al. (2024) shows a panel data analysis carried out from 2000 to 2022, and the results indicate a clear and positive association between the Gross Domestic Product (GDP) and carbon dioxide (CO₂) emissions in the G20 countries. This research aims to show, according to Saidi & Hammami (2015), that economic growth, CO₂ emissions, and energy use complement one another. Furthermore, economic growth and CO₂ emissions had a statistically significant positive impact on energy consumption in the 58 nations studied. As a result, a sustainable economic strategy is required to address the environmental impact of economic development, promote energy efficiency, and embrace renewable energy sources to reduce CO₂ emissions while increasing economic growth.

A previous study by Alyasari & Alzawbaee (2020) shows that increasing CO₂ emissions will negatively impact economic growth, while renewable energy consumption will positively affect CO₂ emissions. Consequently, an increase in carbon dioxide emissions results in decreased economic growth. As the quantity of carbon dioxide emissions discharged into the atmosphere increases, this could lead to various adverse consequences and slow and unstable economic growth. The other studies' findings indicate no causal connection between economic expansion and emissions (Mendoza et al., 2021). This suggests that economic growth rates do not directly cause changes in greenhouse gas emissions or other pollutants, and vice versa. In contrast, the result by Mardani (2018) shows an affirmative association between economic growth and CO₂ emissions in G20 nations. This indicates that there is a positive association between GDP and CO₂ in the nations that make up the G20, even though some of the G20 members have adopted renewable energy, which, in addition to contributing to economic development, also indirectly contributes to an increase in CO₂ emissions in the G20 countries.

For instance, in the Arab state of Saudi Arabia, a unidirectional relationship has a favorable impact, both in the short term and over the long term, on the connection between economic growth and carbon dioxide emissions. A 1% increase in GDP, for instance, will result in a 3.3% increase in carbon dioxide emissions, and this will hold true both in the short term and in the long run (Alajlan & Alreshaidi, 2022). This is related to Aye & Edoja (2017), who found that economic growth adversely affects CO₂ emissions during periods of low growth, while it positively influences emissions during periods of strong growth. This indicates that economic growth and carbon dioxide emissions are correlated, with a decline in carbon dioxide emissions occurring during periods of low economic development. On the other hand, economic growth will raise CO₂ emissions due to increased energy consumption and investment in businesses that produce pollution during production. Furthermore, a nation's economic circumstances may influence both the advantages and disadvantages of economic expansion.

In another research by González-Álvarez & Montañés (2023), increased CO₂ emissions are identified as having adverse environmental impacts. This research shows that there is a strong, inseparable relationship among economic growth, renewable energy consumption, and increased CO₂ emissions. This is supported by Khoshnevis Yazdi & Shakouri (2017); the results of the Granger causality test found that there is a causal relationship between economic growth and CO₂ emissions. Therefore, economic growth and CO₂ emissions can increase CO₂ emissions in a country. In addition, bidirectional Granger causation exists between CO₂ emissions, necessitating the implementation of measures that effectively mitigate environmental degradation, which is sometimes irreparable and requires considerable time to rectify (Mitić et al., 2022). In conclusion, it

is essential to examine the correlation between economic progress and environmental sustainability. This is because, while enhancing well-being, there exists a threshold at which economic growth may positively impact the environment.

2.2 The Nexus of Renewable Energy Consumption on Economic Growth

In previous research, several studies have investigated the impact of renewable energy (REC) use on economic growth. Renewable energy may mitigate CO₂ emissions only in the short term, with no influence on long-term environmental quality, and there is no correlation between renewable energy and environmental degradation (Pata et al., 2022). On the other hand, REC shows that renewable energy consumption positively impacts economic growth in the Visegrad countries (the Czech Republic, Hungary, Poland, and Slovakia). Therefore, it has a particularly positive long-term impact on GDP in Visegrad countries (Suproń & Myszczyński, 2023). Besides, developing nations need to prioritize investment initiatives to boost GDP and reduce CO₂ emissions, while governments and stakeholders should collaborate to identify new renewable energy sources (Pertiwi et al., 2024).

Therefore, renewable energy consumption is one of the methods that can be implemented in order to achieve a sustainable economy. On the other hand, the positive influence of Visegrad countries on renewable energy consumption will indirectly influence developing countries to implement economic and environmental sustainability. This is following the results of research from Marinaş et al. (2018) showing a direct correlation between long-term economic growth and renewable energy use, but the short-term relationship between growth and renewable energy has no clear relationship between economic growth and renewable energy. This does not align with the research by Shahbaz et al. (2020), which shows that when a country switches to renewable energy, it tends to experience sustainable economic growth over time. Therefore, the country needs to adopt a clear, concrete policy for development and environmental sustainability, and implement policies that support sustainable development and economic activities. In summary, a nation's shift to renewable energy is expected to provide significant economic development. The shift to renewable energy may positively and significantly influence economic development, benefiting the government and other stakeholders.

Recently, several countries have transformed their energy policies to include renewable energy sources to ensure long-term sustainable growth (Niyonzima et al., 2022). This statement emphasizes the increasing importance of renewable energy sources in achieving economic growth, making it imperative for G20 countries to continuously adjust their policies to prioritize renewable energy sources to ensure a more sustainable future. In addition, we utilize data spanning 33 years with a total of 660 observations, where we employ one variable, renewable energy consumption, which is still not as commonly used as in earlier research (Alajlan & Alreshaidi, 2022; Alyasari & Alzawbaee, 2020; Khoshnevis Yazdi & Shakouri, 2017; Mitić et al., 2022; Vo et al., 2019). Moreover, prior research has not examined the dynamic interactions between CO₂ emissions and renewable energy usage concerning economic growth in G20 countries. These studies focus on a single country or on several groupings, such as ASEAN countries, GCC countries, and European Union members. There are studies on G20 countries, but few have used the Panel VAR approach (Pala, 2020; Ramadhan et al., 2023; Vo et al., 2019; Zhao & Wang, 2015).

Therefore, this study aims to improve understanding among governments, investors, stakeholders, and related parties of the dynamic interaction between CO₂ emissions and renewable energy consumption, and its impact on economic growth in G20 countries, both in the short and long term. Then, this study focuses only on the duration of observation, the data variables, and the appropriate econometric models used to fill the

gap and produce a pre-planned research plan that provides an overview of the concrete steps academics and non-academics, or related stakeholders, must take. Therefore, this study aims to provide a more complex insight into the dynamic relationship between carbon dioxide emissions, renewable energy consumption, and economic growth in G20 countries. Furthermore, this study is to contribute to the global discourse on reducing CO₂ emissions without reducing economic growth in G20 countries, stakeholders, policymakers, and non-governmental organizations. The article outline of the study is structured as follows: Section 1 – Introduction, problem statement, and research gap; Section 2 - Literature review; Section 3 - Data & research methodology. Section 4 - Results and discussion. Section 5- Conclusion, Section 6 Policy Recommendation, and Section 7- Limitations and Future Recommendations.

Based on the literature above, this research we have two hypothesis to get more undersatand about the research namely: 1) H0: There is no correlation between CO₂ emissions and REC on economic growth in G20 countries, whether in the long-term or short-term and 2) H1: The association between CO₂ emissions and REC on economic growth in G20 countries may be seen in the long and short term.

3. Data and Research Methodology

3.1 Data Collection

The study's objectives are achieved by measuring GDP with independent variables including renewable energy consumption and carbon dioxide emissions, whereas trade openness, urbanization, and foreign direct investment serve as control variables in this research design. It can be seen in Table 1 below:

Table 1: Variables Definition

No	Variable	Description	Units	Sources	References
1	Dependent Variable GDP	CO ₂ Emissions Gross Domestic Product Per Capita	Current US\$	WDI from The World Bank, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD	(Feriansyah et al., 2022a; Suproń & Myszczyzyn, 2023)
2	Independent Variable CO ₂	CO ₂ Emissions	Metric tons per capita	WDI from The World Bank https://data.worldbank.org/indicator/EN.ATM.CO2E.PC	(Feriansyah et al., 2022b; Suproń & Myszczyzyn, 2023)
3	Independent Variable REC	Renewable Energy Consumption	Annual %	WDI from The World Bank https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS	(Suproń & Myszczyzyn, 2023)
4	Control Variables TO	Trade Openness	Annual %	WDI from The World Bank https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS	(Adebayo et al., 2022)
6	Control Variables URB	Urban Population	Annual %	WDI from The World Bank https://data.worldbank.org/indicator/SP.POP.TOTL	(Khoshnevis Yazdi & Shakouri, 2017; Shahbaz et al., 2014)

No	Variable	Description	Units	Sources	References
7	Control Variable	Foreign Direct Investment	Annual %	WDI from The World Bank https://data.worldbank.org/indicator/BX.KLT.DINV.CD.WD	(Pata et al., 2022)

Sources: World Bank Indicators, 2024

The independent variables are concisely delineated as follows:

GDP Growth (Current US\$) as Dependent Variable: The GDP per capita influences the annual performance of this measure. Rising CO₂ emissions are attributable to heightened urbanization and industrial activities within the nation. These characteristics were included in a prior study by Feriansyah et al. (2022b) and Suproń & Myszczyzyn (2023).

CO₂ Emissions (Metric Tons) as an Independent Variable: It assesses the investments of multiple stakeholders in relation to the company and its assets, including investors, governments, and other affiliated entities. This may include investment across many sectors of the nation. These characteristics were included in a prior study by Feriansyah et al. (2022a) and Suproń & Myszczyzyn (2023).

REC (Annual %) as an Independent Variable: Renewable Energy Consumption refers to energy derived from renewable sources, such as solar, wind, hydro, geothermal, biomass, and tidal energy. Unlike fossil fuels, renewable energy sources are sustainable and do not deplete over time. They can meet the world's increasing energy demands without depleting natural resources. This research anticipates a negative relationship since increasing REC will decrease CO₂ emissions (Suproń & Myszczyzyn, 2023).

Trade openness (Annual %) as Control Variable: Trade openness measures a nation's degree of international trade activity relative to its GDP. Previous work also used this variable Adebayo et al (2022).

Urbanization (%) Control Variable: Urbanization is a dynamic moderating phenomenon in which social and economic capacities from rural regions migrate to metropolitan areas. Furthermore, significant population growth may increase CO₂ emissions (Khoshnevis et al., 2019). Previous work also uses this variable, as do Shahbaz et al. (2014).

Foreign Direct Investment (%) Control Variable: FDI refers to an investment made by a person or firm established in one country into economic interests in another country. Previous work also makes use of this variable by Pata et al (2022).

This section outlines the many methodological stages used in the study aimed at examining the dynamic relationship between carbon dioxide emissions, renewable energy utilization, and economic development in G20 nations. This research uses the Panel VAR approach to examine the dynamic interactions between CO₂ emissions and renewable energy usage concerning short- and long-term economic development in G20 nations. This method affects all variables in the cross-sectional time series, integrates geographical dimensions, and accounts for individual variability using panel data (Zhang et al., 2015). In a VAR system, all variables are typically treated as endogenous, and the indices used to elucidate the effects of exogenous events on the system are constrained by theoretical models or statistical data (Abrigo & Love, 2016). Therefore, we have included the PVAR specifications for each variable below, which will underpin the next study (Adebayo et al., 2022; Feriansyah et al., 2022b; Pata et al., 2022; Shahbaz et al., 2014; Suproń & Myszczyzyn, 2023; Zhang et al., 2015). It can be used with these formula below:

$$\begin{aligned} \log GDP_{it} = & \alpha_1 + \sum_{k=1}^p \beta_{11} \log GDP_{i,t-k} + \sum_{k=1}^p \beta_{12} CO2_{i,t-k} + \\ & \sum_{k=1}^p \beta_{13} REC_{i,t-k} + \sum_{k=1}^p \beta_{14} TO_{i,t-k} + \sum_{k=1}^p \beta_{15} URB_{i,t-k} + \\ & \sum_{k=1}^p \beta_{16} FDI_{i,t-k} + \varepsilon_{1it} \end{aligned} \quad (\text{Equ 1.1})$$

$$\begin{aligned} \log CO2_{it} = & \alpha_2 + \sum_{k=1}^p \beta_{11} \log GDP_{i,t-k} + \sum_{k=1}^p \beta_{12} CO2_{i,t-k} + \\ & \sum_{k=1}^p \beta_{13} REC_{i,t-k} + \sum_{k=1}^p \beta_{14} TO_{i,t-k} + \sum_{k=1}^p \beta_{15} URB_{i,t-k} + \\ & \sum_{k=1}^p \beta_{16} FDI_{i,t-k} + \varepsilon_{2it} \end{aligned} \quad (\text{Equ 1.2})$$

$$\begin{aligned} REC_{it} = & \alpha_3 + \sum_{k=1}^p \beta_{11} \log GDP_{i,t-k} + \sum_{k=1}^p \beta_{12} CO2_{i,t-k} + \\ & \sum_{k=1}^p \beta_{13} REC_{i,t-k} + \sum_{k=1}^p \beta_{14} TO_{i,t-k} + \sum_{k=1}^p \beta_{15} URB_{i,t-k} + \\ & \sum_{k=1}^p \beta_{16} FDI_{i,t-k} + \varepsilon_{3it} \end{aligned} \quad (\text{Equ 1.3})$$

$$\begin{aligned} TO_{it} = & \alpha_4 + \sum_{k=1}^p \beta_{11} \log GDP_{i,t-k} + \sum_{k=1}^p \beta_{12} CO2_{i,t-k} + \\ & \sum_{k=1}^p \beta_{13} REC_{i,t-k} + \sum_{k=1}^p \beta_{14} TO_{i,t-k} + \sum_{k=1}^p \beta_{15} URB_{i,t-k} + \\ & \sum_{k=1}^p \beta_{16} FDI_{i,t-k} + \varepsilon_{4it} \end{aligned} \quad (\text{Equ 1.4})$$

$$\begin{aligned} URB_{it} = & \alpha_5 + \sum_{k=1}^p \beta_{11} \log GDP_{i,t-k} + \sum_{k=1}^p \beta_{12} CO2_{i,t-k} + \\ & \sum_{k=1}^p \beta_{13} REC_{i,t-k} + \sum_{k=1}^p \beta_{14} TO_{i,t-k} + \sum_{k=1}^p \beta_{15} URB_{i,t-k} + \\ & \sum_{k=1}^p \beta_{16} FDI_{i,t-k} + \varepsilon_{5it} \end{aligned} \quad (\text{Equ 1.5})$$

$$\begin{aligned} FDI_{it} = & \alpha_6 + \sum_{k=1}^p \beta_{11} \log GDP_{i,t-k} + \sum_{k=1}^p \beta_{12} CO2_{i,t-k} + \\ & \sum_{k=1}^p \beta_{13} REC_{i,t-k} + \sum_{k=1}^p \beta_{14} TO_{i,t-k} + \sum_{k=1}^p \beta_{15} URB_{i,t-k} + \\ & \sum_{k=1}^p \beta_{16} FDI_{i,t-k} + \varepsilon_{6it} \end{aligned} \quad (\text{Equ 1.6})$$

Description Equation :

LogGDP: Log of GDP

LogCO₂ = Log of CO₂

REC = Renewable Energy Consumption (Annual %)

TO = Trade Openness (Annual %)

URB = Urban Population (Annual %)

FDI = Foreign Direct Investment (Annual %)

The World Bank estimates these metrics as logGDP_{it}, logCO₂_{it}, REC_{it}, TO_{it}, URB_{it}, and FDI_{it}—Economic Growth, Carbon Emissions, Consumption of Renewable Energy, Trade Openness, Urbanization, and Foreign Direct Investment. The above model has some logarithmic variables, including GDP and CO₂ emissions. This is related to Wooldridge (2016), who argues that logarithmic data transformation is a practical

approach in statistics that helps achieve goals such as normalizing the data distribution, facilitating interpretation, and reducing the impact of outliers.

4. Results and Discussion

In the first step of our analysis, we checked the stationarity of the panel data. Three tests were conducted: the Levin, Lin & Chu t-test, the ADF (Augmented Dickey-Fuller)-Fisher test, and the Philips-Perron (PP)-Fisher test. Levin, Lin, and Chu found that not all variables are stationary at level. Therefore, we tested stationarity at the first difference, and all variables showed stationary results. The test results of the three tests can be seen in Tables 2, 3, and 4 below, where the test results show that all variables are stationary at the first level because the probability value is smaller than 0.05.

4.1 Result of Analysis

Tabel 2: Unit Root Test Results by Levin, Lin, Chu (LLC) Test First difference

Test Types	LogGDP	LogC02	REC	TO	URB	FDI
C	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***
CT	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***

Source: Author's computation

Table 3: Unit Root Test Results by Augmented Dickey-Fuller (ADF) First difference

Test Types	LogGDP	LogC02	REC	TO	URB	FDI
C	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.2083)	(0.0000)***
CT	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***

Source: Author's computation

Table 4: Unit Root Test Results by Phillips-Perron (PP) Test First difference

Test Types	LogGDP	LogC02	REC	TO	URB	FDI
C	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0003)***	(0.0000)***
CT	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***

Notes: (*) Significant at 1%; (**) Significant at 5%; (***) Significant at 10% and (no) Not Significant.

Source: Author's computation

In this step, we consider that lag selection for VAR models can be determined based on various criteria, including the Akaike Information Criterion (AIC). Based on the AIC analysis, it is concluded that lag 2 is the most optimal lag length, as stated by Gujarati & Porter(2009). In addition, the results shown in the table support that lag 2 is considered the best choice for the research model. Thus, this lag is expected to produce more accurate and representative estimates in the context of analysis.

Table 5: Lag Order Criteria Test Results for VAR Model

Lag	LR	FPE	AIC	SC	HQ
0	NA	0.000669	9.718097	9.767180	9.737325
1	1726.852	2.65e-05	6.490375	6.833953*	6.624968
2	134.6817	2.34e-05*	6.363192*	7.001266	6.613150*
3	37.80053	2.49e-05	6.426203	7.358773	6.791527
4	30.90451	2.69e-05	6.502231	7.729297	6.982920
5	61.39336*	2.72e-05	6.515144	8.036706	7.111198
6	47.00816	2.84e-05	6.556280	8.372338	7.267700

Note: * indicates lag order selected by the criterion: LR: sequential modified LR test statistic (each test at 5% level), FPE: Final prediction error, AIC: Akaike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion

Source: Author's Computation

Table 6: Cointegration Test Result

Hypothesized No. of CE(s)	Fisher Stat.* (from trace test)	Prob	Fisher Stat.* (frm max-eigen test)	Prob.
None	572.2	0.0000	320.4	0.0000
At most 1	276.0	0.0000	138.9	0.0000
At most 2	163.9	0.0000	90.70	0.0000
At most 3	100.5	0.0000	54.61	0.0616
At most 4	78.47	0.0000	56.30	0.0452
At most 5	85.76	0.0000	85.76	0.0000

Note: Trace test indicates 6 cointegrating eqn(s) at the 0.05 level, * denotes rejection of the hypothesis at the 0.05 level

**MacKinnon-Haug-Michelis (1999) p-values

Source: Author's computation

The results in Table 6 show that the cointegration test failed to yield a p-value below 0.05 for all variables tested. Based on this finding, this study chose to use the Vector Autoregression (VAR) statistical model as recommended by Gujarati & Porter (2009). Considering that the cointegration test cannot provide a p-value lower than 0.05, it may be concluded that there is insufficient evidence to establish a long-run equilibrium connection between the examined variables. Conceptually, the cointegration test states that the null hypothesis, which states no cointegration, should be rejected if the p-value is less than 0.05. This is because the variables are considered related in the long run. However, in this study, the null hypothesis cannot be rejected because one of the variables, trade openness, has a p-value of 0.0616, which exceeds the 0.05 threshold. This indicates the absence of cointegration among the analyzed variables. Thus, the VAR model is chosen as a more suitable method for further analysis in this study.

The Granger causality test is a statistical method used to assess the predictive capacity of one time series in relation to another series (Osobajo et al., 2020; Ouzillou et al., 2024). We conducted the Granger causality test on all relevant variables, including LogGDP (economic growth), LogCO₂ (carbon emissions), REC (renewable energy consumption) (annual %), TO (Trade Openness) (annual %), URB (Urban Population) (annual %), and FDI (Foreign Direct Investment) (annual %). Table 4.7 displays the outcomes of the Granger causality test.

Table 7: Granger Causality Test Result

Null Hypothesis:	Obs	F-Statistic	Prob.
LOG_C02 does not Granger Cause LOG_GDP	620	3.01639	0.0497*
LOG_GDP does not Granger Cause LOG_C02		3.19169	0.0418*
REC does not Granger Cause LOG_GDP	620	2.03686	0.1313
LOG_GDP does not Granger Cause REC		1.28536	0.2773
TO does not Granger Cause LOG_GDP	620	1.51237	0.2212
LOG_GDP does not Granger Cause TO		0.45377	0.6354
URB does not Granger Cause LOG_GDP	620	0.83892	0.4327
LOG_GDP does not Granger Cause URB		1.63656	0.1955
FDI does not Granger Cause LOG_GDP	620	0.32604	0.7219
LOG_GDP does not Granger Cause FDI		0.6198	0.5383
REC does not Granger Cause LOG_C02	620	2.63997	0.0722
LOG_C02 does not Granger Cause REC		1.10146	0.3330
TO does not Granger Cause LOG_C02	620	0.57728	0.5617
LOG_C02 does not Granger Cause TO		3.00374	0.0503
URB does not Granger Cause LOG_C02	620	2.77328	0.0632
LOG_C02 does not Granger Cause URB		0.20971	0.8109
FDI does not Granger Cause LOG_C02	620	0.63312	0.5313
LOG_C02 does not Granger Cause FDI		0.03235	0.9682
TO does not Granger Cause REC	620	0.62075	0.5379
REC does not Granger Cause TO		3.79198	0.0231*
URB does not Granger Cause REC	620	0.99724	0.3695
REC does not Granger Cause URB		0.21889	0.8035
FDI does not Granger Cause REC	620	1.07907	0.3406
REC does not Granger Cause FDI		0.25461	0.7752
URB does not Granger Cause TO	620	0.31661	0.7287
TO does not Granger Cause URB		1.10220	0.3328
FDI does not Granger Cause TO	620	1.75535	0.1737
TO does not Granger Cause FDI		0.25780	0.7728
FDI does not Granger Cause URB	620	1.07308	0.3426
URB does not Granger Cause FDI		0.24420	0.7834

Note: The asterisk (*) shows that the null hypothesis is rejected.

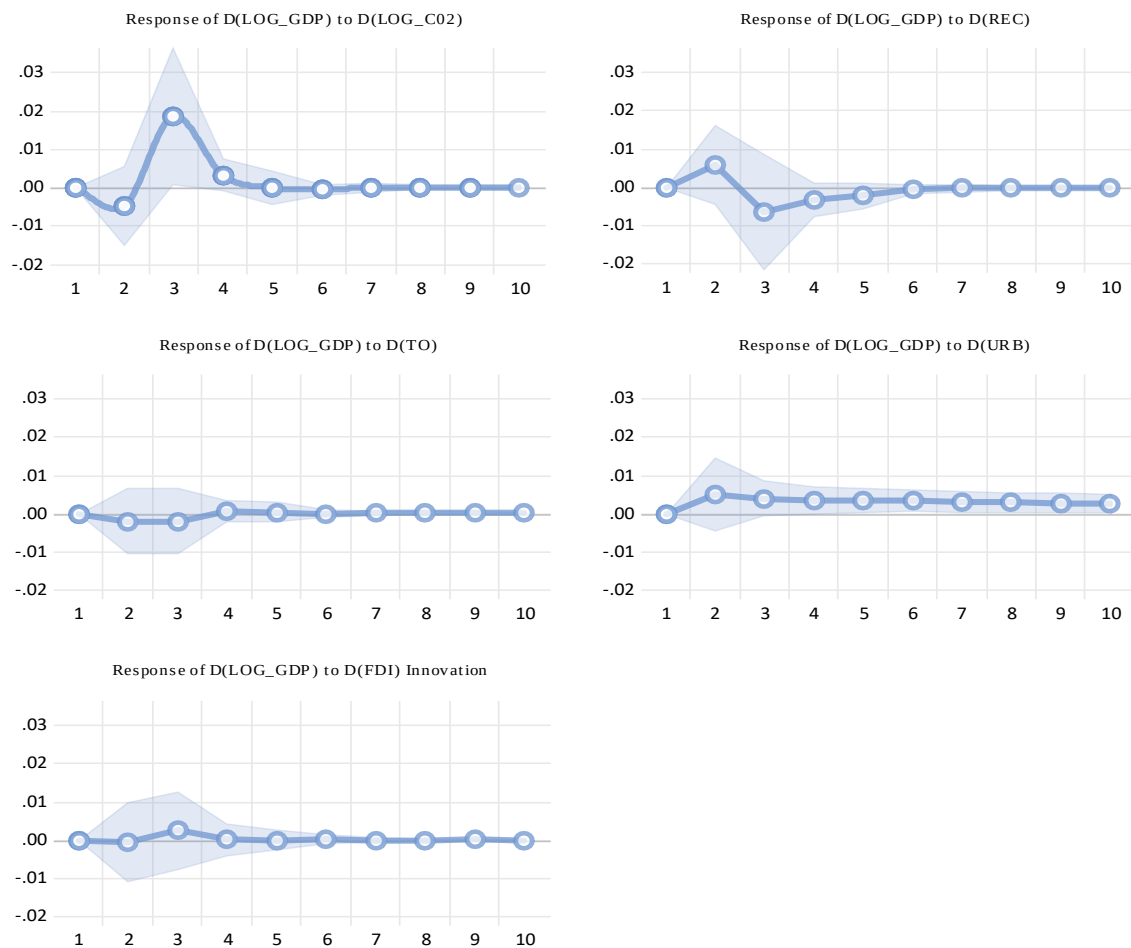
Source: Author's Computation.

The Granger causality results above show a causal relationship between GDP and CO₂ emissions, and the Granger causality results show that changes in GDP have a causal relationship with CO₂ emissions. This means that GDP fluctuations can be used to predict changes in CO₂ emissions, or vice versa; both influence each other statistically. This reflects the economic linkage with environmental impacts, which is relevant for sustainable policies. In addition, the Granger causality results between GDP and Renewable Energy Consumption show no causal relationship between the two, which means that changes in GDP cannot be used to predict renewable energy consumption and vice versa. This indicates that the two variables do not have a direct statistical relationship in the time analyzed.

4.2 Impulse Response Function (IRF)

According to Lütkepohl (2005), the Impulse Reaction Function (IRF) is a technique used to characterize the dynamics of the reaction of variables in a model to abrupt changes or shocks in other variables. The ability of this approach to recognize patterns of correlations between variables, both in the short term and over the long term, makes it an indispensable instrument for the study of Vector Autoregression (VAR) models. In addition, IRF provides quantitative information on the magnitude and duration of the effect of a shock on a variable and other variables, making it very useful in understanding the transmission mechanism of influence between variables in the system. Thus, the use of IRF not only supports the evaluation of dynamic relationships between variables but also provides deep insights into the stability and sensitivity of variables in the context of empirical research.

Figure 3: Response D(Log_GDP) with Some Variables (LogC02, REC, TO, URB, FDI)
Response to logGDP to logC02 REC TO URB TO FDI

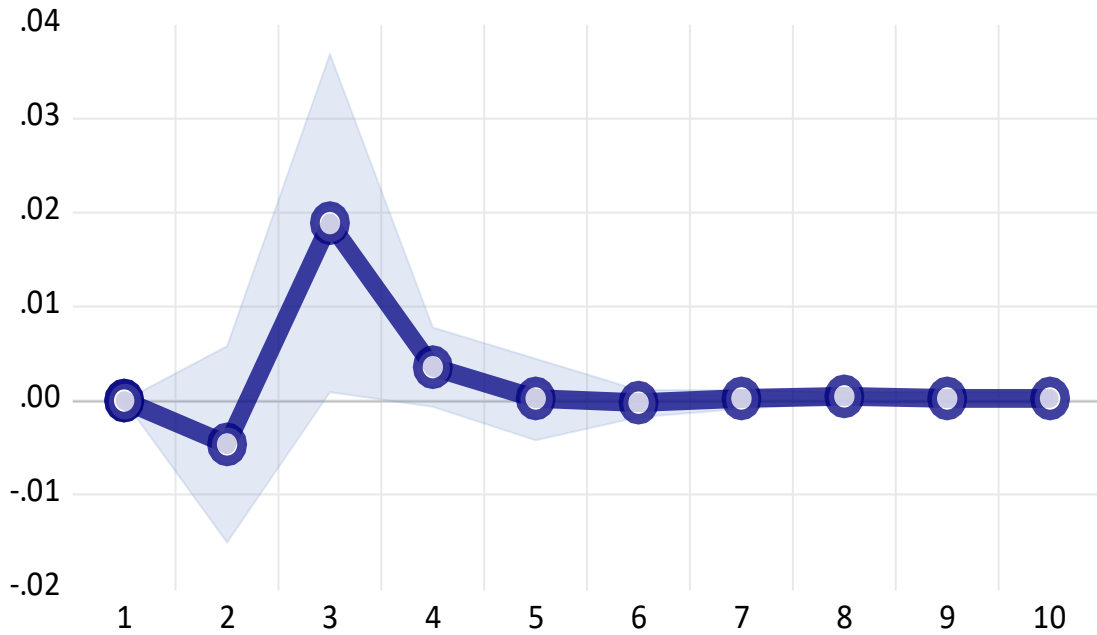


Source: Author's Computation.

Figure 3 illustrates the dynamic effects of various disruptions on economic growth in G20 countries through an impulse response function analysis. CO₂ emissions initially have a detrimental effect on the growth of the Gross Domestic Product, but the effect progressively diminishes as the economy adjusts and stabilizes in the subsequent period. In contrast, renewable energy consumption (REC) positively influences GDP, both in the short and medium term, with the effect gradually stabilizing in the long term. In addition, trade openness has a negative impact on economic growth in the short run but contributes

positively in the long run. There is a significant influence that urbanization has on economic development in the near term; however, the benefits of urbanization tend to wane with time until a stable equilibrium is reached. On the other hand, foreign direct investment (FDI) has a significant positive impact on gross domestic product (GDP), which is vital in the long term since it impacts fluctuations in the economy and helps to sustain economic growth. For the purpose of facilitating evidence-based decision-making in the process of adopting economic policies in G20 nations, our findings highlight the significance of performing a complete analysis of the short-term and long-term consequences of a range of economic variables.

Figure 4: Response of D(LOG_GDP) to D(LOG_C02)

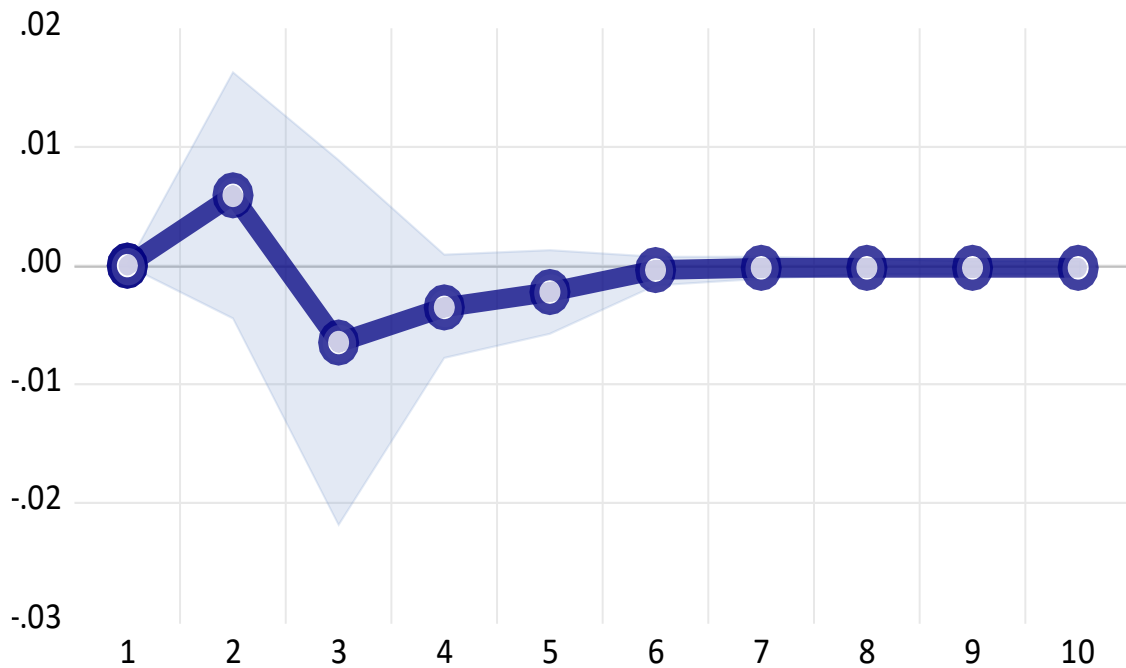


Source: Author's Computation.

Figure 4 shows positive and negative impacts on economic growth due to CO₂ emissions, where initial economic activities can lead to economic growth from increased CO₂ emissions. However, this growth cannot be sustainable and is detrimental to the economy in the long run. Therefore, there is a need for concrete steps in sustainable growth practices that can balance economic growth and environmental preservation. As shown in Figure 4, GDP has a different response over time. In the initial period, CO₂ had no response to GDP, which means that CO₂ had no significant influence in the short term. Furthermore, in the second period, there is a decrease in the response of CO₂ emissions to GDP, which is influenced by other factors. However, in the third period, the response of CO₂ emissions to GDP experienced a very significant and drastic growth, where high CO₂ emissions in this period will negatively impact GDP. Furthermore, the impulsive response decreased in the fourth period, when GDP decreased, which was almost close to zero. This indicates that CO₂ emissions will have a negative impact on economic growth, which is further supported in the fifth and sixth periods, where an increase in CO₂ emissions is predicted to harm GDP. Figure 4.2 illustrates that increasing GDP will directly accompany high economic growth. However, the response of GDP to CO₂ emissions could potentially jeopardize economic growth in G20 countries. In conclusion, initially, the increase in CO₂ emissions has a positive impact on economic growth in the G20 countries but has a negative impact or jeopardizes the economic situation in the long

run. Based on the explanation above, CO₂ emissions have a positive impact on GDP but have a negative impact on G20 countries in the long run.

Figure 5: Response of D(LOG_GDP) to D(REC)



Source: Author's Computation.

Figure 5 shows the impact of using renewable energy sources in G20 countries. This can be seen in the GDP reaction in the first period, which showed a positive reaction to renewable energy consumption, illustrating that investment in the early stages will help the economy. Furthermore, the Impulse Response in the second period experienced a relatively drastic and significant increase from GDP to renewable energy consumption. Hence, an increase or positive response occurred in the second period. However, it experienced a very drastic decline in the third period, showing a downward trend and finally reaching zero. Furthermore, the transition costs and the disuse of fossil fuels make the response of GDP to REC negative during the fourth and fifth periods. However, there is a change in the response of GDP to REC from the sixth period to the tenth period. This shows that GDP response to renewable energy sources has a positive influence, where using renewable energy sources will increase economic growth in G20 countries. Based on the impulse responses presented, it can be concluded that REC has a negative impact in the short term but has a positive impact in the long term in G20 countries.

4.3 Discussion and Findings

The results of the impulse response on the dynamic interaction between short-term and long-term CO₂ emission shocks to GDP in G20 countries become a comprehensive and multidimensional issue, which, in the short term, where CO₂ emission shocks have an indirect impact by providing economic fluctuations through their impact on economic growth activities, which increase CO₂ emissions. In addition, shocks in the long term have a very significant impact on driving climate change and implementing changes in the transition from the use of fossil energy to the use of renewable energy. Therefore, the G20 countries are important in achieving low-carbon development goals. For example, G20 countries are estimated to account for 85% of global GDP and are

responsible for 80% of carbon emissions in the energy sector worldwide (Sucahyo & Arsala Rahmani, 2023).

Furthermore, the results of the impulse response function illustrate the importance of understanding the factors that can affect GDP. This is under research from Pertiwi et al. (2024) that there is a clear and positive association between the Gross Domestic Product (GDP) and carbon dioxide (CO₂) emissions in the G20 countries. In the short term, the increase in carbon dioxide emissions has a beneficial effect on the economic expansion of the G20 countries; however, in the long term, it has a detrimental effect or makes the economic situation uncertain. This is following the results of research from A. Mardani et al. (2018) that there is a positive correlation between economic growth and CO₂ emissions in the G20 countries. This shows that there is a negative impact of increasing CO₂ emissions on economic growth in G20 countries. However, several G20 countries have implemented the use of renewable energy to be able to contribute to economic growth, reduce dependence on fossil fuels, and reduce CO₂ emissions. In contrast to the research results of Niyonzima et al. (2022), ECM analysis shows a correlation between GDP and CO₂ emissions in the long term has a positive impact, while the short term has a negative impact. Based on the above understanding, the difference in research results makes policies or concrete steps still need to be reassessed regarding the relationship between GDP and CO₂ emissions in the world.

The growth in Gross Domestic Product (GDP) during the third period demonstrates a strong and abrupt increase, which reflects a favorable short-term reaction to the changes that happened in the period before the current one. As a consequence of this, it would seem that high levels of carbon dioxide emissions during the first phase promote economic activity, which in turn has a beneficial influence on the growth of GDP. In addition, there is a positive direct reaction, which is that an increase in economic activity is directly correlated with a rise in GDP. Over time, however, the positive effects that CO₂ has on GDP gradually diminish and, in the long run, even become negative. Taking into consideration these phenomena, it seems that a persistent rise in carbon dioxide emissions may have a negative impact on the economic development of nations that are members of the G20. This is related to Alyasari & Alzawbaee (2020), who found that rising CO₂ emissions will adversely affect economic development, but the usage of renewable energy will beneficially influence CO₂ emissions. Furthermore, this aligns with the Environmental Kuznets Curve; evidence indicates that mere economic and industrial expansion is insufficient to mitigate global greenhouse gas emissions (Alakbarov et al., 2024).

On the other hand, economic growth is related to environmental degradation, where if economic growth increases, it will indirectly have an impact on the increase in CO₂ emissions (Alakbarov et al., 2024). However, when a country's income reaches a certain point, it will have an impact on economic growth and environmental quality. Similarly, economic growth can have an impact on environmental degradation with the development and industrialization of both developing and developed countries (Osobajo et al., 2020). Therefore, G20 countries have to take concrete steps and policies to immediately make a renewable energy transition in order to contribute to reducing CO₂ emissions, especially G20 members who still use fossil fuels as their main income. Furthermore, some G20 countries that have made the renewable energy transition have to be able to provide policy proposals that can help the country in order to be able to get renewable energy products in the country.

The research results of Gillani & Sultana, (2020), show that the relationship between carbon emission and income is very relevant to the EKC hypothesis, where when a country's income increases, it can slowly reduce CO₂ emissions in a country. This is also supported by Khoshnevis Yazdi & Dariani (2019), who stated that the Granger test

shows a causal relationship between economic growth and CO₂ emissions. On the other hand, this illustrates that the relationship between income and CO₂ emissions is relevant to the EKC theory, which states that when a country's income increases, it can periodically reduce the increase in CO₂ emissions (Grossman & Krueger, 1995; Mendoza et al., 2021). Therefore, G20 countries have to take preventive action in order to provide concrete and targeted policy action so that CO₂ reduction can be implemented and increase economic growth in G20 countries effectively and efficiently.

Then, economic growth in both the long and short term in the G20 countries has a fairly comprehensive relationship in relation to shocks from renewable energy consumption. On the other hand, initially the GDP response to RECs causes economic adjustments but has a positive impact in the long term, where the results can be seen in Figure 3, which shows fluctuating changes. Therefore, there is a need for a transition to renewable energy by the G20 countries, which have the highest incomes in the world and contribute to the increase in CO₂ emissions in the world today. In addition, renewable energy consumption can increase economic growth. However, the initial transition can be detrimental to GDP due to the large costs of switching from non-renewable to renewable energy. This result follows the research from Shahbaz et al. (2020), which showed that renewable energy has a significant positive impact on economic growth. In addition, using sustainable technology is one step to maintain economic expansion and mitigate increased CO₂ emissions (González-Álvarez & Montañés, 2023). Therefore, all policymakers have to be able to promote economic policies that can encourage the implementation of renewable energy use by providing incentives in fiscal and regulatory policies that are adjusted to the situation and conditions of the country concerned (Gillani & Sultana, 2020).

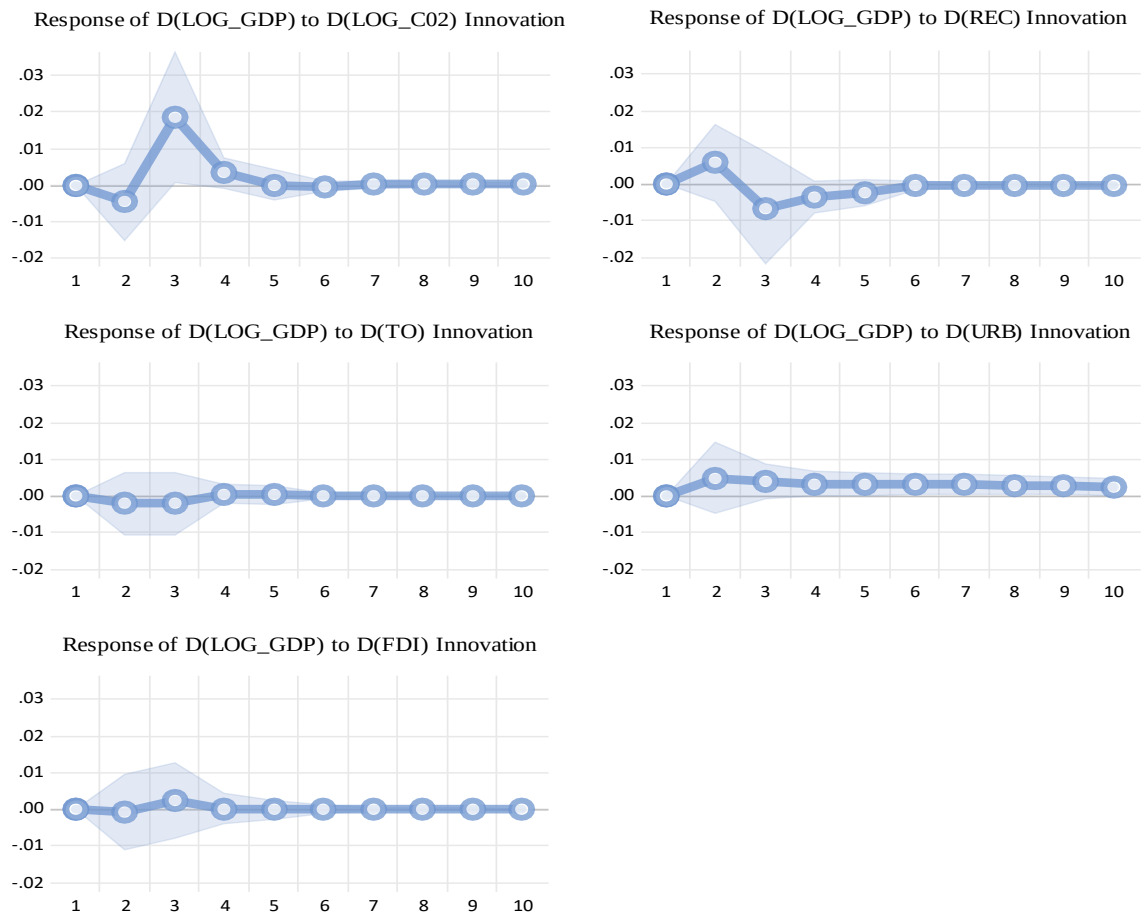
In conclusion, although renewable energy consumption has a short-term decline, it will increase economic growth in the long term. Therefore, policymakers should understand the long-term impact of renewable energy consumption and CO₂ emissions on economic growth (Mitić et al., 2022). This is very relevant to the results of research from Ntanos et al. (2018) that several factors can hinder the use of renewable energy sources, namely the lack of financial resources, which still depend on non-renewable energy, especially in several countries in the European Union. Another thing is also reinforced by Bhuiyan et al. (2022) that the use of technology in renewable energy requires quite a large cost, so an effective and efficient policy is needed. Therefore, one step is to make a policy that is proportional to the needs of the country to support the implementation of renewable energy, especially in the G20 countries. Several G20 countries have implemented this, including Australia, Canada, Japan, Germany, England, the United States, Sweden, the Netherlands, Ireland, India, South Africa, Spain, etc., where renewable energy can have a positive impact on economic growth by 58% (Shahbaz et al., 2020). Furthermore, there is a need to conduct a more comprehensive study of the dynamic relationship between GDP and other factors and to make policies that are in accordance with the conditions of the G20 member countries.

4.4 Robustness

As part of the process of determining whether or not the impulse response function in this research model is robust, we carried out the stages of model sensitivity analysis. Specifically, we altered the order in which the variables were positioned in relation to the dependent variable in order to determine whether or not the model was resilient to these modifications (Grossmann et al., 2014).

Figure 6: First Model in Robustness Test

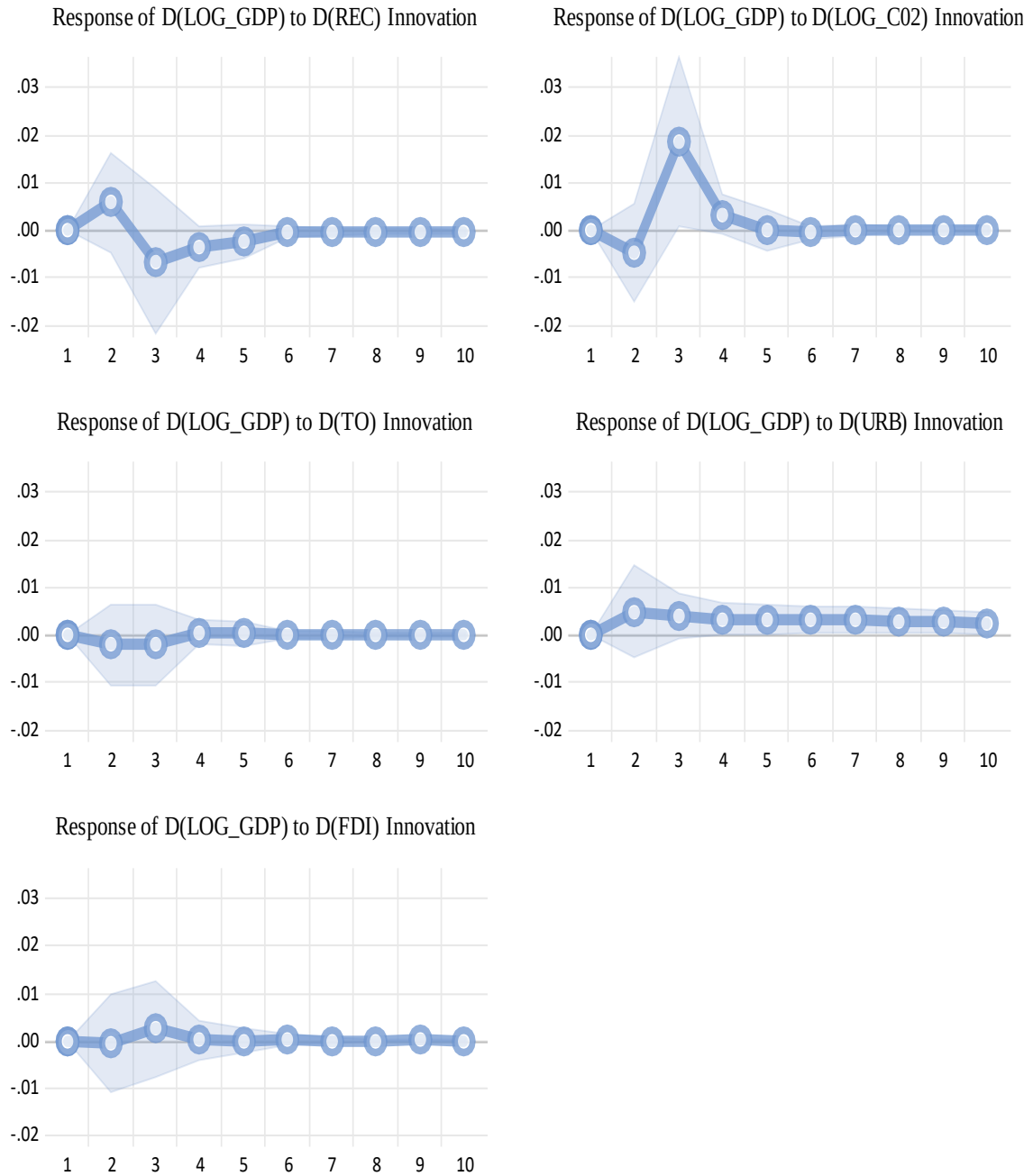
GDP → C02 → REC → TO → URB → FDI
 Response to Cholesky One S.D. (d.f. adjusted) Innovations
 95% CI using analytic asymptotic S.E.s



Source: Author's Computation.

Figure 7: Second Model in Robustness Test

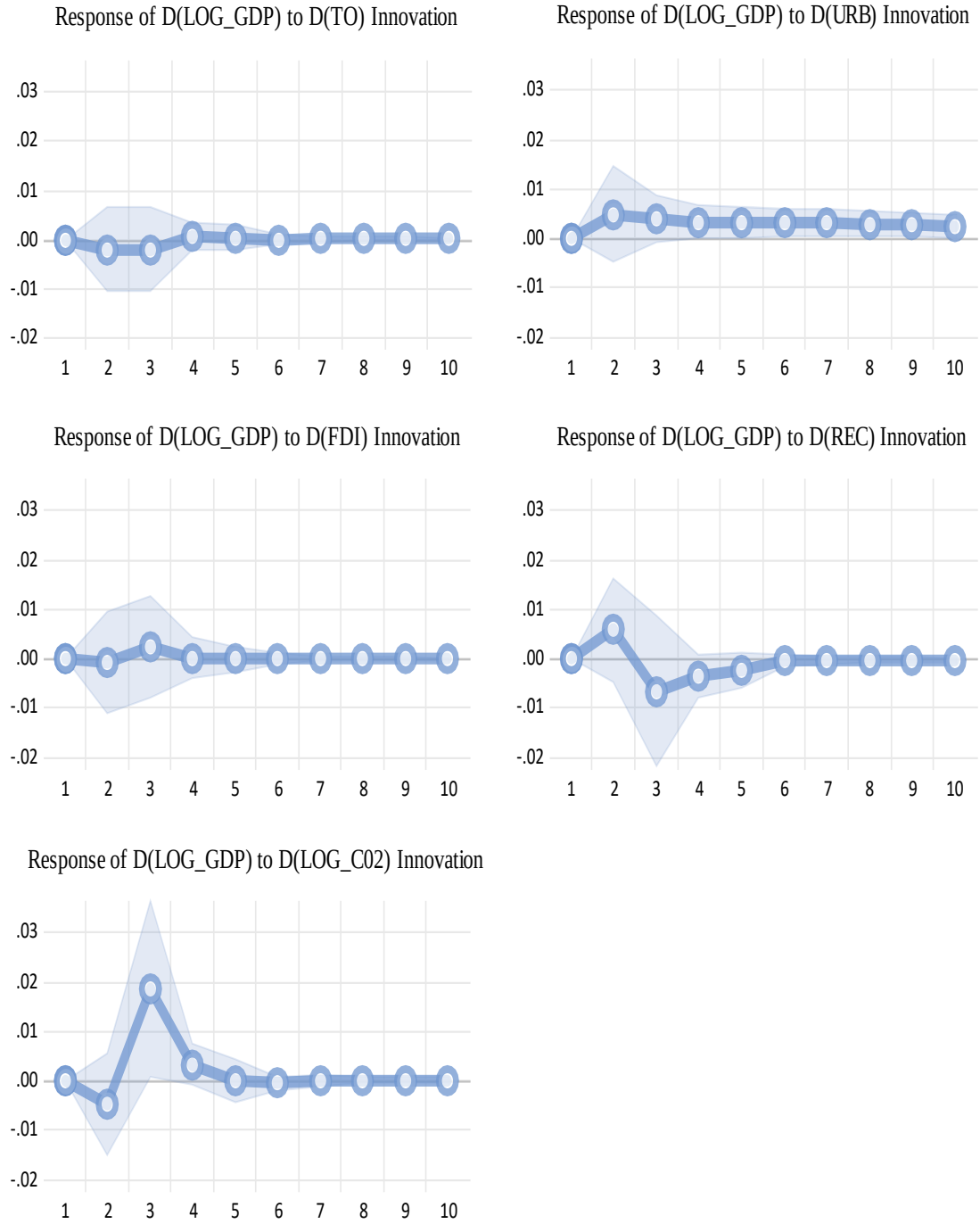
GDP → REC → C02 → TO → URB → FDI
 Response to Cholesky One S.D. (d.f. adjusted) Innovations
 95% CI using analytic asymptotic S.E.s



Source: Author's Computation.

Figure 8: Third Model in Robustness Test

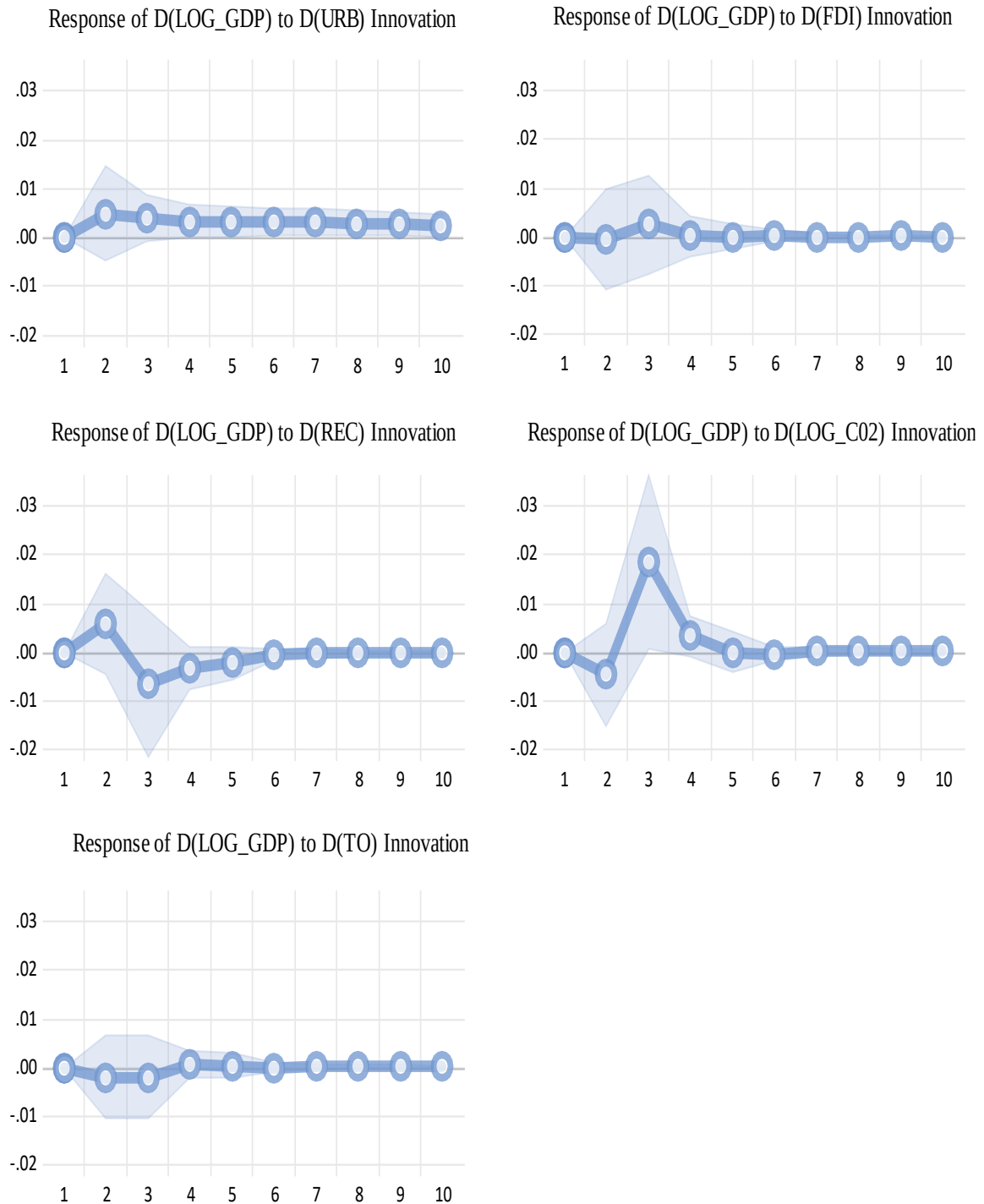
GDP → TO → URB → FDI → REC → C02
Response to Cholesky One S.D. (d.f. adjusted) Innovations
95% CI using analytic asymptotic S.E.s



Source: Author's Computation.

Figure 9: Fourth Model in Robustness Test

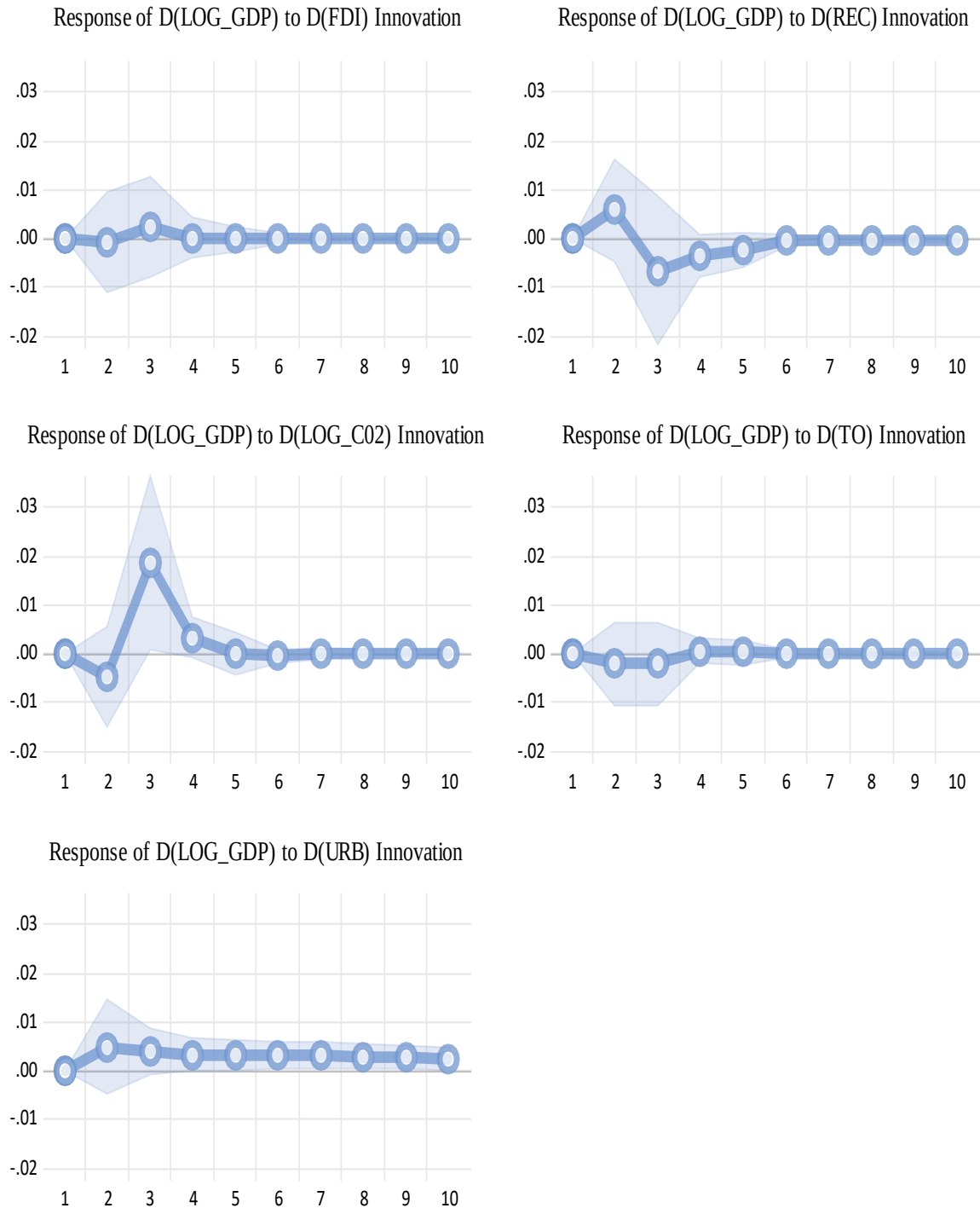
GDP → URB → FDI → REC → CO2 → TO
 Response to Cholesky One S.D. (d.f. adjusted) Innovations
 95% CI using analytic asymptotic S.E.s



Source: Author's Computation.

Figure 10: Fifth Model in Robustness Test

GDP → FDI → REC → C02 → TO → URB
 Response to Cholesky One S.D. (d.f. adjusted) Innovations
 95% CI using analytic asymptotic S.E.s



Source: Author's Computation.

The results of the impulse response function indicate that the GDP's reaction to all independent factors is unaffected by changes in the order of the variables, which is the conclusion that we draw from the findings. Furthermore, the impulse response function shows robust behavior in the variance decomposition results. An impulse response

function analysis shows that the reaction of GDP to the independent factor does not affect the ordering of the variables, thereby proving the conclusions' robustness. Furthermore, this robustness demonstrates that the impulse response function (IRF) findings are consistent and reliable. This proves that the IRF findings' primary relationships and general dynamics remain unchanged even when the variables' order changes.

5. Conclusion

This research contributes substantially to understanding the short- and long-term economic growth of G20 countries by examining the dynamic interactions between CO₂ emissions and renewable energy consumption on economic growth in G20 countries. This research is relevant to both academics and non-academics. Consequently, we will conclude the findings that have been obtained, including:

a) The results show that CO₂ positively impacts countries in the short term. This is because some G20 countries are still using fossil fuels or non-renewable energy, which can increase CO₂ emissions. On the other hand, when the industry begins to develop rapidly with more energy consumption, it will directly impact economic growth that rises dramatically for the G20 countries. In addition, this short-term economic growth phenomenon has several positive impacts, including increased employment, stronger economic growth, and greater economic stability in the G20 countries. However, the effect of increasing CO₂ emissions in G20 countries cannot be sustained in the long term due to the resulting impacts, including environmental degradation and health impacts for G20 countries.

b) The findings of the relationship between CO₂ emissions and GDP show a negative impact in the long run, so concrete actions have to be taken to immediately make a renewable energy transition, especially in G20 countries that still make fossil fuels the main income of the country. Furthermore, although there are benefits in the short term from CO₂ emissions to economic growth, different perspectives in the long term have negative consequences, including environmental damage and health problems, which can affect economic growth for G20 countries.

c) The findings show that the relationship between renewable energy consumption and GDP in the short term has a negative impact due to the need for investment at the beginning of the transition from non-renewable energy to renewable energy. Therefore, G20 countries have to have a mutual agreement on implementing or applying renewable energy sources in G20 countries. Furthermore, several G20 countries have implemented this, including Australia, Canada, Japan, Germany, England, the United States, Sweden, the Netherlands, Ireland, India, South Africa, Spain, etc., where renewable energy can have a positive impact on economic growth by 58% (Shahbaz et al., 2020). This can encourage other G20 members to find renewable energy, such as wind and hydropower, to boost economic growth and create jobs.

d) The research findings of the relationship between renewable energy consumption and GDP in the long run have a positive impact, where renewable energy consumption can increase economic growth. This result follows the research from Shahbaz et al. (2020), which showed that renewable energy has a significant positive impact on economic growth. In addition, using sustainable technology is one step to maintain economic expansion and mitigate increased CO₂ emissions (González-Álvarez & Montañés, 2023). Therefore, policymakers should understand the long-term impact of renewable energy consumption and CO₂ emissions on economic growth (Mitić et al., 2022). This should immediately be a concrete action for G20 countries to use renewable energy to mitigate the increase in CO₂ emissions for G20 countries.

6. Policy Recommendations

Based on the findings on the dynamic interaction of CO₂ emissions and renewable energy consumption on economic growth in G20 countries with the VAR Panel approach, there are several policy recommendations that can be applied by G20 members, including:

a) Firstly, G20 countries have to begin to reduce the use of fossil fuels or non-renewable energy to encourage sustainable economic growth for G20 countries. On the other hand, G20 countries need to take preventive action by immediately finding renewable energy sources according to the conditions and natural resources owned by each country in the G20. In addition, there is a need for more investment at the beginning of the transition period from non-renewable energy to renewable energy. One of the actions is subsidizing grants for renewable energy, which is done to reduce non-renewable energy dependence and indirectly reduce CO₂ emissions over time for G20 countries.

b) Secondly, G20 countries need to raise awareness for G20 member countries that one of the concrete steps that can be taken is to improve policy standards to mitigate the increase in CO₂ emissions by implementing renewable energy without reducing economic growth in G20 countries. In addition, G20 countries can optimize the use of more environmentally friendly and energy-efficient technologies, which can reduce dependence on non-renewable energy consumption and emissions and move towards more proactive energy sources to contribute to sustainable development and economic growth that promote the use of renewable energy sources so that they can be applied in several G20 countries that are still in the renewable energy transition phase.

7. Limitations and Future Recommendations

The research boundary of this study is limited to G20 countries, namely Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Turkey, the United Kingdom, the United States, and the European Union. This is due to differences in reporting standards and macroeconomic factors across countries, which may only partially reveal the sectoral phenomena, dynamics, or impacts of renewable energy technologies in those countries. In addition, while the Panel VAR methodology can examine the dynamic interaction between CO₂ emissions and renewable energy use in relation to economic development, this method must comprehensively account for other related impacts. Therefore, G20 countries need to adopt plans to shift from fossil fuels to renewable energy sources. Furthermore, the data may be historical, which requires a comprehensive account of the progress of renewable energy technologies or regulations across G20 countries.

In addition, future studies may overcome constraints in various phases, including plans to improve uniformity and quality standards for each G20 country. This suggests that G20 countries can work with many international bodies or organizations to use more advanced data analysis methods and standardize data collection methods. This will allow them to analyze data from many sources with better data quality, resulting in more accurate studies. The dynamic relationship between CO₂ emissions, renewable energy use, and economic growth in G20 countries is investigated in this study using the Panel VAR approach. Then, additional research might include independent variables instead of

dependent variables or vice versa, thus offering data on technical innovations and government actions intended to enhance sustainable economic development for G20 countries.

Furthermore, it is important to investigate energy and non-energy factors that have not received much attention, such as technological innovation, emissions levies, and the availability of fundamental policies that can mitigate change without compromising economic development in G20 countries. Conversely, it is necessary to include more energy variables in the model equation to better understand their impact across a wider study area. Future studies might provide policy recommendations tailored to the economic status and specific circumstances of each G20 country. Methodologically, research should investigate more advanced econometric approaches that can overcome the limitations of panel variance analysis. By using Panel Data VAR, the research could also conduct a comprehensive study of the G20 group and other countries, such as OIC countries, GCC countries, D-8 countries, Visegrad countries, Scandinavian countries, ASEAN countries, etc.

Therefore, future research can look at the short-term and long-term dynamic interactions between one variable and another with better data quality, the application of new variables, the expansion of the coverage of recent years, the use of extraordinary techniques, and more thorough comparative analysis so that future researchers can overcome the limitations of this study. This will ensure that further studies are very useful and helpful in clarifying the appropriate policy for the situation and setting. Lastly, since we excluded GDP2 as an independent variable, our study did not include the complete EKC theory in our research model. We suggest that the independent variable in future studies should be GDP2.

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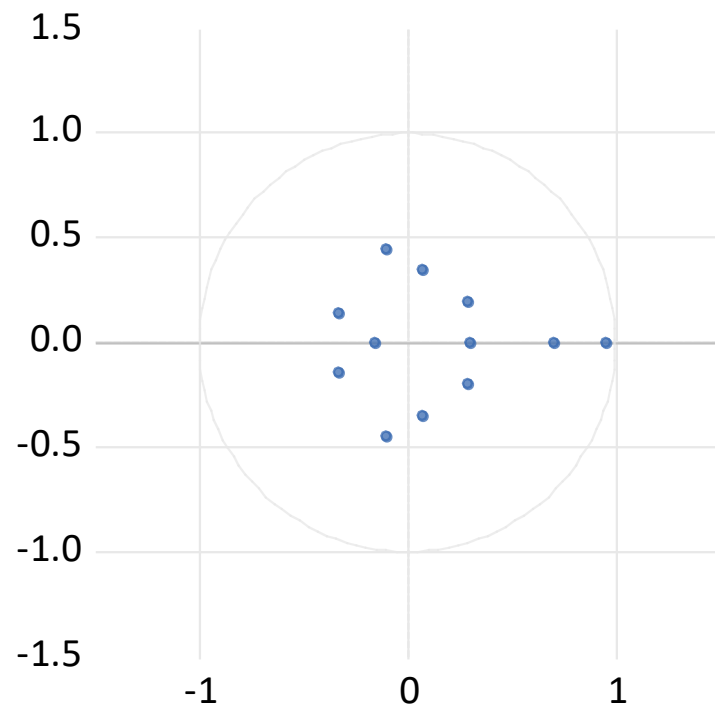
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Appendix

Inverse Roots of AR Characteristic Polynomial]



VAR Residuals

