ENERGY CONSUMPTION, ECONOMIC GROWTH & EMISSIONS LEVEL: A COMPARATIVE STUDY OF QUAD COUNTRIES

A Thesis

Submitted in Fulfilment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

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Declaration

I, **Matali Mahajan** hereby declare that the thesis entitled, "**Energy Consumption, Economic Growth & Emissions Level: A Comparative Study of QUAD Countries**" submitted to Thapar Institute of Engineering and Technology (Deemed to be University), Patiala, in fulfilment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY** in **ECONOMICS**, is a record of original research work carried out by me under the guidance and supervision of **Dr. Ash Narayan Sah**, Associate Professor, Department of Humanities and Social Sciences, Thapar Institute of Engineering and Technology. The matter embodied in this thesis has not been submitted in part or full to any other institute for the award of any degree.

Mahajan.

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Certificate

This is to certify that the thesis entitled, "**Energy Consumption, Economic Growth, & Emissions Level: A Comparative Study of QUAD Countries**" which is being submitted by Ms. Matali Mahajan in fulfilment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** in **ECONOMICS**, is a record of the candidate's original research work carried out under my supervision and guidance. The matter embodied in this thesis has not been submitted in part or full to any other institute for the award of any degree. I also certify that she has complied with the Plagiarism Guidelines of the University.

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Dedicated to:

Dr. Rajat Mahajan

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"It always seems impossible until it's done."

~ Nelson Mandela

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With Gratitude,

Matali Mahajan

Abstract

Nations worldwide aspire for higher economic growth and development to improve living conditions and secure the welfare of their citizens. The trajectory of economic progress is intricately connected to the energy resources a nation depends upon, which frequently reflect its level of development. This study explored the relationship between CO2 emissions and key macroeconomic and socio-economic variables in the QUAD (Australia, India, Japan, and the USA) nations from 1970 to 2021 using annual data. The QUAD nations include three developed and one developing nation, representing a unique and influential group in the global energy-emission-growth nexus due to their substantial contribution in global energy consumption, GHG emissions, and economic growth. The objective of the study is to identify the key macroeconomic parameters impacting the CO2 emission level of these nations, to test the presence of Environmental Kuznets Curve (EKC) hypothesis, and to assess the influence of socio-economic variables on the CO2 emissions. The research aims to fill a significant gap in the literature by focusing on this underexplored group of nations, given their high share in the total global emissions. The data used in the study is sourced from World Development Indicators (WDI) and Our World in Data (OWID).

By employing HP filter on annual dataset, the result indicates that emissions are procyclical in nature i.e., emissions move in line with economic growth, fossil fuel use, and trade, making them sensitive to economic cycles. A key finding of the analysis is the validation of the Environmental Kuznets Curve (EKC) hypothesis in three of the four countries studied, using a Quadratic Regression technique. For India, the USA, and Australia, the results confirmed an inverted U-shaped relationship between economic growth and emissions, suggesting that emissions initially

increase with economic growth but eventually decline once a certain level of income is reached. On the contrary, Japan displayed a more linear relationship between CO_2 emissions and economic growth. Additionally, evidence from the Two Stage Least Square regression (2SLS) analysis confirmed that GDP, energy use, urban population, population density, and rural population are significant determinants of emissions.

Overall, the findings contribute to understanding the complex interplay between economic development and environmental sustainability in advanced and emerging economies, providing a comprehensive empirical basis for further research on growth–energy–emission nexus. The study provides both theoretical and practical implications. It suggests that policy interventions should prioritize the adoption of renewable energy, promote sustainable urban development, and implement country-specific strategies to address emissions.

List of Contents

List of Tables

List of Figures

List of Abbreviations

ADF	Augmented Dickey-Fuller
ARDL	Autoregressive Distributed Lag
CBD	Convention on Biological Diversity
CDM	Clean Development Mechanism
CO2e	Carbon Dioxide equivalent
EKC	Environmental Kuznets Curve
FEVD	Forecast error Variance Decomposition
GDP	Gross Domestic Product
GHG	Green House Gas
HP	Hodrick-Prescott
IEA	International Energy Agency
IPCC	International Panel for Climate Change
IRF	Impulse Response Function
JI	Joint Implementation
LNG	Liquified natural Gas
NDC	Nationally Determined Contributions
OLS	Ordinary Least Squares
OWID	Our World in Data

PM	Particulate Matter
PP	Philips Perron
SDG	Sustainable Development Goals
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, And Technology
SVAR	Structural Vector Autoregression
UNFCCC	United Nations Framework Convention on Climate Change
VIF	Variance Inflation Factor
VOCs	Volatile Organic Compounds
VECM	Vector Error Correction Model
WDI	World Development Indicators
2SLS	Two-Stage Least Square

CHAPTER 1

Introduction

1.1 Background

The climate change has emerged as one of the greatest global challenges with profound implications for sustainable development. The various prominent cities across the continents are becoming increasingly vulnerable as human-induced greenhouse gas emissions drive up temperatures and disrupt the delicate balance of the Earth's climate systems. According to the Intergovernmental Panel on Climate Change, CO_2 emissions persist in the atmosphere for 300 to 1000 years, intensifying global warming and contributing to irreversible impacts such as the melting of polar ice caps. These environmental disruptions threaten the social, economic, and environmental foundations of development, particularly in developing and least developed countries that are both highly exposed and least equipped to cope with climate-related shocks. Recognizing these climate risks, the 2030 Agenda for Sustainable Development places sustainability at the core of international cooperation through its 17 Sustainable Development Goals that emphasizes the interdependence of economic growth, energy consumption, and environmental protection. The agenda identifies climate change as a major obstacle to achieving sustainable development.

Nations across the globe aspire to achieve rapid economic growth and development to improve living standards and ensure the well-being of their populations. However, the trajectory of economic progress is deeply intertwined with the types of energy resources a country utilizes, which often reflects its developmental stage. For developing nations, the challenge is two-fold: to promote economic prosperity and improve the quality of life for their citizens while addressing the pressing environmental concerns that threaten the global sustainability. The pattern of energy consumption in a country not only reveals its current economic status but also shapes its energy portfolio, determining the mix of resources it depends on. The debate on energy consumption patterns and their effect on a country's growth and development, the quality of life of its people, the effect on climate, and other essential aspects of social and economic life has been going on among academicians and policymakers for a long time. Developing countries such as India and China have historically relied on conventional energy sources like coal and oil (IEA, 2020; National Bureau of Statistics of China, 2020), which, while driving economic growth, have also contributed significantly to environmental degradation through high levels of carbon dioxide (CO_2) emissions. In 2017, global energy related CO_2 emissions reached a staggering 32.5 gigatons (iea, 2017), surpassing the natural capacity of land and ocean sinks to absorb CO_2. Fossil fuels have been the backbone of global economic expansion since the Industrial Revolution, but their widespread use has come at a steep environmental cost. Fossil Fuels are major emitters of greenhouse gases (GHGs) and pollutants such as nitrogen dioxide (NO_2), sulphur dioxide (SO_2), volatile organic compounds (VOCs), and particulate matter (PM). These emissions are the key drivers of global challenges, including climate change, ozone layer depletion, and air pollution, which pose severe risks to human health and ecological systems (Audi et al., 2020). The reliance on fossil fuels is a problem faced by both developed and developing nations, however it is particularly pronounced in developing nations, where energy access and affordability often take precedence over environmental considerations. For instance, in India, the primary energy sources include coal and biomass, resulting in environmental degradation, hindering agricultural productivity by reducing soil fertility and increasing the vulnerability of ecosystems. Furthermore, air pollution has severe health impacts, such as respiratory and cardiovascular disease which places a heavy burden on public health systems and extends the cycles of poverty. According to the World Health Organization, over 90% of the global population breathes air that exceeds safe pollution levels, and air pollution is linked to approximately 6.7 million premature deaths annually, with the majority occurring in developing nations (WHO, 2024).

To address these challenges, researchers from the Asia Pacific Energy Research Centre (Asia Pacific Energy Research Centre, 2007) introduced the concept of the "four A's", which serve as the pillars of energy security, namely, Availability, Accessibility, Affordability, and Acceptability (Sankhyayan & Dasgupta, 2019). While the availability of energy resources is a necessary condition for energy security, it is not sufficient on its own. True energy security can only be achieved when energy is not only available but also accessible to all segments of the population, affordable for households and businesses, and acceptable in terms of environmental and social impacts. For instance, without adequate infrastructure, energy resources may be available but will remain inaccessible to remote or marginalized communities. Similarly, even if energy is accessible, high costs may render it unaffordable for low-income households, limiting its acceptability. Therefore, achieving energy security requires a holistic approach that includes developing infrastructure, formulating policies to combat poverty, and integrating renewable energy sources into daily activities to reduce environmental pollution and promote sustainability. The transition to renewable energy has been a gradual process. For instance, nuclear energy only became a part of the global energy mix in the 1960s, while modern renewables like solar energy and wind energy were not widely adopted until the 1980s (Ritchie & Rosado, 2020). Despite their late entry, these renewable energy sources have gained significant traction in recent decades due to technological advancements, declining costs, and growing awareness of their environmental benefits. However, the integration of renewables into the energy systems of developing nations remains a challenge, particularly in regions where infrastructure and financial resources are limited. As per the IEA report 2021, 80% of India's energy demand is met by conventional sources of energy such as coal, oil, and solid biomass, which accounts for 6-7% of the global CO_2 emissions (International Energy Agency, 2021). Developing countries, which represent around 77% of the world's population, contribute approximately 63% of total GHG emissions. This underscores the critical role of energy choices in shaping both economic and environmental outcomes of the third world countries including India and China, and its implications for the whole world. Thus, the relationship between economic growth and environmental sustainability has been extensively studied in economic literature.

In the recent decades, the escalating threat of global warming has intensified research into the drivers of GHG emissions, with studies highlighting the significant contributions of the energy, transportation, and industrial sectors (Calvin et al., 2023). The popular frameworks used to examine the relationship between energy, economic growth, and environment includes EKC hypothesis, STIRPAT model, Kaya identity, and Pollution Heaven hypothesis. In this study, we particularly employed EKC hypothesis and STIRPAT model to analyse the nexus. The EKC hypothesis posits that environmental degradation initially increases with economic growth but eventually declines as economies reach higher levels of development (Grossman & Kruger, 1991). This trend is influenced by structural changes in the economy, such as the shift from agrarian to industrial activities, which initially heightens environmental pressure but later leads to the adoption of cleaner technologies and practices as the income level rises. However, the scale effect of economic activities where increased production leads to greater waste and emissions remain a significant challenge. As economies expand, the demand for energy rises to meet basic human needs and enhance productivity, further intensifying the strain on the environment (Asumadu-Sarkodie & Owusu, 2016; Edenhofer et al., 2012). The study seeks to examine how different factors such as the level of development, energy consumption, the distribution of populations between rural and urban areas affects the emission level, and moreover what policy implications can be given to help these countries meet the global emission targets. As global energy demand continues to rise, the need for sustainable energy solutions become increasingly urgent. In the year 1990, the world energy landscape was dominated by fossil fuels wherein, coal, oil, and natural gas were the primary energy sources, reflecting the industrial and economic priorities of the time. While this reliance has persisted, the growing awareness of environmental challenges has spurred a gradual shift towards the cleaner energy sources.

The figure 1.1 shows the share of various components of energy in the year 1990. It depicts that Coal contributed 25.51% of the global energy supply, underscoring its critical role in electricity generation and industrial processes. The widespread use of coal was driven by its abundance, affordability, and established infrastructure, particularly in industrialized nations (Ministry of Coal, 2024). However, the environmental implications of coal combustion were becoming increasingly apparent, though they had not yet driven significant shifts in energy policy. Oil emerged as the dominant energy source in 1990, accounting for 37.22% of the global energy mix. Its flexibility and high energy density made it indispensable for transportation, industrial applications, and as a feedstock for petrochemical products (International Energy Agency, 2024). The global economy’s dependence on oil was further reinforced by the expansion of the automotive industry and the growth of international trade, which relied heavily on oil-based fuels. Despite its advantages, the environmental and geopolitical challenges associated with oil extraction and consumption were beginning to draw attention, particularly in light of climate change and energy security (Oppenheimer, 1992).

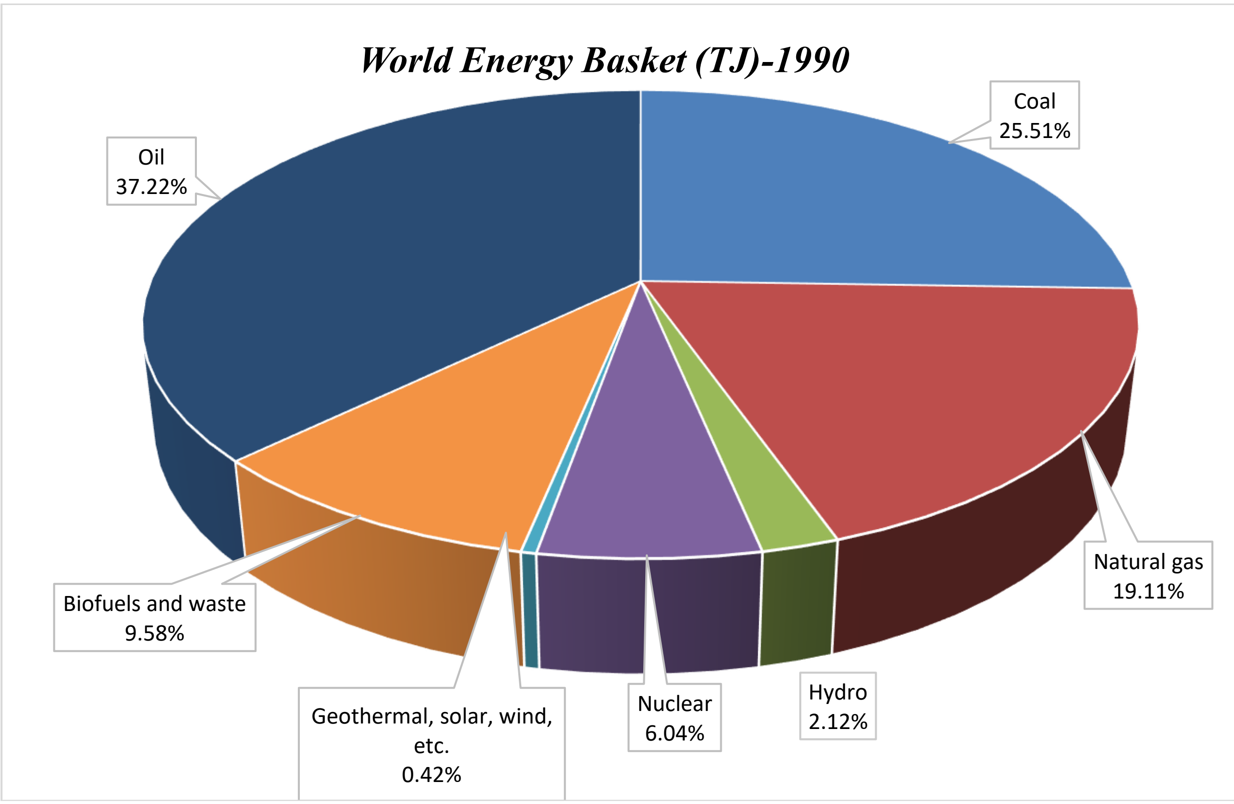


Figure 1.1 Share of world energy in 1990.
Data Source: IEA World Energy Balances https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

Natural gas, contributing 19.11% of the global energy supply, played a significant but secondary role compared to coal and oil. Its use was primarily concentrated in heating, electricity generation, and as an industrial fuel. Natural gas was often viewed as a cleaner alternative to coal and oil due to its lower CO_2 emissions per unit of energy produced. However, its infrastructure was less developed, and its market penetration was limited by logistical challenges, such as the need for pipelines and liquefied natural gas (LNG) facilities.

The fig 1.1 shows that the world energy basket of the year 1990 was almost 80% comprised of fossil fuels. This clearly shows the reliance of the world economy on traditional energy sources for running economy and business. Biofuels and waste, accounting for 9.58% of the global energy mix, represented a smaller but notable share of energy consumption. This category included traditional biomass, such as wood and agricultural residues, which were widely used for cooking and heating purpose in less developed nations. While biofuels and waste were considered a renewable energy source, their use was often associated with inefficiencies and ecological concerns, like deforestation and indoor air pollution (Malik et al., 2024). Nuclear energy contributed 6.04% of the global energy supply in 1990, primarily in the form of electricity generation. The adoption of nuclear power was driven by its ability to produce large amounts of energy with minimal greenhouse gas emissions. However, the growth of nuclear energy was constrained by concerns over safety, nuclear waste disposal, and high capital costs (The Global Nuclear Future, 2009). Hydroelectric power, representing 2.12% of the energy mix, was another renewable energy source, though its contribution was limited by geographical and environmental constraints. Geothermal, solar, wind, and other emerging renewable energy sources collectively accounted for a mere 0.42% of the global energy supply in 1990. These technologies were in their initial stages, with limited infrastructure and high costs hindering their widespread adoption. The energy landscape of 1990 was thus heavily dominated by fossil fuels, with renewable energy sources playing a marginal role. Combinedly, the proportion of renewable energy within the global energy portfolio of 1990 is not more than 20%. This reliance on fossil fuels created the environmental and energy challenges that lead to a shift towards a more environmentally friendly energy framework in the decades to come.

On the contrary, the world energy basket of 2022 as shown in the figure 1.2 indicates that it has not undergone significant changes, however, some progress has certainly taken place on the renewable energy front, reflecting the growing awareness of climate change, advancements in technology, and shifts in energy policy. While fossil fuels continued to dominate, their share in the energy basket had evolved, and renewable energy sources had begun to play an important role (International Energy Agency, 2023b). Coal accounted for 25.51% of the global energy supply in 1990, and its share increased to 27.63% by 2022. This growth is closely linked to the rapid industrialization and urbanization observed in emerging economies, particularly China and India. For instance, China's coal consumption alone rose by 4.3% in 2022 (Cao et al., 2024); additionally, the conflict between Russia and Ukraine led to significant natural gas shortages across Europe, prompting several European nations to increase coal usage to satisfy their energy requirements (Huang et al., 2023). Nevertheless, the substantial environmental impacts of coal, such as increasing CO_2 emissions and air pollution has intensified global calls for shift toward non-conventional energy sources.

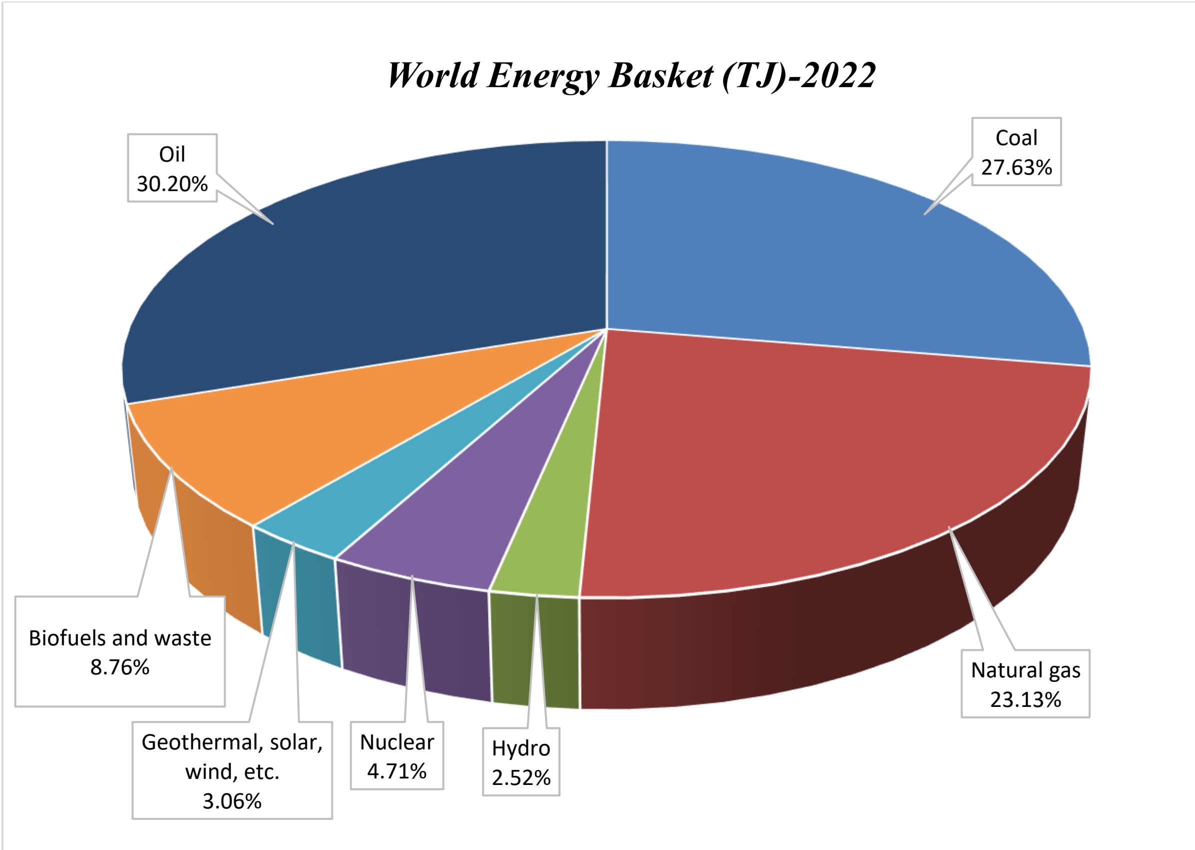


Figure 1.2 Share of World Energy in 2022.
Data Source: IEA World Energy Balances https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

The proportion of oil in the world energy basket declined from 37.22% in 1990 to 30.20% in 2022, reflecting a gradual shift away from oil in certain sectors. The transportation sector, which had historically been heavily reliant on oil, began to see the adoption of alternative fuels and electric vehicles (International Energy Agency, 2023a). Moreover, the improvements in energy efficient systems and the diversification of energy sources contributed to the reduced reliance on oil. Despite this decline, the oil remained a critical component of the global energy system, particularly in industries such as aviation, shipping, and petrochemicals. Natural gas experienced a notable increase in its share of the world energy basket, rising from 19.11% in 1990 to 23.13% in 2022. This growth was driven by the expansion of natural gas infrastructure, including pipelines and LNG terminals, as well as its perception as a cleaner alternative to coal and oil. Natural gas became a key energy source for electricity generation, heating, and industrial processes, particularly in regions transitioning away from coal. However, the environmental impact of natural gas, particularly methane emissions during extraction and transportation, remained a concern. Biofuels and waste saw a slight decline in their share of the world energy basket, from 9.58% in 1990 to 8.76% in 2022. Although the traditional biomass remains prevalent in developing countries, the advancement of modern biofuels, like ethanol and biodiesel, has been hindered by issues related to sustainability, land use, and competition with food production (Onu et al., 2024). Efforts to improve the efficiency and sustainability of biofuels are ongoing, but their contribution to the world energy basket remained relatively less. Nuclear energy's share of the world energy basket decreased from 6.04% in 1990 to 4.71% in 2022. This decline was influenced by factors such as the high costs of nuclear power plants, public opposition following nuclear accidents, and competition from other energy sources. However, nuclear energy continued to play a role in providing low-carbon electricity in several countries. Hydroelectric power maintained a relatively stable share in the world energy basket, increasing slightly from 2.12% in 1990 to 2.52% in 2022. While hydro-electricity remained a reliable and renewable energy source, its growth was limited by geographical constraints and environmental concerns related to large-scale dam projects. The most significant change in the world energy basket between 1990 and 2022 was the rise of geothermal, solar, wind, and other emerging non-conventional energy sources. Their collective share increased from a mere 0.42% in 1990 to 3.06% in 2022, reflecting significant advancements in technology, declining costs, and supportive policy frameworks. Solar and wind energy, in particular, experienced rapid growth, driven by their scalability, declining costs, and ability to generate electricity with minimal environmental impacts. The expansion of renewable energy was further supported by the international efforts to combat climate change, such as the Paris Agreement, which emphasized the need to transition to low-carbon energy systems.

Hence, the world energy basket of 2022 as shown in the figure 1.2 reflected a gradual but significant shift towards a more diverse and sustainable energy system. While fossil fuels continued to dominate, the growing share of renewable energy sources signaled a transition towards a low-carbon future. This evolution was driven by a combination of technological advancements, policy interventions, and increasing awareness of the environmental and social impacts of energy production and consumption (Pathak et al., 2023). While the global energy landscape is undergoing a transformative shift towards sustainability, the role of specific regional alliances and key geopolitical actors remains critical to understanding the broader dynamics of this transition. Among these, the QUAD countries i.e., the United States, India, Japan, and Australia occupy a central position in the energy-emission-economy nexus, given their substantial contributions to global energy consumption, greenhouse gas emissions, and economic output. Their combined and individual efforts to mitigate climate change, along with their strategic geopolitical influence, makes them essential for the discussion on achieving a sustainable energy future (*Quad Leaders' Joint Statement*, 2023). The QUAD countries represent a unique and influential group in the global energy-emission-economy nexus. These nations, while diverse in their economic structures, energy resources, and developmental trajectories, collectively account for a significant share of global energy consumption, GHG emissions, and economic output. Their strategic importance in addressing the climate change arises from their role as major emitters, technological innovators, and policy leaders. The QUAD nations are not only critical players in shaping global energy markets but also pivotal in driving international efforts to combat climate change. Their collective actions and policies have far-reaching implications for global sustainability, making them critical for understanding the association between energy, emissions, and economic growth.

The United States, as the largest economy of the world and historically the biggest emitter of GHGs (Mehling et al., 2019), has a profound influence on global energy and climate policies. Despite its reliance on fossil fuels, particularly oil and natural gas, the U.S. has made significant progress in transitioning to renewable energy sources such as wind and solar (eia, 2020). The U.S. has also been a leader in technological innovation, investing heavily in clean energy R&D, carbon capture and storage (CCS), and electric vehicle (EV) infrastructure (Idoko Peter Idoko et al., 2024). These efforts underscore the U.S.'s dual role as both a major emitter and a driver of global climate solutions. Another important member of the QUAD, India, on the other hand, represents the challenges and opportunities faced by the rapidly developing economies. As the third-largest emitter of GHGs in 2023 (Crippa et al., 2024a), India's energy consumption is heavily dependent on the coal, which accounts for over 70% of its electricity generation (Kumar &Majid, 2020). However, India has also emerged as a world leader in non-conventional energy, particularly solar power, with ambitious targets to achieve 500 gigawatts (GW) of renewable energy capacity by 2030 as announced in the COP-26 (Ministry of Renewable Energy, 2025). The country's commitment to the Paris Agreement, coupled with initiatives such as the International Solar Alliance (ISA), highlights its proactive approach to balancing economic growth with environmental sustainability. India's energy transition is critical not only for its own development but also for global climate goals, given its large population and rapidly growing energy demand. In the recent years, India has accomplished a landmark in its energy transition journey by achieving 50% of its installed electricity capacity from renewable sources five years ahead of the target under its Nationally Determined Contributions (NDC) to the Paris agreement. This significant milestone highlights India's commitment to climate action and sustainable development (Ministry of New and Renewable Energy, 2025).

Japan, as a technologically advanced nation with limited natural resources, has long been a pioneer in energy efficiency and innovation (Tolliver et al., 2021). Following the 'Fukushima nuclear disaster' in 2011, Japan faced significant challenges in restructuring its energy mix, leading to increased reliance on fossil fuels such as coal and liquefied natural gas (LNG). However, the country has since reaffirmed its commitment to climate action, setting a target to achieve carbon neutrality by 2050 (eia, 2012). Japan's Green Growth Strategy, which focuses on promoting renewable energy, hydrogen fuel, and energy-efficient technologies, reflects its leadership in addressing climate change through innovation and policy. Additionally, Japan's role as a major provider of climate finance and technology transfer to developing countries further underscores its importance in the global energy-emission-economy nexus (Ministry of Foreign Affairs of Japan, 2022). Australia, endowed with abundant natural resources, is a major exporter of coal and liquefied natural gas (LNG), making it a key player in global energy markets. However, its reliance on fossil fuels has also made it one of the highest per capita emitters of GHGs (Alzaabi et al., 2023). Despite this, Australia has made significant progress in renewable energy development, particularly in solar and wind power, which now accounts for a growing share of its electricity generation (Blakers et al., 2021). The country's commitment to the Paris Agreement and its emissions reduction plans, which aims to achieve net-zero emissions by 2050, reflects its efforts to align its energy policies with global climate goals (Department of Climate Change). The Australia's role in the QUAD is particularly significant given its strategic location in the Indo-Pacific region, where climate change poses severe risks to ecosystems, food security, and human livelihoods.

The QUAD countries' collective efforts to combat climate change are not limited to their individual actions but also extend to their collaborative initiatives. The QUAD Climate Working Group, established in 2021, aims to enhance cooperation on climate mitigation and adaptation, clean energy innovation, and sustainable infrastructure development (Ministry of External Affairs, 2021). This group provides a platform for sharing technological know-how and allocating resources to tackle the challenge of climate change. For instance, the QUAD's focus on clean hydrogen as a future energy source highlights its commitment to advancing innovative solutions that can help decarbonize sectors such as heavy industry and transportation. The QUAD plays a crucial role in mitigating the influence of significant emitters like China, which continues to depend on coal and is the largest global emitter of GHGs. By promoting sustainable energy practices and climate-resilient infrastructure in the Indo-Pacific region, the QUAD aims to promote regional stability and economic growth while addressing the need for climate action. This strategic aspect makes the QUAD's role in the world of energy even more complicated, making it a key player in shaping the future of energy and climate policy. Hence, the QUAD countries occupy a central position in the nexus given their significant contributions to energy consumption, GHG emissions, and economic output. Their diverse approach to address climate change, ranging from technological innovation and renewable energy deployment to policy leadership and international cooperation highlights their collective potential to drive global sustainability. This study aims to investigate and examine the relationship between energy consumption, GHG emissions, and economic growth, with a particular focus on QUAD nations. By examining this nexus, this study aspires to provide valuable insights into the challenges and opportunities associated with achieving a sustainable energy future. The findings of this research will not only contribute to the academic discussion on energy and climate but also inform policy decisions that can accelerate the transition to a low-carbon economy.

1.2 Definition of Climate Change

As per United Nations Framework Convention on Climate Change (UNFCCC), the climate change refers to "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (United Nations, 1992a).

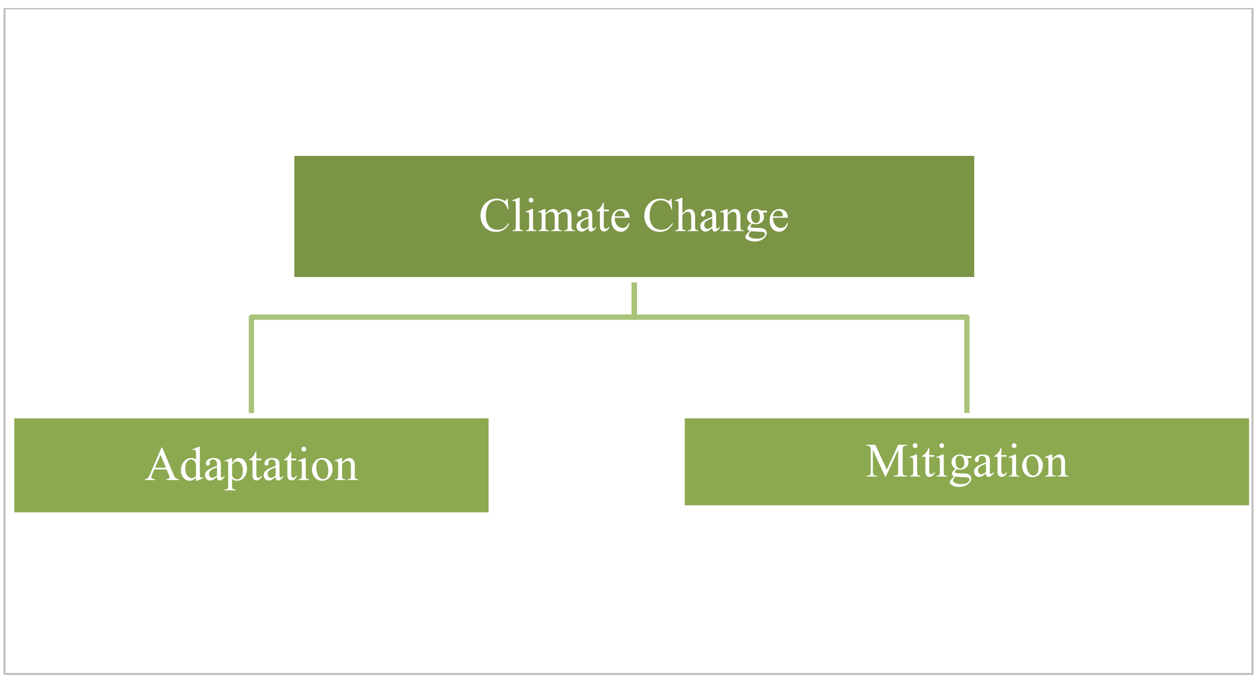


Figure 1.3 Strategies to address climate change.
Source: Authors own compilation.

It can be managed through two approaches i.e., mitigation and adaptation.

a) **Adaptation:** Adaptation refers to "the prevention and alleviation of negative impacts being brought about by climate change such as sea level rise and drought" (MOFA, 2022).

b) **Mitigation:** Mitigation refers to "the efforts on the reduction of industrial, household, and other GHG by diverse sectors in the society; the GHG reduction through energy conservation and the use of low-carbon energy such as renewable energy; and the CO2 absorption done by plants" (MOFA, 2022).

1.3 Types of Green House Gases

According to the UNFCCC, GHGs are gaseous components of the atmosphere, both natural and anthropogenic that absorb and re-emit infrared radiation (United Nations, 1992a). Building on this, the Intergovernmental Panel on Climate Change (IPCC, 2021) explains that GHGs trap heat from the sun creating the "greenhouse effect," which warms the Earth's surface. While this effect is natural and necessary for life, human activities particularly fossil fuel combustion and land-use changes have significantly elevated the concentration of these gases, contributing to global warming and climate change. These emissions are quantified in terms of million metric tons and carbon dioxide equivalent (CO_2e).

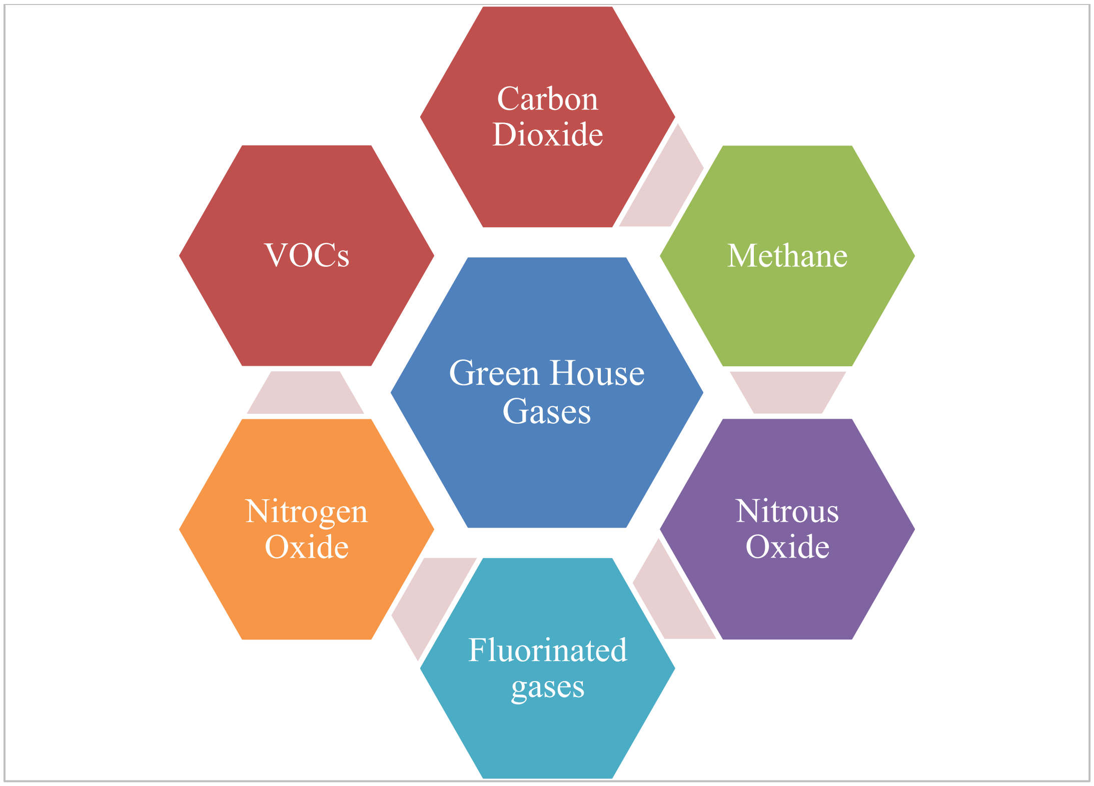


Figure 1.4 Types of Green House Gases.
Source: Authors own compilation.

a) **Carbon dioxide**: It is the primary greenhouse gas released as a result of human activity. It naturally exists in the atmosphere as a component of the Earth's carbon cycle and accounts for largest share in the overall greenhouse gas emissions from anthropogenic activity. The primary anthropogenic source of CO2 emissions is the combustion of fossil fuels (coal, natural gas, and oil) for energy production, transportation, industrial activities, and land use changes (EPA).

b) **Methane**: It is emitted during the extraction and transportation of coal, natural gas, and oil. Likewise, agricultural practices, land use, decay of organic waste in municipal solid waste landfills, and livestock also result in Methane emissions. Its lifetime in the atmosphere is much shorter than carbon dioxide (CO_2), but CH_4 is more efficient at trapping radiation than CO_2, the comparative impact of CH_4 is 28 times greater than CO_2 over a 100-year period (Stocker et al., 2013).

c) **Nitrous oxide**: It is emitted during agricultural, land use, industrial activities, combustion of fossil fuels and solid waste; as well as during treatment of wastewater. Nitrous oxide molecules stay in the atmosphere for an average of 121 years, the impact of 1 pound of N_2O on warming the atmosphere is 265 times that of 1 pound of carbon dioxide (Stocker et al., 2013).

d) **Fluorinated gases**: Unlike many other greenhouse gases, fluorinated gases have no significant natural sources and come almost entirely from human-related activities. These are the most potent and long-lasting greenhouse gases that are emitted from a variety of household, commercial, and industrial applications and processes. There are four main categories of fluorinated gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3), they are sometimes referred to as high-GWP gases (Stocker et al., 2013).

e) **Nitrogen Oxides**: Nitrogen oxides (NOx) refer to a group of gases, mainly nitric oxide (NO), and nitrogen dioxide (NO_2), that are released from both natural sources and human activities such as vehicle emissions and fuel combustion. Although NOx is not a GHG itself, it contributes indirectly to climate change. High concentrations of nitrogen dioxide can harm the human respiratory system. Additionally, NOx can react with volatile organic compounds (VOCs) in the atmosphere to produce ozone (Queensland Government, 2025).

f) **Volatile Organic Compounds**: Volatile organic compounds (VOCs) are organic chemicals that can easily evaporate into the air under normal environmental conditions (Faroon et al., 2005). They are present in a wide range of products and materials. VOCs play a significant role in the formation of ground-level ozone, which is a key component of smog and contributes to air pollution

1.4 Millenium Development Goals

The Millennium Development Goals (MDGs) were a set of eight global development objectives established following the United Nations Millennium Summit in September 2000. During this summit, world leaders adopted the Millennium Declaration, committing to address key global issues such as poverty, hunger, disease, lack of education, environmental degradation, and gender inequality. Endorsed by all UN Member States, the MDGs were designed to be achieved by 2015.

Figure 1.5 Millenium Development Goals.
Source: https://www.mdgmonitor.org/outline-of-the-mdgs-notable-challenges/

Each goal included specific targets and indicators to measure progress from 1990 levels, providing a structured framework for international cooperation in addressing major global challenges. (*Millennium Development Goals (MDGs)*, 2018).

1.5 Sustainable Development Goals

The Sustainable Development Goals (SDGs), also called the Global Goals, were established by the United Nations in 2015 as a worldwide initiative to eliminate poverty, protect the environment, and promote peace and prosperity for all by 2030. These 17 goals serve as a comprehensive framework for building a more sustainable and equitable future. The SDGs are interconnected, emphasizing that progress in one area can influence others, and that sustainable development must balance social, economic, and environmental dimensions (United Nations Development Programme, 2015). Among these, SDG 8 and SDG 13 are key pillars of sustainability. SDG 8 focuses on promoting inclusive and sustained economic growth, increased productivity, and innovation. It also encourages a shift towards green jobs, digital advancements, and economic policies that prioritize human well-being. SDG 13 addresses climate change by urging immediate action to reduce its impacts. It supports providing financial aid and technological resources to help developing countries strengthen their climate resilience.

Figure 1.6 Sustainable Development Goals.
Source: https://www.un.org/sustainabledevelopment/news/communications-material/

1.6 Problem Statement

As nations strive to balance economic development with environmental sustainability, the association among energy utilization, GDP, and environmental emissions has become a central focus of empirical research and policy discourse. For the QUAD countries this issue holds particular importance given their significant roles in global economic activity and their substantial contributions to the global energy utilization and emissions. During the last decades, the interest in global warming has inspired many academicians to study the driving factors of GHG emissions. Despite comprehensive research investigating these associations, the literature continues to be inconclusive regarding the type, direction, and amplitude of the interactions among these variables. While some studies report a positive correlation between energy use and economic growth, others highlight the potential for energy efficiency improvements (Mercan & Karakaya, 2015). This means that it is possible for a country's economy to keep growing without causing more pollution, this process is often called decoupling economic growth from environmental harm. Similarly, the EKC hypothesis which posits that environmental degradation initially increases with economic growth before declining after reaching a certain income threshold (Kuznets, 1955), has shown mixed empirical support, with variations across countries, time periods, and environmental indicators. For the QUAD countries, there is an urgent need to empirically verify whether the EKC holds, especially given the diverse stages of economic development, industrial structures, and environmental policies found across these nations. Moreover, many existing studies in this field have focused mainly on providing broad correlations between energy consumption, economic growth, and emissions without fully exploring their complex interconnections. While such studies have contributed valuable insights, there remains a need for more detailed examination that considers how these variables interact within specific country contexts, especially for the QUAD countries.

To address these gaps, this study investigates the overall relationships among energy consumption, economic growth, and emissions levels, offering updated and comprehensive evidence that aligns with its key research objectives. By rigorously examining these interconnections across the QUAD countries, the study aims to enhance understanding of how energy use and economic development influence environmental outcomes, thereby contributing to the literature on the energy-growth-environment nexus. Additionally, the research seeks to examine if the EKC hypothesis is true within this important group of countries, providing fresh, context-specific insights. Furthermore, the study seeks to explore the differences in the rural and urban energy consumption, economic growth, and emissions levels within the QUAD countries, recognizing that these areas may follow distinct patterns due to varying socioeconomic and infrastructural conditions. Ultimately, the findings of this study aim to contribute to academic discussions and policymaking by supporting the development of strategies that enable both advanced and emerging economies to balance economic growth while promoting environmental sustainability and achieving the Sustainable Development Goals (SDGs) established by the United Nations.

1.7 Research Questions

The research questions in this study are designed to systematically examine the dynamic relationship between energy consumption, economic growth, and emissions levels within the QUAD countries. The purpose of these questions is to bridge the theoretical and empirical gaps in understanding how economic growth and energy consumption influences the emission level, considering the distinct social and institutional characteristics of QUAD countries. The key research questions are:

RQ1: What is the association between energy consumption, economic growth, and emissions levels in the QUAD countries?

This research question seeks to analyze the complex interactions among energy consumption, economic growth, and emissions.

RQ2: Does the Environmental Kuznets Curve (EKC) hypothesis indicate an inverted U-shaped relationship between economic growth and environmental degradation in the QUAD countries?

This question explores whether the EKC hypothesis, which suggests an inverted U-shaped relationship between economic growth and environmental degradation, is valid in the context of the QUAD countries.

RQ3: How do rural and urban populations influence emission levels in the QUAD countries? This question examines how rural and urban populations differ in their impact on emissions levels in the QUAD countries.

1.8 Objectives of the Study

The complex interactions among energy utilization, economic growth, and environmental emissions have become increasingly important in today's global push for sustainable development. As countries face the dual challenge of maintaining economic growth while reducing environmental harm, it is essential to provide empirical evidence that elucidates the relationships among these key variables. The QUAD countries, given their major roles in global economic and environmental dynamics, offer a valuable insight for such investigation. Hence, the following objectives were carefully formulated to provide in-depth knowledge specific to the QUAD context in the study:

- **Objective 1:** To examine the relationship among energy consumption and economic growth and emissions level.
- **Objective 2:** To test the EKC hypothesis for QUAD countries.
- **Objective 3:** To investigate the difference between energy consumption, economic growth, and emissions level in rural and urban areas of QUAD countries.

1.9 Hypotheses of the Study

The hypotheses are constructed according to the respective objective of the study. The following hypotheses are to be tested in the study:

O1: To examine the relationship among energy consumption, economic growth, and emissions level

$HO1_1$: There exists a relationship between energy consumption and economic growth.

$HO1_2$: There exists a two-way relationship among energy utilization and GDP.

$HO1_3$: There exists a relationship between energy consumption and emissions.

$HO1_4$: There exists a unidirectional relationship between energy consumption and emissions.

$HO1_5$: There exists a bidirectional relationship between energy consumption and emissions.

O2: To test the EKC hypothesis for QUAD countries.

$HO2_1$: There exists an association amongst GDP and emissions.

$HO2_2$: There exists a unidirectional relationship between economic growth and emissions

O3: To investigate the difference between energy consumption, economic growth, and emissions level in rural and urban areas of QUAD countries.

$HO3_1$: There exists significant difference in emission levels between rural and urban population in the USA.

$HO3_2$: There exists significant difference in emission levels between rural and urban population in India.

HO3₃: There exists significant difference in emission levels between rural and urban population in Japan.

HO3₄: There exists significant difference in emission levels between rural and urban population in Australia.

1.10 Rationale of the Study

The accelerating challenges of global warming and climate change are primarily attributed to rising greenhouse gas emissions and continued reliance on fossil fuels to sustain global economic activities. Since the onset of the Industrial Revolution, the world has witnessed unprecedented economic growth, leading to substantial improvements in living standards. However, this economic advancement has been accompanied by significant environmental degradation worldwide. This study focuses on the QUAD countries: India, Australia, Japan, and the United States of America given their significant contribution to global emissions level and their diverse economic structures. The QUAD represents characteristics of both developed and emerging economies. While the USA, Australia and Japan share the features of developed nations, India is a major emerging economic power house from ASIA. This heterogeneous composition provides a unique context for examining how different macroeconomic and socio-economic factors influences the emission trajectories within the QUAD countries. The study is particularly significant as it investigates both the short-term and long-term impact of key economic factors on the rising emissions, and economic growth. Hence, contributing to Sustainable Development Goals, specifically, SDG-8 (decent work and economic growth) and SDG-13 (Climate action).

This study seeks to contribute to the ongoing discourse on energy, environment, and economic growth by addressing the heterogeneity among the QUAD nations and their implications for global sustainability. Additionally, it aims to offer valuable insights into how QUAD countries can reduce their emissions while maintaining their economic progress. Also, it aims to inform policy decisions that support the transition to a more sustainable and equitable energy future.

1.11 Chapter-Wise Structure of the Study

This thesis comprises six chapters, each meticulously structured to facilitate a thorough understanding of the association between energy consumption, GDP, and carbon emissions in the QUAD countries. The chapter organization intends to establish a logical flow of concepts. The detailed framework of the thesis is presented as follows:

Chapter 1: Introduction

The first chapter provides an overview and comparison of the world energy basket with special reference to the QUAD nations. The chapter also explains the meaning of important terms used in the context of emissions, sustainability, and economy of a nation. It further highlights the research questions that the study aims to answer, along with the list of three main objectives of the study. Lastly, the chapter explains the significance of the study in terms of its contribution to the current literature, for policymakers, and academicians.

Chapter 2: Energy Consumption, Emissions, and Economic Growth.

The second chapter provides an overview and trend analysis of the world Energy basket, top twenty global GHG emitters, and the economic growth. The chapter also provides an insight into the QUAD's GHG emissions and energy basket scenario for the past three decades. This is further followed by a discussion about the international initiatives and agreements concerning climate change and QUAD's contribution to meeting the climate targets.

Chapter 3: Review of Literature.

The third chapter reviews the theoretical and empirical studies available on Economic growth, emissions, and energy use. It provides a foundation by discussing the foundational theories such as the EKC hypothesis, IPAT, STIRPAT, and others. The chapter explores empirical literature that examines the energy-growth-emission nexus, focusing on both positive and negative conclusions as observed in several contexts. A detailed discussion on how variables such as economic growth, renewable energy, non-renewable energy, total energy use, urbanisation, and technological progress impact the emission level is included. The chapter concludes by identifying the existing research gaps, such as the need for a deeper examination of country-specific factors.

Chapter 4: Methodology

The fourth chapter presents the research methodology, providing a comprehensive overview of the dataset, variables, and econometric techniques employed to analyse the nexus between energy consumption, CO2 emissions, and economic growth in QUAD nations. Initially, the data was thoroughly examined, including the sample size, time-period (1970–2021) of the study, and key macroeconomic and socio-economic variables. These variables include GDP, CO2 emissions, total energy consumption, urban and rural population, trade volume, and population density, along with their respective definitions and sources. The analysis utilizes the cointegration test to identify the existence of long-term relationship between emissions; the Structural Vector Autoregressive (SVAR) model and two-stage least square regression model to examine the association among variables; and the quadratic regression to investigate the presence of a curved relationship between economic growth and CO_2 emissions. This chapter establishes a robust groundwork for empirical analysis by carefully defining the data and methodology.

Chapter 5: Empirical Results

The fifth chapter presents the empirical findings on the relationship between CO_2 emissions and macroeconomic variables in the QUAD countries from 1970 to 2021. The analysis begins with the trend analysis followed by descriptive statistics and preliminary tests such as unit-root test, correlation heatmap, and VIF tests. The study employs the Structural Vector Autoregressive Model (SVAR) to capture the impact of each variable on the other, and quadratic regression was applied to establish the EKC hypothesis. Additionally, two-stage least square (2SLS) model was employed to estimate the relationships among the variables. The results highlight various key macroeconomic and socioeconomic factors and their impact on the emissions of QUAD nations.

Chapter 6: Conclusion

This chapter concludes the study by summarizing its key findings, theoretical and practical implications, and avenues for future research. The study focused on the QUAD nations and explored the relationship between CO_2 emissions and other macro and socio-economic variables. The findings of the study highlighted the relationship between emissions, economic growth, energy consumption, urban and rural population, trade volume, and population density. The chapter revisited the research objectives and confirmed their fulfilment through empirical evidence. Additionally, the study provided policy recommendations for mitigating emissions and supporting sustainable development. Lastly, the limitations of the study were acknowledged along with the proposed future research directions.

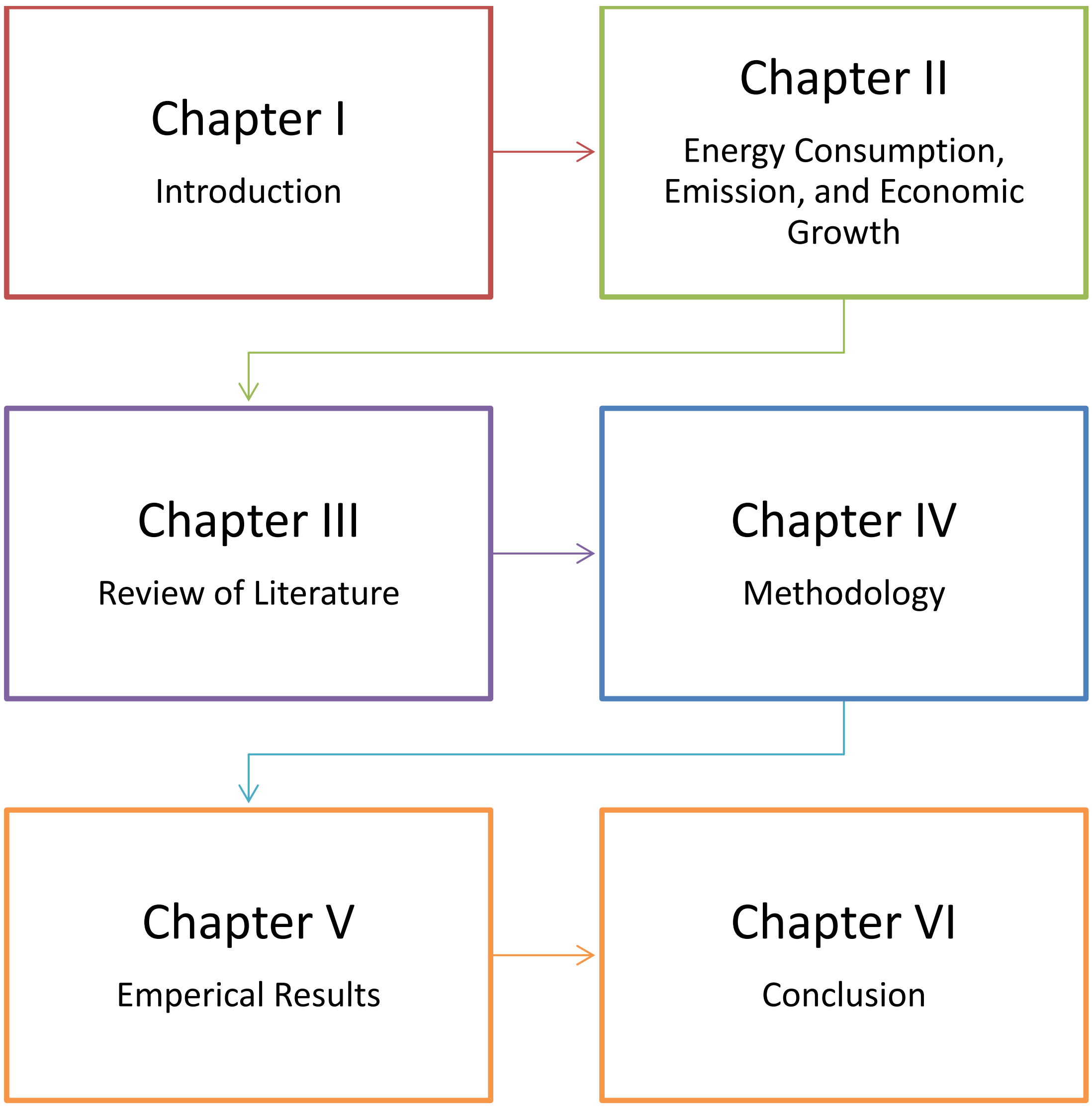


Figure 1.7 Flow of Chapters
Source: Authors own compilation.

1.12 Summary of Chapter

The first chapter provides an overview and comparison of the world energy basket for the year 1990 and 2022 with special reference to the QUAD nations. The chapter also explains the meaning of important terms used in the context of emissions, sustainability, and economy of a nation. It further highlights the research questions that the study aims to answer, along with the list of three main objectives that the study aims to achieve. Moreover, the chapter also mentions about the hypothesis to be tested in the study. Lastly, the chapter explains the significance of the study in terms of its contribution to the current literature, for policymakers, and academicians.

CHAPTER 2

Energy Consumption, Emission, and Economic Growth

2.1 Overview

Energy serves as the foundation of modern civilization, driving economic growth, enabling technological advancements, and enhancing the living standard for billions of people across the globe. Its availability and accessibility are essential for economic growth and societal development, as it supports industrial operations, transportation, and daily human activities. However, the increasing global demand for energy has led to significant environmental challenges, particularly the rise in GHG emissions, which pose a severe threat to global climate sustainability. This interplay between energy and emissions lie at the center of one of the most urgent challenges of balancing growing energy demand with the need to mitigate its adverse environmental impacts. Further, energy use patterns not only reflect the current state of a nation's economic development but also determine the composition of its energy basket, whether it is predominantly reliant on fossil fuels, renewable sources, or both. At the same time, energy continues to play a vital role in driving economic growth, as it is essential for improving living standards, reducing poverty, and supporting industrialization of a nation (Stern, 2011). This dual role of energy as both a stimulus for development and a source of environmental harm creates a complex and often conflicting dynamics within the energy-emission-economic growth nexus. Balancing the need for development with the goal of environmental protection remains a significant challenge for policymakers and researchers worldwide. The debate surrounding energy consumption patterns and their implications for economic growth, social well-being, and environmental sustainability has been a central focus of academic and policy discussions for decades.

2.2 Global Scenario

The global demand for energy has grown exponentially over the past few decades, driven by population growth, urbanization, and industrialization. In 2017, the global carbon dioxide (CO_2) emissions from fossil fuel combustion and industry reached 36.8 gigatons, twice the natural rate at which CO_2 is absorbed by land and ocean sinks (Le Quéré et al., 2018). Fossil fuel has been the primary energy resource and the reliance on these sources has significantly worsened environmental quality, with coal, oil, and natural gas accounting for the majority of global GHG emissions (Çoban, 2020). Conventional sources are also considered as a major contributor to air pollution, releasing harmful pollutants such as nitrogen dioxide (NO_2), sulphur dioxide (SO_2), volatile organic compounds (VOCs), and particulate matter (PM) into the atmosphere (Kopel & Brower, 2019). These pollutants are linked to global warming, ozone depletion, severe public health issues, including respiratory and cardiovascular diseases, and are the primary drivers of climate change (Wieczorek et al., 2024). Energy is fundamental to all aspects of modern life, and countries striving to improve the living standards of its population have historically relied on fossil fuels to meet their energy needs. Access to reliable and affordable energy has been a key driver of industrialization and urbanization, enabling nations to address poverty and improve standard of living. However, this reliance on fossil fuels has come at a heavy environmental price. The combustion of coal, oil, and natural gas is the primary source of CO_2 emissions, which are the main contributors to global warming and climate change (Hassan, 2024). The global community is increasingly recognizing the necessity for a shift to greener energy sources to mitigate the effects of climate change and ensure a sustainable future. This transition requires not only technological innovation and policy interventions but also a fundamental shift in how energy is produced, distributed, and consumed.

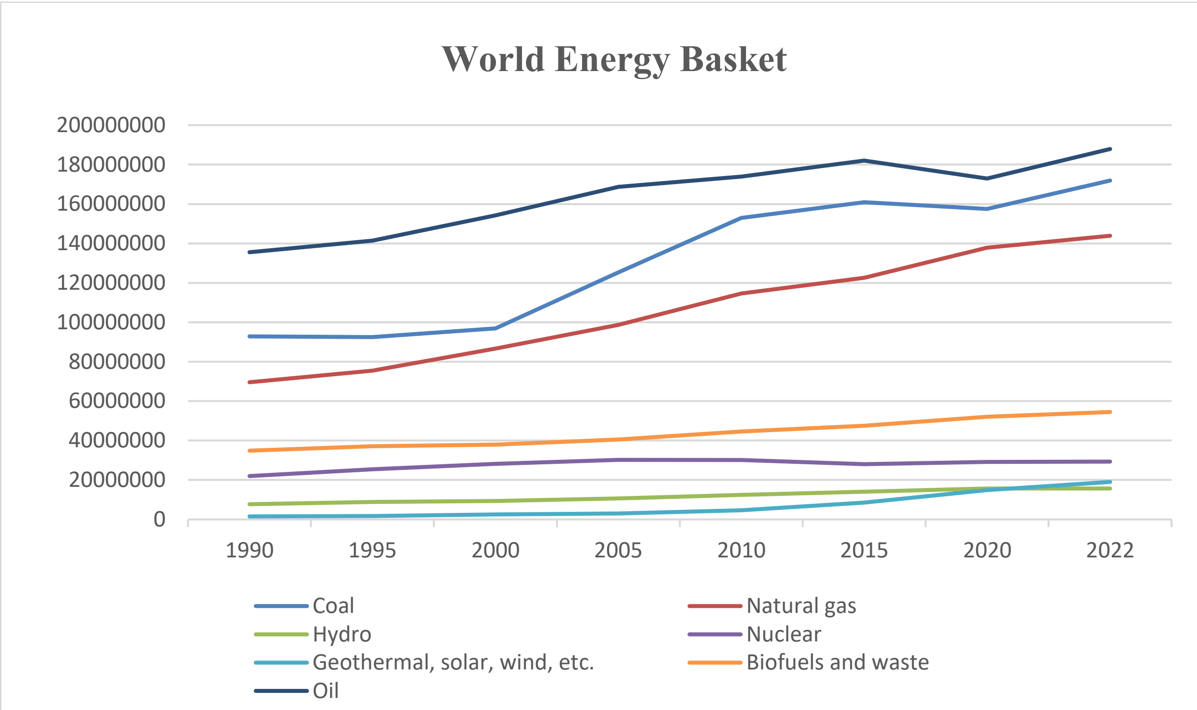


Figure 2.1 Trend of the World Energy basket from 1990-2022.
Source: Authors own compilation

Figure 2.1 represents the trend of the world energy basket from 1990-2022. It is evident that in the past three decades the global energy landscape has undergone significant transformations, reflecting shifts in energy consumption patterns, technological advancements, and evolving policy frameworks. Over this period, the world's energy basket comprising of conventional and modern renewable sources has witnessed notable changes in the contribution of each energy source. These trends highlight the interplay between economic growth, environmental concerns, and achieving the sustainable development targets. The global energy system is characterized by a diverse mix of energy sources, each with its own advantages and environmental implications. In 1990, conventional energy sources dominated the world energy mix, with coal, oil, and natural gas collectively accounting for the majority of energy consumption. Coal, a cornerstone of industrialization, was widely used for electricity generation and industrial processes, particularly in developing and emerging economies. Oil, the most versatile fuel, remained the primary energy source for transportation and as a feedstock for various industries (eia, 1994). Natural gas, while less prominent than coal and oil, gained traction as a cleaner alternative for heating and electricity generation. Together, these fossil fuels led the global economic growth but also contributed significantly to GHG emissions and environmental deterioration. The time-period from 1990 to 2022 saw a gradual but steady rise in the use of natural gas, driven by its reduced carbon intensity relative to coal and oil. Advances in extraction technologies, such as hydraulic fracturing and liquefied natural gas (LNG) infrastructure, expanded its accessibility and affordability (Bresciani et al., 2020). By 2022, natural gas had become a critical component of the global energy basket, particularly in regions transitioning away from coal. However, the reliance on fossil fuels persisted, with coal and oil remaining dominant in many parts of the world, especially in rapidly industrializing economies. Renewable energy sources, though marginal in 1990, began to gain momentum in the early 21st century. Hydropower is one of the oldest forms of clean energy sources, maintained a steady share of the energy mix, providing reliable electricity generation in regions with abundant water resources. Nuclear energy, despite its potential for low-carbon electricity, faced challenges such as high capital costs, safety concerns, and public opposition, leading to a relatively stable but limited contribution to the global energy basket (Nuclear Power and Secure Energy Transitions, 2022). The most remarkable shift in the energy landscape has been the rapid growth of modern renewables, including geothermal, solar, and wind energy. From negligible levels in 1990, these technologies experienced exponential growth, driven by declining costs, technological innovations, and supportive policy frameworks. By 2022, modern renewables had become a significant and growing component of the world energy mix, particularly in developed nations and regions with favorable natural conditions. Biofuels and waste, which include traditional biomass and modern biofuels played a significant role in the energy portfolio. Although conventional biomass including wood, crop residues, and animal dung, remained a primary energy source for cooking and heating in rural areas, especially in regions with limited availability of new age energy infrastructure. It provided an affordable and accessible energy solution for millions; however, its use is often associated with inefficiencies, indoor air pollution, and adverse health impacts (P. Kumar et al., 2024). Modern biofuels gained dominance as a renewable alternative for transportation and industrial applications, offering the potential to reduce reliance on fossil fuels and lower GHG emissions. However, the sustainability of biofuels has been a subject of debate, with concerns over land use, food security, and lifecycle emissions.

Despite the growth of renewables, fossil fuels continued to dominate the global energy basket in 2022, underscoring the challenges of transitioning to a low-carbon energy system. Coal, though declining in some regions, remained a major energy source in countries with abundant reserves and growing energy demands. Oil, while facing competition from electric vehicles and biofuels, retained its dominance in the transportation sector (Ausfelder & Wagemann, 2020). Natural gas, played a dual role in reducing emissions relative to coal while still contributing to GHG emissions (Garg et al., 2023). The trends in the world energy basket from 1990 to 2022 reflect the complex interplay between economic development, energy security, and environmental sustainability. While fossil fuels have historically driven global growth, their environmental impacts have spurred a gradual shift towards cleaner and more sustainable energy sources. The rise of modern renewables, coupled with the steady growth of natural gas and the persistent role of coal and oil, highlights the challenges and opportunities of the global energy transition. As the world moves towards a more sustainable energy future, the evolution of the energy basket will continue to shape the trajectory of economic growth and environmental protection. Yet, the ongoing dependence on fossil fuels in many regions has resulted in a steady increase in global carbon dioxide (CO_2) emissions, with the top 20 emitting nations responsible for the majority of the share of GHG emissions. By examining the emissions data of the top 20 emitters, we gain a deeper understanding of the global emission scenario and its implications for climate action.

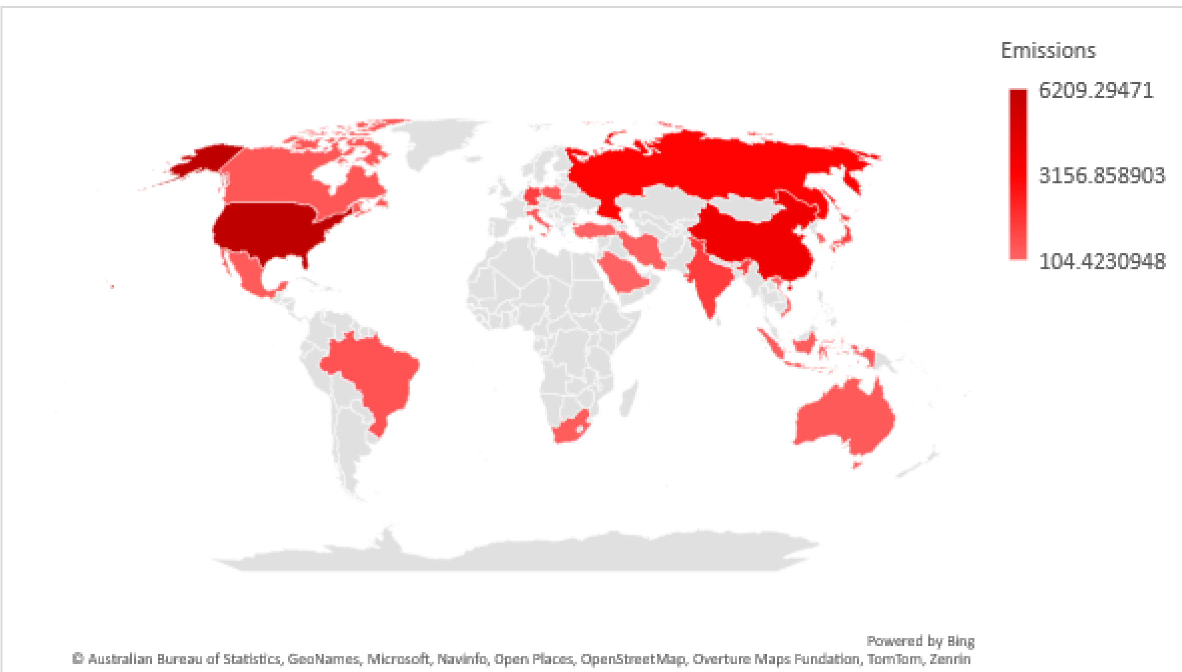


Figure 2.2 Top 20 GHG emitter nations in the year 1990.
Source: Authors own compilation

The figure 2.2 illustrates the top 20 GHG emitters of the world in 1990. It offers a valuable historical perspective on global emissions, providing insights on how emission patterns have evolved over time. The use of a gradient of shades- darker for higher emissions and lighter for lower emissions provides a clear visual representation of the disparities in emissions among nations during this period. In 1990, the global energy landscape was heavily dominated by fossil fuels, particularly coal and oil, which were the primary drivers of economic growth in developed nations. The global energy system was defined by this strong dependence on fossil fuels, which established the foundation of the emission trends for the next decades. The United States, as the leading emitter in 1990, contributed approximately 6,209.29 million metric tons of GHG equivalent, reflecting its dominant role in global energy consumption and industrial activities at the time (EPA, 2018). Following closely were China and Russia, the second and third highest emitters, with 3,876.38 and 3,065.69 million metric tons of emissions, respectively. This highlights the concentration of emissions among both developed and developing nations, each playing a significant role in shaping the global emissions landscape. Further, countries like India, Japan, and Germany were among the top emitters, with emissions of 1383.06, 1317.21, and 1235.87 million metric tons, respectively (Climate Change Secretariat, 2012; Nick Reimer & Dr Ulf Reimer, 2018). These figures underscore their contributions to the prevailing challenge of climate change, driven by industrialization, urbanization, and energy-intensive economic activities. Even the 20th-ranked emitter, Vietnam, with emissions of about 104.42 million metric tons, highlights the early phases of industrialization in many countries and their related environmental consequences. The figure also stresses on the early stages of industrialization and urbanization, which were largely concentrated in developed nations at the time. Many developing countries had not yet undergone significant economic transformation, and their contributions to global emissions were relatively less. This historical context is crucial for understanding how the world energy basket has evolved over time. The emissions data from 1990 serves as a baseline, illustrating the starting point from which global energy consumption and emissions have grown exponentially.

Building on the emission scenario of 1990, the figure 2.3 illustrates the changes in the emission patterns of the top 20 GHG emitters of the world over the past three decades using a similar approach to represent emission levels, wherein darker shades indicate higher emissions, while lighter shades denote lower emissions. This comparison underscores the dramatic shifts in global emissions, driven by economic growth, industrialization, and evolving energy utilization patterns. In 1990, a small group of developed countries controlled the majority of the world's emissions, with the US at the top of the list ("U.S. 1990-2005 Greenhouse Gas Emissions up 16 Pct," 2007).

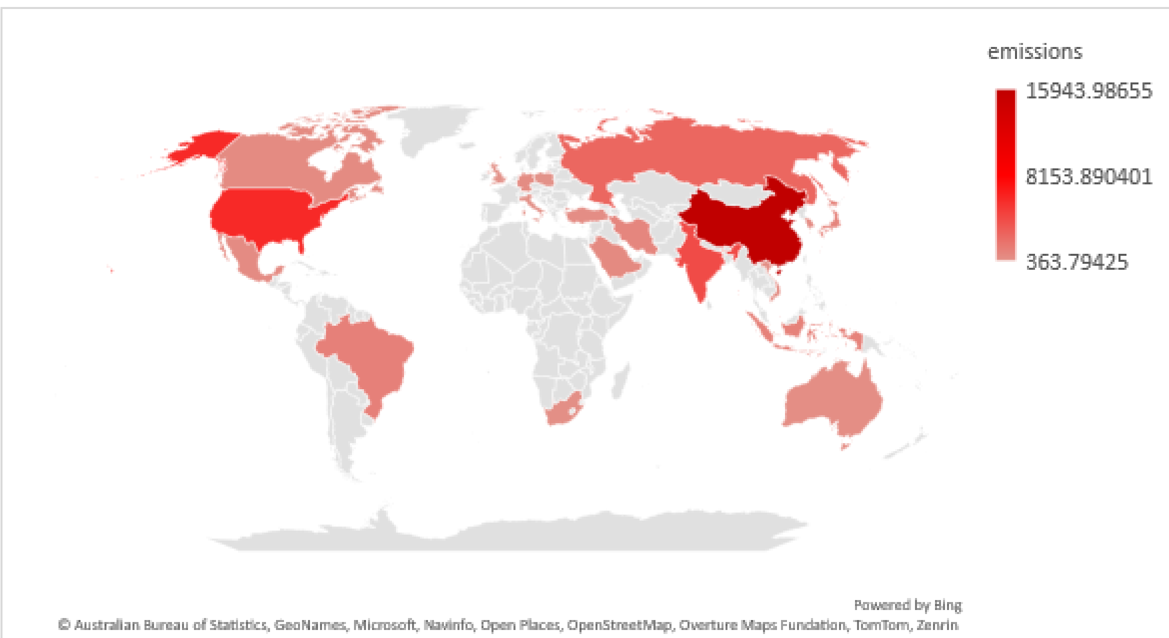


Figure 2.3 Top 20 GHG emitter nations in the year 2023.
Source: Authors own compilation

By 2023, the situation has changed dramatically to reflect the rise of emerging economies and the ongoing challenges in reducing emissions in a world that is developing rapidly. The figure highlights how some nations have seen exponential growth in their emissions, particularly China, which has transitioned from being the second-highest emitter in 1990 to the leading emitter in 2023 (Ritchie et al., 2024), with emissions skyrocketing to approximately 15,943.99 million metric tons of CO_2 equivalent. This rapid increase in its emission highlights its rapidly industrializing and energy-intensive economy. Meanwhile, India and the United States together contribute around 10,094.36 million metric tons of CO_2 equivalent, underscoring their significant roles in global emissions and the broader climate challenge. The figure also reveals the growing role of smaller economies within the top 20 emitters, such as Vietnam and Indonesia, which were not prominent in the year 1990. This shift reflects the broader trend of globalization and the spread of industrial activities to developing regions. Even the least-emitting nations within the top 20, such as the United Kingdom (379.31 million metric tons), Italy (374.12 million metric tons), and Poland (363.79 million metric tons), represent a notable share of global emissions, illustrating how both large and small economies contribute to the overall GHG burden. While these nations contribute less in absolute terms compared to the top emitters, their rising emissions highlight the need for inclusive climate action that supports sustainable development worldwide.

The figure further serves as a reminder of the shared responsibility of nations, regardless of their size or development stage, in addressing the climate crisis. The data highlights the challenges of balancing economic growth with environmental sustainability, particularly in nations with large populations, extensive industrial activities, and high energy demands. The concentration of emissions among the top 20 emitters underscores the urgent need for targeted climate action. While international climate change agreements like the Paris Agreement aim to reduce global emissions, the data suggests that progress must be accelerated in these high-emitting nations. According to the 'Intergovernmental Panel on Climate Change' (IPCC), average global temperatures have already risen by approximately 1.1°C above pre-industrial levels, with severe implications for ecosystems, weather patterns, and human livelihoods. The impacts of climate change are already being felt around the world, in the form of rising sea levels, melting ice caps, extreme weather events, and disruptions to agriculture and water resources (IPCC, 2022). CO_2 emissions resulting from the combustion of fossil fuels are the primary driver of climate change, hence, strategies such as transitioning to renewable energy, improving energy efficiency, and implementing carbon pricing mechanisms are essential for reducing emissions while maintaining economic growth (IEA, 2021). Additionally, the figure serves as a reminder of the shared responsibility of both developed and developing nations in addressing the climate crisis. While developed countries have historically been the largest emitters, many developing nations are now significant contributors due to their rapid industrialization and urbanization. This analysis underscores the importance of accelerating the transition to cleaner energy systems, particularly in high-emitting nations. It also highlights the need for international cooperation, as emissions from any one country have global consequences.

2.3 QUAD's Scenario

The QUAD is a framework for multilateral dialogue on security among countries with diverse economic structures. The United States, Australia, and Japan are advanced industrialized nations, while India is a rapidly emerging economy, which is a significant contributor to global CO2 emissions. In the recent years, the QUAD nations have demonstrated a strong commitment towards addressing climate change through initiatives such as the QUAD Climate Change Adaptation and Mitigation Package (Q-CHAMP), launched in 2022 and efforts to strengthen clean energy supply chains (Ministry of External Affairs, 2021). The group is actively collaborating on projects to enhance climate resilience in the Indo-Pacific region, including improving access to climate data for the Pacific Island countries and promoting sustainable infrastructure development. Moreover, significant financial commitments have been made to support clean energy projects, reflecting the QUAD's strategic focus on mitigating climate impacts and promoting environmental sustainability in the region. These collaborations highlight the potential for policies that transcend the traditional Global North and South divide, enhancing greater international cooperation in emissions reduction efforts. The QUAD’s actions align closely with global frameworks like the COPs (Conferences of the Parties) under the UNFCCC, where the nations are committed to their climate change initiatives. The QUAD countries may influence the international agreements by promoting clean energy transitions, advocating for emission reduction targets, and supporting the climate-resilient initiatives. Its unified stance at global climate negotiations underscores the importance of multilateral cooperation in achieving the targets of agreements such as the Paris Agreement and the Glasgow Climate Pact. The shared vision enhances their collective capacity to address global challenges, including the dynamic interplay between economic growth and environmental sustainability, thereby reinforcing their commitment to mitigating climate change.

The figure 2.4 provides an overview of GHG emissions trend for the QUAD countries from 1990 to 2023. It highlights the evolving emission patterns of these nations over three decades, reflecting their economic growth, energy consumption, and climate policies. By examining the GHG emissions of the QUAD countries, we gain a deeper understanding of the global emission scenario and the importance of tailored climate strategies.

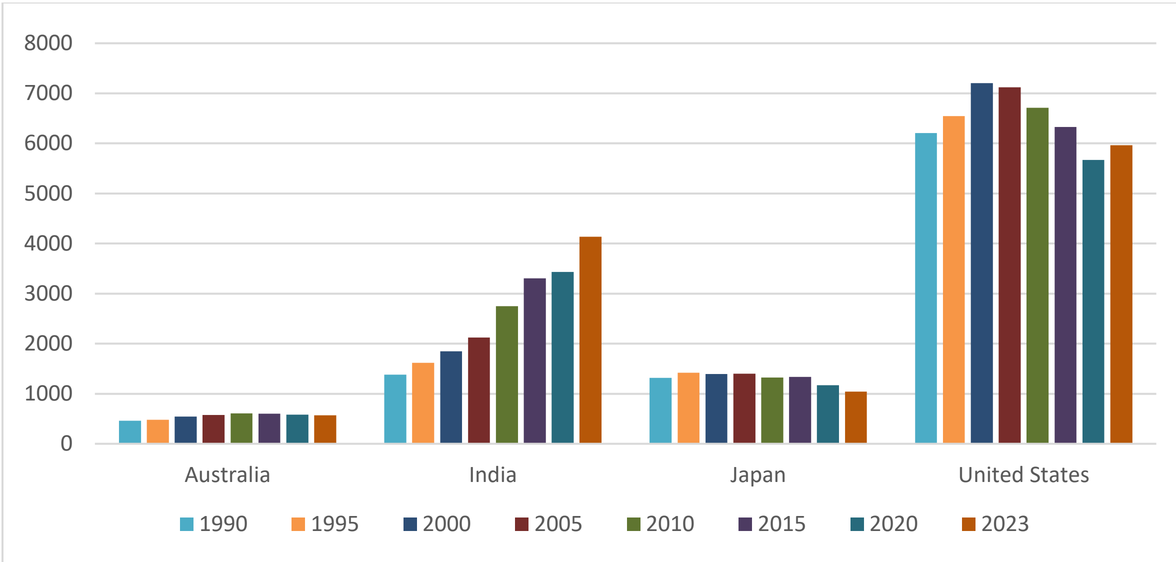


Figure 2.4 GHG emissions of QUAD nations from the year 1990 to 2023.
Source: https://edgar.jrc.ec.europa.eu/report_2024?vis=co2tot#howtocite

The figure 2.4 underscores the diverse emission trajectories of the QUAD countries, shaped by their unique economic, political, and environmental contexts and offers valuable insights into the challenges and opportunities of addressing climate change. In the early 1990s, the United States and Japan were among the world's largest GHG emitters, primarily due to their industrial activities and high levels of energy consumption. The United States, had a significant carbon footprint due to its reliance on coal and oil. However, over the decades, both nations have made notable progress in reducing emissions. The U.S. achieved this through a shift from coal to natural gas, advancements in renewable energy, and energy efficiency measures (Lashof & Hausker, 2023). Japan experienced a temporary increase in emissions following the nuclear tragedy at Fukushima in 2011. Since then, it has prioritized energy efficiency, renewable energy consumption, and the gradual reintroduction of nuclear power, contributing to a decline in emissions. In contrast, India's emissions have risen significantly since 1990, reflecting its rapid economic growth, urbanization, and population expansion (Crippa et al., 2024b). As a developing nation, increase in the energy demand of India lead to an increased reliance on coal and oil. However, worldwide India is also recognized as a leader in renewable energy, particularly solar power, as part of its commitment to the Paris Agreement. Despite these efforts, its emissions continued to grow, highlighting the problem of ensuring long-term environmental sustainability while also fostering economic growth. Furthermore, Australia's emission trends present a unique case of almost constant emissions over the three decades. The mid-2000s saw a noticeable increase in emissions, coinciding with the expansion of Australia's mining sector, particularly in coal and natural gas. The figure highlights this trend, with emissions peaking in the late 2000s and early 2010s. During this period, Australia's LNG exports also grew significantly, adding to its overall emissions profile. The figure further indicates a slight decline in Australia's emissions in the recent years, reflecting the gradual use of sustainable energy sources such as solar and wind energy.

The emission trends of the QUAD countries provide a foundation for understanding their broader energy landscapes. By examining the composition of their energy baskets ranging from fossil fuels to renewables, we can gain deeper insights into how these nations are navigating the dynamic relationship among economic growth, energy security, and sustainable environment. The figure 2.5 provides a comprehensive view of Japan's energy basket from 1990 to 2023. As evident from the figure, the oil usage has been on decline since 1990. However, the usage of coal in the energy basket of Japan shows a moderate growth overtime since 90s. from the figure it is clearly visible that progress in hydra, geothermal, solar, wind, and biofuel has been stagnant over the years. It is also evident that there was a sudden decline in the nuclear power generation in the backdrop of Fukushima nuclear disaster.

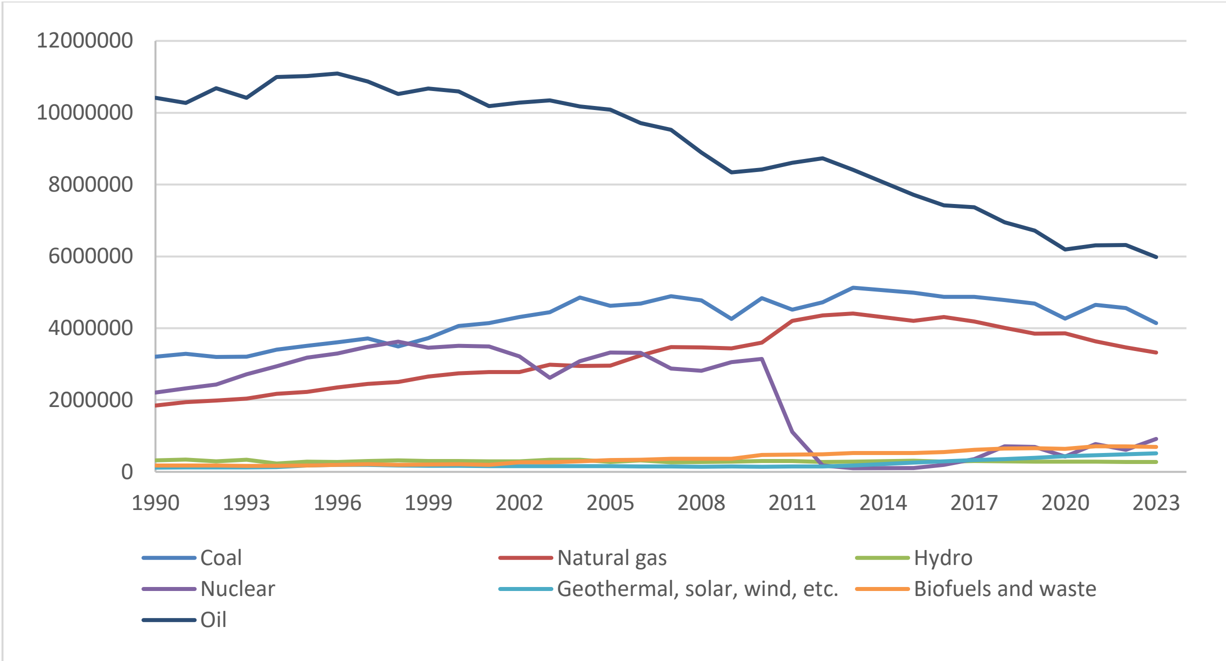


Figure 2.5 Energy basket of Japan from the year 1990 to 2023.
Source: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

The figure 2.5 gives valuable insights into the evolution of its energy mix over three decades. It reflects Japan's efforts to balance energy security, economic growth, and environmental sustainability, while navigating significant challenges such as the 2011 Fukushima nuclear tragedy and global climate commitments. Historically, Japan's energy basket has been dominated by conventional fuels, particularly coal, oil, and natural gas. Natural gas, often seen as a greener alternative to coal and oil, gained prominence over the years, especially after the 2011 Fukushima nuclear tragedy (Kouchakji, 2021). The disaster marked a turning point, leading to a significant decline in nuclear power generation as many reactors were shut down for safety reviews and upgrades. The figure illustrates this decline, succeeded by a steady reintroduction of nuclear energy in recent years. It also led to a temporary increase in fossil fuel usage as Japan sought to compensate for the loss of energy generated by the nuclear power, highlighting the country's reliance on a diverse energy mix to ensure energy security. This transition highlights the balance that Japan should maintain between fulfilling immediate energy requirements and achieving long-term environmental objectives. Furthermore, Japan has made notable progress in expanding its renewable energy capacity. The figure shows a gradual increase in the share of renewables, driven by government policies, technological advancements, and public support for clean energy (Energy Information Administration, 2024). Solar and wind power have seen significant growth, benefiting from Japan's commitment to reducing GHG emissions and enhancing energy security. Hydropower has also been a consistent contributor to Japan's energy portfolio, while geothermal energy though limited by geographical constraints, has played an important role. Biofuels and waste have further diversified Japan's renewable energy portfolio. This growth in renewables reflects Japan's proactive approach to diversifying its energy sources and reducing its carbon footprint. The evolution of Japan's energy basket reflects its response to changing economic, environmental, and geopolitical factors.

Similarly, figure 2.6 presents a detailed analysis of India's energy basket from 1990 to 2023. As per the figure 2.6, the consumption of coal in India has been increasing at an exponential rate since 1990s. Although there was some decline in 2008, but the overall trend is positive. The next important component in the energy basket of India during the sample period was found to be coal. Its usage has been rapidly increasing over the years. Also, the usage of biofuel as an energy source in India has been growing at a moderate rate since 90s as evident from the figure. The figure also highlights the fact that the progress in context of developing non-conventional sources of energy like natural gas, hydro, geothermal, solar, wind, etc. has been stagnant during the sample period.

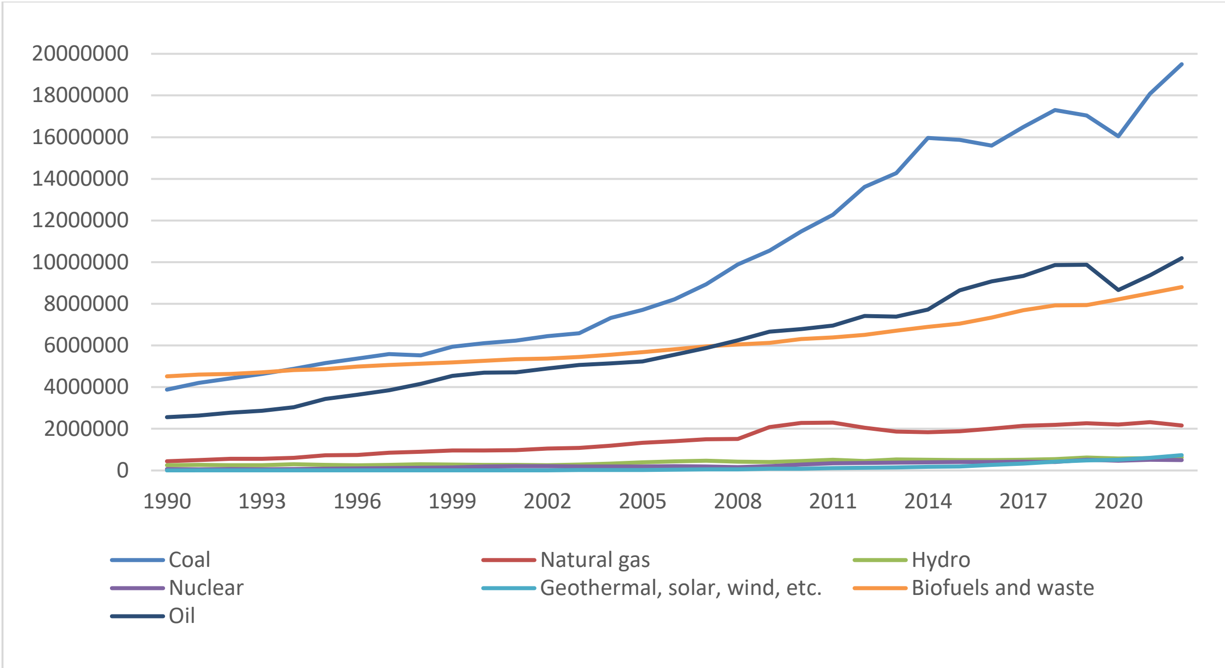


Figure 2.6 Energy basket of India from the year 1990 to 2023.
Source: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

The energy basket of India like Japan has also historically been dominated by coal. The figure shows a firm rise in the coal consumption over the years reflecting India's rapid industrialization and urbanization since 1990s. As one of the world's largest coal producers and consumers, India has relied heavily on this resource of energy to fuel its economic growth and development.

However, this dependence on the coal has also led to the country's GHG emissions and environmental degradation in a significant manner, highlighting the challenges of balancing development with environmental quality. In addition to coal, the figure highlights India's increasing dependence on oil, which has become a critical component of its energy basket. The steady rise in oil consumption over the decades is driven by the expansion of the automotive sector, urbanization, and the growing demand for petrochemical products (Mohanty & Dutta, 2024). Despite efforts to promote electric vehicles and biofuels, oil continues to dominate this sector, highlighting the need for innovative solutions to decarbonize transportation (Dawda, 2024). In addition to coal and oil, the figure highlights the growing role of natural gas often seen as a cleaner alternative to coal and oil in India's energy mix. The expansion of LNG infrastructure and domestic gas production has supported this shift, reflecting India's efforts to reduce its carbon footprint while meeting the rising energy demands. Renewable energy sources, such as hydroelectric, solar, wind, and biofuels, have also seen significant growth in India's energy portfolio. The figure shows a gradual increase in the share of renewables, driven by government policies, technological advancements, and international climate commitments. Hydropower has been a consistent contributor, particularly in regions with abundant water resources. Solar and wind energy, on the other hand, have experienced exponential growth in recent years, benefiting from India's ambitious renewable energy targets and favorable natural conditions. Biofuels and waste have also played a role, though their contribution remained relatively less. This growth in renewables reflect India's proactive approach to diversifying its energy sources while decreasing its reliance on conventional fuels. Nuclear energy, while a small part of India's energy basket, represents an important component of its long-term energy strategy. The figure reflects a steady but limited growth in nuclear power, constrained by technological challenges, high costs, and public concerns. Nevertheless, nuclear energy remains a key part of India's efforts to minimize its dependence on fossil fuels and achieve a low-carbon energy future. The evolution of India's energy basket reflects its response to the dual challenges of meeting growing energy demands and addressing environmental concerns. As a rapidly developing nation with a large and growing population, India faces the difficult task of ensuring energy access and affordability while transitioning to cleaner energy sources.

The figure underscores the importance of continued investment in renewable energy, energy efficiency, and infrastructure development to achieve these goals.

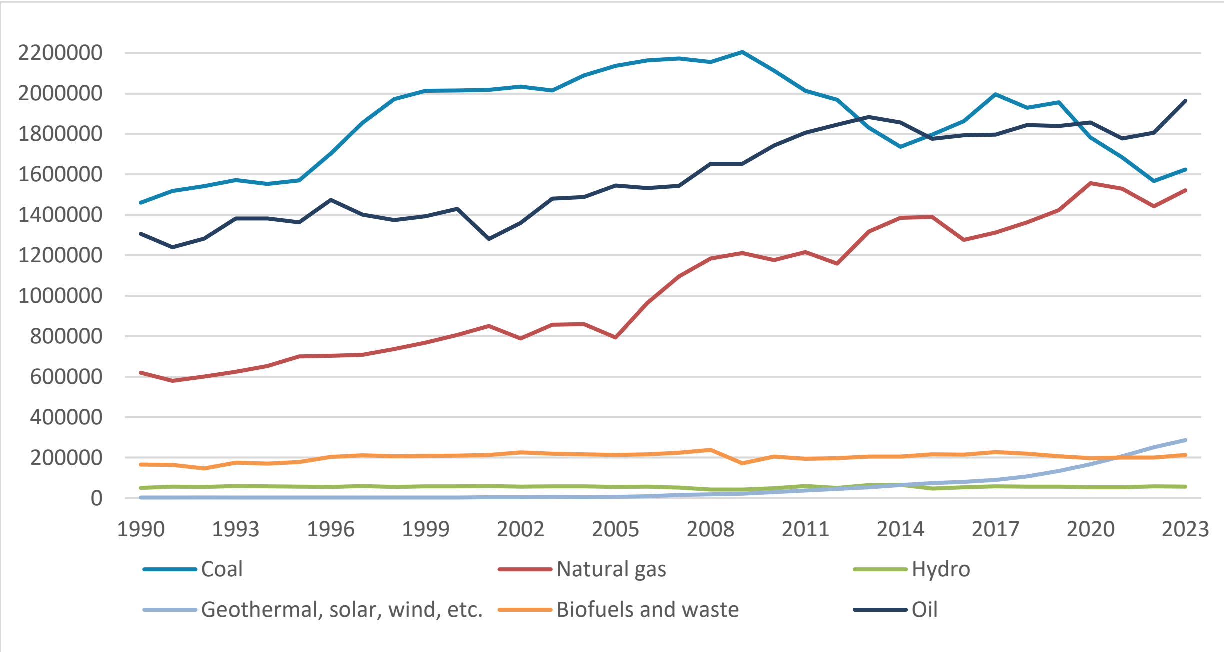


Figure 2.7 Energy basket of Australia from the year 1990 to 2023.
Source: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

The figure 2.7 shows Australia's energy basket and evolution of its energy mix over the three decades. It reflects Australia's efforts to balance energy security, economic growth, and environmental sustainability, while addressing the challenges of a resource-rich yet emissions-intensive economy (Budget 2023-24, 2023). In case of Australia the figure depicts that the usage of coal has been rising from 1990 to 2008. However, there is a substantial decline in the usage of coal after the 2008 financial crisis. The figure also shows a steady increase in coal consumption over the years, reflecting Australia's reliance on this abundant and affordable resource. Being one of the largest coal exporters of the world, Australia has not only used coal domestically but also supplied it to other Asian economies (Geoscience Australia, 2021). Oil has also been a key component in Australia's energy basket, primarily used in transportation and as a vital input for various industries. It is clearly evident from the figure 2.7 that the usage of oil in the energy basket of Australia has been increasing at a rapid rate since 90s indicating probably substitution of coal source by oil. This steady rise in oil consumption over the decades, driven by the expansion of the automotive sector and industrial activities. Like oil, the usage of natural gas in Australia has been on the substantial rise from 1990 to 2023. Natural gas, often seen as a cleaner alternative to coal, has gained prominence as a source of electricity and industrial fuel. The expansion of LNG infrastructure and domestic gas production has supported this shift, reflecting Australia's efforts to reduce its carbon footprint while meeting rising energy demands. Despite this progress, natural gas remains a significant contributor to emissions, underscoring the need for further decarbonization efforts. Like Japan and India, the progress on the front of developing non-conventional sources of energy like hydro, biofuel and waste except geothermal, solar, and wind energy together has been stagnant in Australia. The figure shows a gradual increase in the share of renewables, driven by government policies, technological advancements, and public support for clean energy. It is important to note that solar and wind energy, have experienced exponential growth since 2008, benefiting from Australia's abundant natural resources and favorable climate conditions. Biofuels and waste have also contributed to Australia's renewable energy portfolio, though their share remains relatively less. The evolution of Australia's energy basket reflects its response to changing economic, environmental, and geopolitical factors. The country's reliance on fossil fuel exports, particularly coal and natural gas, has posed significant challenges in aligning domestic energy policies with global climate goals (Australian Government, 2023). At the same time, Australia has made strides in adopting renewable energy, driven by the need to reduce emissions and enhance energy security. This dual focus on sustainability and economic competitiveness has shaped Australia's energy policies, making it a unique case in the global energy transition.

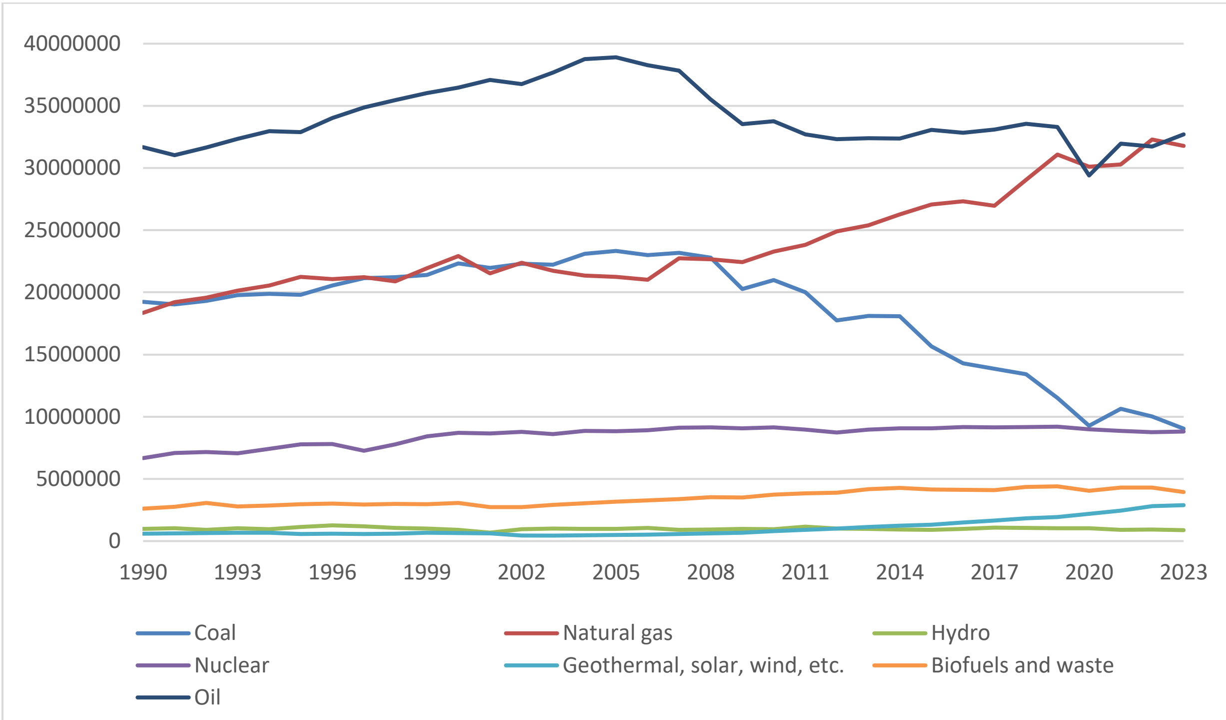


Figure 2.8 Energy basket of the USA from the year 1990 to 2023.
Source: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

The figure 2.8 shows the USA energy mix during 1990-2023. The energy basket of the USA clearly shows diversions in its energy usage patterns after the 2008 Sub-Prime financial crisis. The USA energy basket shows a clear-cut response to the pressing issues of climate change and global warming particularly after the 2008 financial crisis. The trend in consumption of oil and coal has been on significant decline after 2008. However, the trend in natural gas consumption in the USA has been rapidly increasing since 2008. Coal, once the primary source of electricity generation, has seen a significant decline in the recent years, as reflected in the figure 2.8. This decline is largely due to the shift toward cleaner energy sources, driven by environmental regulations, market forces, and technological advancements (Gruenspecht, 2019). The figure shows a steady decrease in coal consumption, particularly after 2008, as natural gas and renewables gained prominence. A substantial increase in natural gas consumption over the decades is primarily driven by the shale gas revolution and the expansion of hydraulic fracturing (fracking) technology. However, its role as a "bridge fuel" in the energy transition has raised concerns about methane emissions and long-term sustainability. Oil remained a critical part of the U.S. energy basket, primarily used in transportation and as a vital resource for various industries. The figure shows a constant growth in oil consumption, reflecting the expansion of the automotive sector and industrial activities over the years. Also, renewable energy sources, including hydro, solar, wind, and biofuels, have seen significant growth in the U.S. energy mix. The figure shows that solar and wind have experienced exponential growth in recent years, benefiting from declining costs and favorable policy environments. Hydropower has been a consistent contributor, while geothermal energy, though limited by geographical constraints, has played a small role. Biofuels and waste have also contributed to the U.S.'s renewable energy portfolio, though their share remains relatively modest. This growth in renewables reflects the U.S.'s proactive approach to diversifying its energy sources and reducing its reliance on fossil fuels. In the case of nuclear energy, even though it has been a stable component of the U.S. energy basket, providing a low-carbon source of electricity. The figure reflects a consistent but limited growth in nuclear power, constrained by high costs, safety concerns, and public opposition (Office of Nuclear Energy, 2024). Nevertheless, nuclear energy remains a key part of the U.S.'s efforts to reduce emissions and achieve a low-carbon energy future. However, like Japan, Australia, and India, the progress in developing non-conventional sources of energy in the USA has also been broadly stagnant but some progress was made in the case of nuclear energy, biofuel, and waste energy. The evolution of the U.S. energy basket reflects its response to changing economic, environmental, and geopolitical factors. The decline of coal, the rise of natural gas and renewables, and the steady role of oil and nuclear energy illustrate the complexities of transitioning to a cleaner energy system.

2.4 International Initiatives to Combat Global Warming

International agreements and cooperation on climate change are essential frameworks that enable countries to tackle the global challenge of climate change together. These agreements, create mandatory commitments for nations to regulate GHG emissions, encourage sustainable practices, and transition towards low-carbon economies. By establishing shared objectives, they provide a systematic approach for addressing environmental deterioration while balancing diverse national interests. Key agreements include the Montreal Protocol (1987), which effectively eliminated ozone-depleting substances (Ozone Secretariat, 1989); the Rio Earth Summit (1992), which established the foundation for international climate diplomacy via the UNFCCC (UN Climate Change, 1992); the Kyoto Protocol (1997), the first-ever treaty requiring emission reductions from developed countries (UNFCCC, 1997); and the Paris Agreement (2015), which brings together 196 nations in the endeavor to restrict global warming to significantly below 2°C (preferably 1.5°C) above pre-industrial levels through nationally determined commitments (UNFCCC, 2016). These agreements jointly seek to improve global responses to climate change via collaborative governance. However, achieving effective international cooperation is challenging due to diverse national interests, economic aspirations, and different levels of commitment among nations. Given that climate change is borderless, effective international cooperation is vital for encouraging technological innovation and ensuring sustainable investment flows. Highlighting mutual interdependence, these international agreements act as a framework for nations to collectively address environmental challenges that cannot be managed independently.

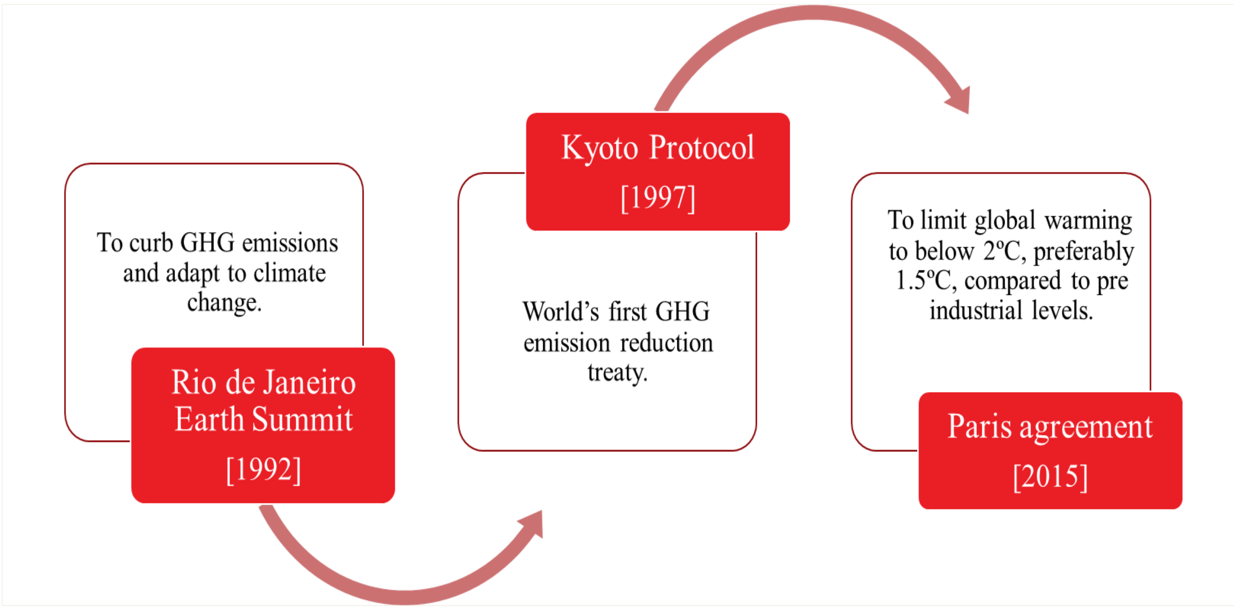
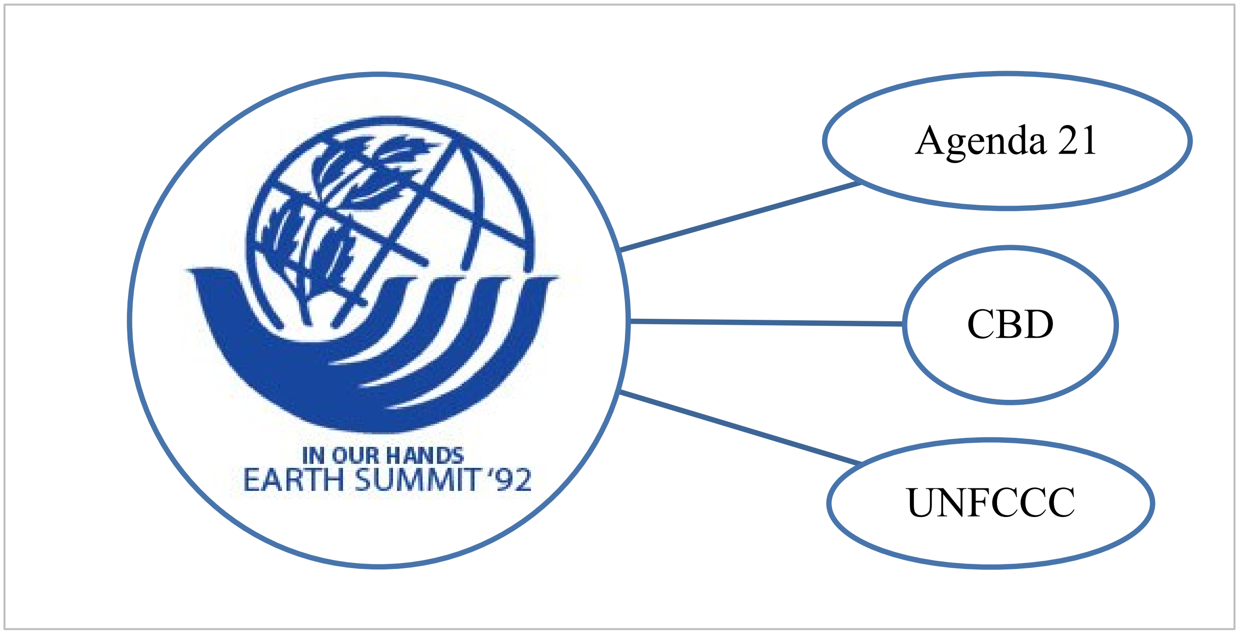


Figure 2.9 International Climate agreements.
Source: Authors own compilation.

a) Rio de Janeiro earth summit

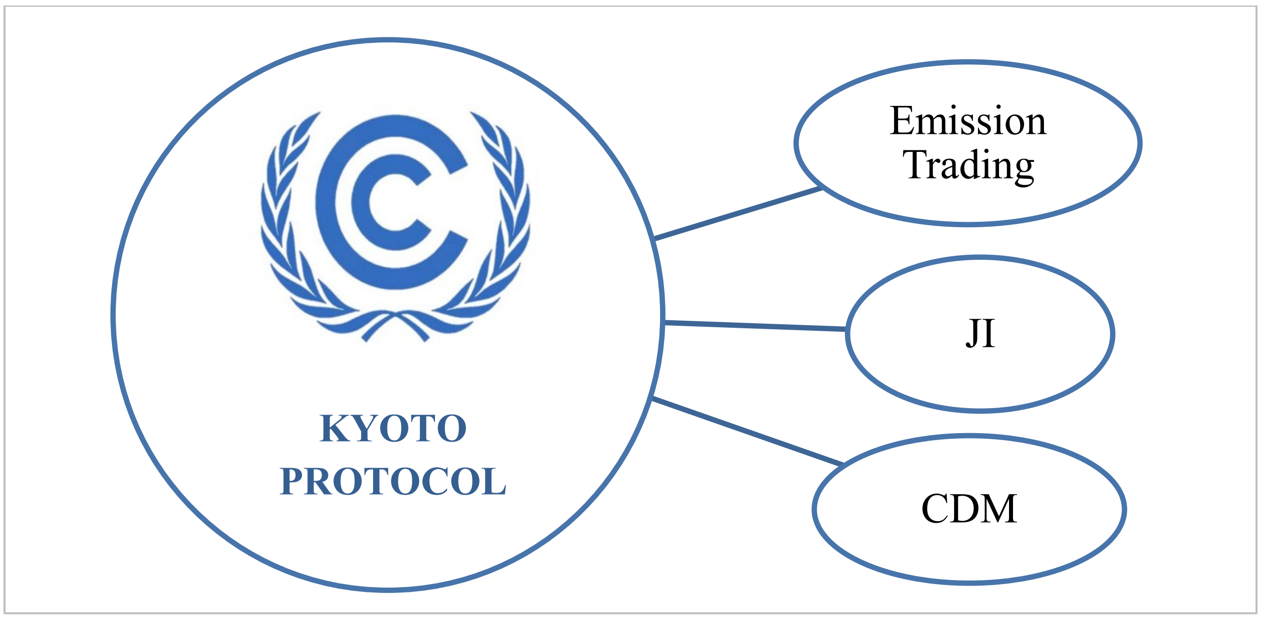
The Earth Summit, formally known as the United Nations Conference on Environment and Development (UNCED), was held at Rio de Janeiro, Brazil, in June 1992. It established the foundational framework for addressing the interconnected challenges of climate change, biodiversity loss, and sustainable development. Also, it marked a key moment in international environmental diplomacy, with the creation of the United Nations Framework Convention on Climate Change (UNFCCC), Agenda 21, and Convention on Biological Diversity (CBD) (United Nations, 1992b). The central aim of the summit was to reconcile worldwide economic development with environmental protection, recognizing that sustainable development must balance economic, social, and environmental priorities.



One of its most significant accomplishments was the adoption of the Rio Declaration on Environment and Development, a set of 27 principles intended to guide countries toward sustainable development in the decades ahead (United Nations, 1993). Another major outcome was Agenda 21, a comprehensive, non-binding action plan for sustainable development to be implemented globally, nationally, and locally. Agenda 21 addressed a wide range of issues, including poverty, consumption patterns, population growth, and resource management, and called for the establishment of the role of major groups in society, such as women, youth, and indigenous peoples (UNCED, 1992). The summit also produced the Forest Principles, a non-legally binding statement offering guidelines for the management, conservation, and sustainable development of forests worldwide. Despite its ambitious agenda, the Earth Summit faced criticism for the non-binding nature of many of its agreements and the challenges of translating commitments into action.

b) Kyoto Protocol

The Kyoto Protocol was adopted in December 1997 and came into effect in February 2005, was the first major international treaty to set legally binding targets for reducing GHG emissions among industrialized nations. The Protocol operated on the principle of "common but differentiated responsibilities," recognizing that industrialized nations should take the lead in combating climate change due to their historical emissions and greater economic capacity (United Nations, 1998).

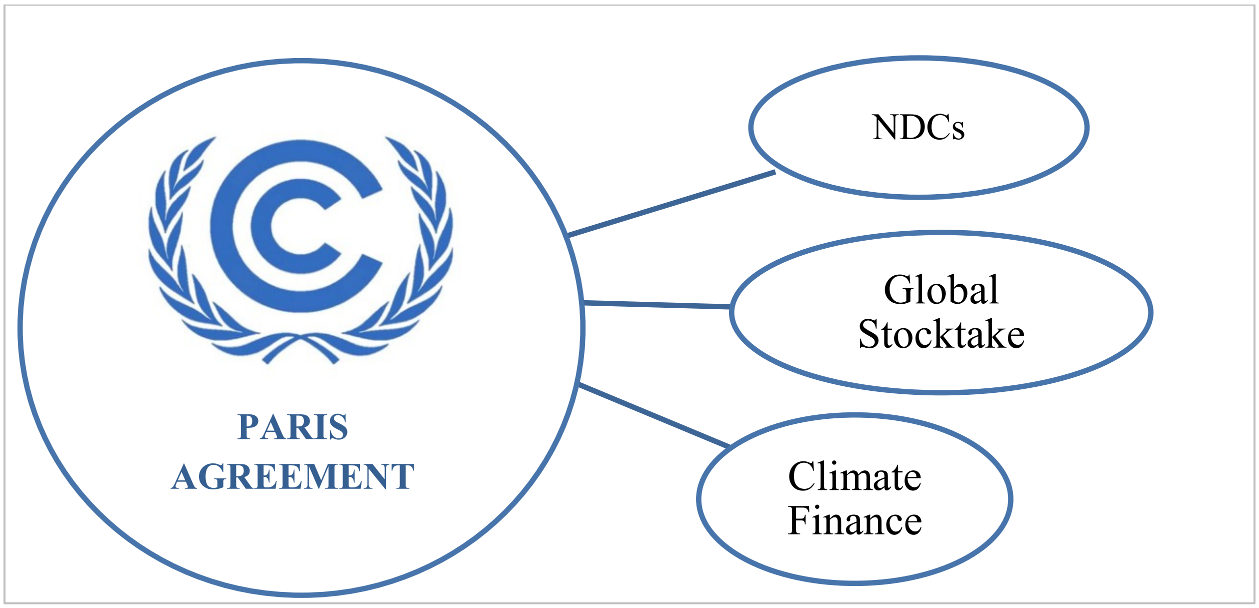


Building on the foundation established by the 1992 UNFCCC, the Protocol recognized the scientific consensus that human activities, especially the burning of fossil fuels were driving global warming. The Protocol targeted six key GHGs: hydrofluorocarbons (HFCs), carbon dioxide (CO_2), perfluorocarbons (PFCs), methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6) (UNFCCC, 2005). National targets varied, with the European Union pledging an 8% reduction, the United States 7% (though it later withdrew), and Japan 6%

reduction (UNFCCC, 2008). To help countries meet their targets, the Protocol introduced three market-based mechanisms: emissions trading between Annex I parties (nations which were assigned legally binding emission reduction targets), the Clean Development Mechanism (CDM) to facilitate emission reduction projects in developing countries, and Joint Implementation (JI) for collaborative projects between developed nations (UNFCCC, 1998). These allowed countries to earn or purchase emission reduction credits through investments in emission-reducing projects abroad, fostering international cooperation and cost-effective mitigation. However, the Protocol's effectiveness was constrained by several structural limitations. Major emitters like the United States declined to approve the agreement, while rapidly industrializing nations operated without binding commitments, hence restricting its global scope. Furthermore, the rigid distinction between developed and developing nation obligations became increasingly problematic as global economic dynamics shifted. These challenges ultimately informed the development of subsequent agreements, particularly the Paris Agreement.

c) Paris Agreement

The Paris Agreement, adopted in December 2015, signifies a major advancement in international climate policy through the implementation of a hybrid strategy that merges nationally defined contributions with shared global objectives. The Agreement establishes a long-term objective to restrict the global temperature rise to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, acknowledging that this would substantially mitigate the risks and implications of climate change (UNFCCC, 2015). In contrast to the Kyoto Protocol's top-down approach, which imposes binding targets solely on industrialized countries, the Paris Agreement presents a hybrid governance framework. The agreement established three principal long-term objectives, the first requires both developed and developing countries to submit an updated national climate action plans every five years known as the Nationally Determined Contributions (NDCs). The second objective is to implement a global stocktake that encompasses a five-year evaluation cycle to review collective advancement towards the Agreement's objectives.



The ultimate objective is to extend financial assistance to emerging nations to alleviate climate change, improve resilience, and enhance their capacities to adapt to climate change. The Agreement distinguishes itself from other international accords by permitting nations to establish their contributions according to their own circumstances, while upholding shared responsibility standards. As of 2023, the pact has been ratified by 195 countries (UNFCCC, 2023). This inclusive strategy has resulted in significant policy transformations globally, with countries accounting for over 80% of worldwide emissions and GDP implementing net-zero targets.

2.4.1 QUAD's Role in Achieving these Agreements

Recognizing the urgency of climate change and its significant impacts on the Indo-Pacific region, the QUAD has redirected its emphasis from security concerns to climate cooperation. The QUAD nations have made significant contributions to achieve the goals of international climate agreements via focused initiatives and policy measures. Within the framework of the Paris Agreement, these nations have established specific programs that actively contribute to global mitigation and adaptation initiatives. Japan has implemented its Joint Crediting Mechanism (JCM) in accordance with Article 6 of the Paris Agreement, executing 265 projects in 30 partner countries as of May 2025 (JCM, 2025). Since 2013, these projects have collectively reduced emissions by 2.4 million tons of CO2 equivalent. India has surpassed its initial Paris NDC target by reaching 50% of its installed electricity capacity from non-fossil energy sources five years ahead of its schedule (Ministry of New and Renewable Energy, 2025).At the same time, it has established the International Solar Alliance (ISA), with the aim of installing 1000GW of solar energy capacity (Ministry of New and Renewable Energy, 2024). Australia has allocated $1.3 billion to fund climate resilience projects over 2020-2025 in Pacific countries, thereby directly contributing to the global adaptation goal of the Paris Agreement (Australian Government, 2024). In 2021, the QUAD launched the Climate Working Group (CWG) to coordinate initiatives on mitigation, adaptation, resilience, technology, capacity-building, and climate finance, ensuring their alignment with global climate objectives. Moreover, the launch of the Quad Climate Change Adaptation and Mitigation Package (Q-CHAMP) in 2022 further operationalized this commitment, focusing on decarbonizing shipping, promoting clean energy transitions, supporting resilient supply chains for clean technologies, and facilitating high-integrity carbon markets in line with Article

6 of the Paris Agreement (The White House, 2022). These achievements illustrate the transition of international climate commitments into practical implementation. Thus, the QUAD demonstrates a model for regional cooperation that facilitates the implementation of global climate frameworks through measurable outcomes.

2.5 Summary of Chapter

The second chapter provides an overview of the relationship between energy consumption, emissions levels, and economic growth globally, with a particular focus on the QUAD countries. This chapter examines the evolution of the energy basket on a global scale and within QUAD countries, revealing the shifts in the share of various energy sources from 1990 to 2022. Additionally, it offers a comparison of the top twenty GHG emitters globally, accompanied by a trend analysis of QUAD's GHG emissions. Lastly, the chapter discusses the international initiatives and agreements concerning climate change and underscores QUAD's contribution to meeting the climate targets.

CHAPTER 3

Review of Literature

A literature review is an important component of academic research, providing a structured overview of existing studies and establishing the foundation for a new study. It allows researchers to engage with the existing studies and identify ongoing debates in the field. It highlights the existing gaps, inconsistencies, and areas that have not been thoroughly explored, thereby justifying the need for the present study. This process helps in defining research objectives, research questions, and guiding methodological choices. Moreover, it ensures that the study provides new insights rather than replicating earlier findings, thus establishing both its relevance and originality. In this study, the literature review is particularly important for analysing the association between energy utilization, GDP, and CO2 emissions levels within the QUAD countries (Australia, Japan, India, and the United States). It provides understanding of how various economic and demographic factors, including renewable energy, population, innovation, GDP, etc. influence emission trajectories. By exploring country-specific and comparative insights, it supports a deeper understanding of how these variables interact across different economic and policy contexts.

Section 3.1 discusses the EKC hypothesis theory in detail. Section 3.2 includes the methodology and working of IPAT, ImPACT, IPBAT, and STIRPAT models. Section 3.3 includes an overview of Kaya identity while section 3.4 deals with the Tapio decoupling approach. Further in section 3.5, a comprehensive literature review is provided for different variables which affects the emissions of a nation and EKC hypothesis. The variables included are energy use: conventional and non- conventional energy, urbanization, innovation, GDP, and emissions. In the end, section 3.6 outlines the identified gaps in the existing literature.

3.1 Theoretical Frameworks:

3.1.1 Environmental Kuznets Curve Hypothesis

The Environmental Kuznets Curve (EKC) hypothesis was first proposed by Grossman and Krueger in 1992 (Grossman & Kruger, 1991), and restated by them in 1995. According to the EKC-hypothesis, rise in economic growth leads to improved environmental quality after an economy has reached an adequate level of economic growth. In the early stages of economic growth, when primary production dominates, there is an abundance of natural resource stock and a limited generation of wastes because of limited economic activity. During development and through industrialization, there occurs a significant depletion of natural resources and wastes accumulate. During this phase, a positive association exists between income or economic growth and environmental degradation (per capita). With further increase in economic growth, services, improved technology, and information diffusion at higher income levels limit the material basis of the economy and result in reduced environmental degradation (Panayotou, 2003).

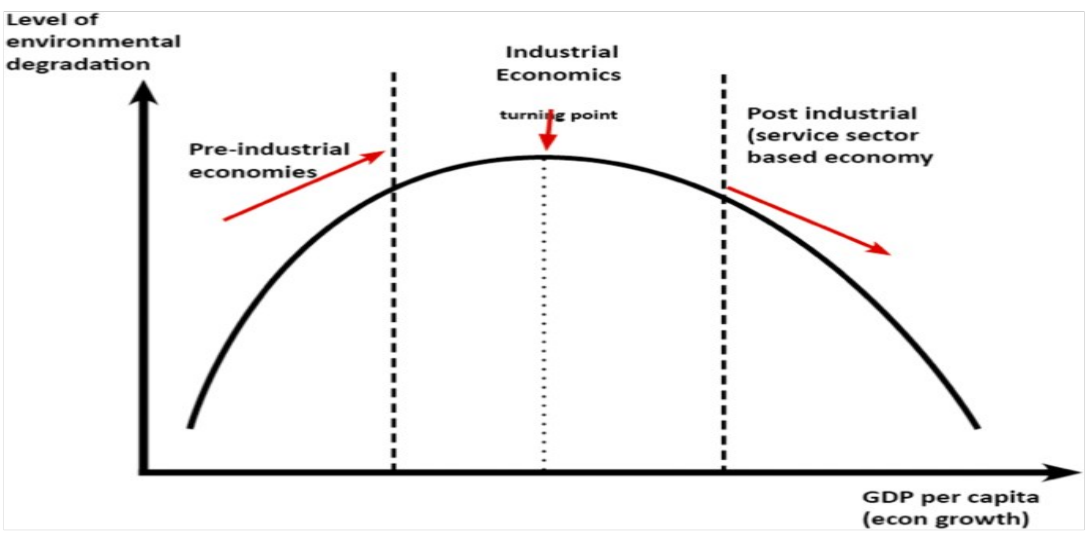


Figure 3.1 EKC Hypothesis.
Source: https://doi.org/10.1007/s11356-019-06276-7

The form of an EKC-curve is shown in Fig.1. The association between per capita environmental deterioration and per capita income is represented as an inverted U-shaped curve and is similar to the original curve proposed by Simon Kuznets (Kuznets, 1955) regarding the association between income disparity and economic growth. The turning point in Fig. 1 represents the level of income (per capita) beyond which environmental degradation can be de-linked from the process of economic growth. For higher income levels, economic growth improves the quality of environment. In Fig. 1, the dependent variable on the vertical axis is an indicator of environmental degradation. Indicators of environmental degradation can be emissions of a specific air pollutant, concentration of a particular pollutant in a local level or an alternative form of environmental degradation like deforestation. The most common forms of pollution that are studied in empirical EKC-estimations are air pollution, water pollution, and land or soil pollution. The independent variable on x- axis in Fig. 1, is income or alternatively economic growth (per capita) which is calculated by dividing the Gross Domestic Product (GDP) with the population of the economy.

Building on this foundation, various theoretical models, such as the green Solow model, macroeconomic production functions, and utility functions, have been developed to explore the EKC relationship. Drawing from these theoretical and empirical frameworks, the standard EKC model can be defined as follows:

$$E_{it} = \alpha_i + \delta_t + \beta_1 X_{it} + \beta_2 X_{it}^2 + \beta_3 X_{it}^3 + \varepsilon_{it} \quad (3.1)$$

where E_{it} is the dependent variable representing environmental degradation and X_{it} represent economic progress, α_i and δ_t are intercept parameters that vary across countries 'i' and years 't', capturing country-specific and time-specific effects. The error term 'ε_{it}' accounts for unobservable factors and β_i are the estimated coefficients of the explanatory variables.

Depending on the study, the model (3) varies. For instance, the integration of the square term of GDP per capita (X_{it}^2) is intended to model the potential for an inverted U-shaped curve, the cubic term of GDP per capita (X_{it}^3) is included in studies that try to examine an N-shaped rather than an inverted U-shaped association between ecological degradation and income. Many studies work on a (natural) logarithmic transformation using ln(x) and ln(y) instead of x and y in order to avoid zero or negative indicators (Stern, 2004). In any case, the final choice of the functional form is done on the model that best fits the available data and has the higher explanatory power inside the data range (Lieb, 2003).

In general, the estimation of the model tests the significance of the coefficients βi. The following seven hypotheses must be satisfied to arrive at a conclusion, whether the EKC hypothesis holds or not for a region (Dinda, 2004):

i. β1 = β2 = β3 = 0: No effect on emissions.

ii. β1 > 0 and β2 = β3 = 0: linear increasing and positive effect on the emissions.

iii. β1 < 0 and β2 = β3 = 0: linear decreasing and negative effect on the emissions.

iv. β1 > 0, β2 < 0, and β3 = 0: Growth-Emission association takes an inverted U-shaped form.

v. β1 < 0, β2 > 0 and β3 = 0: Growth-Emission association takes a U-shaped form.

vi. β1 > 0, β2 < 0, and β3 > 0: Growth-Emission association takes a N-shaped form.

vii. β1 < 0, β2 > 0, and β3 > 0: Growth-Emission association takes an inverted N-shaped form.

Here, only the furth (iv) hypothesis proves the existence of EKC hypothesis. As per the EKC hypothesis, the anticipated value for β_1 and β_2 are positive and negative respectively. This implies that the EKC point of inflection is $-\frac{\beta_1}{2\beta_2}$.

3.1.2 Porter's Hypothesis

Proposed by Harvard Business School professor Michael Porter in 1991, the Porters Hypothesis challenges the conventional economic perspective that environmental regulation inevitably diminishes firm competitiveness. Porter asserts that a well-designed environmental regulation can stimulate innovation in enterprises, enabling them to mitigate compliance costs while enhancing efficiency and gaining a competitive advantage over global competitors. Academic literature discusses three versions of the Porter Hypothesis: the "narrow," "weak," and "strong." The narrow form suggests that flexible, market-oriented regulation increases incentives for innovation. The weak version asserts that environmental restrictions induce a certain level of innovation. The strong form claims that well-designed environmental regulations not only stimulate innovation but also leads to overall improvement in business competitiveness. This means that the gains derived from innovations stimulated by adherence to environmental regulations exceeds the associated costs of those regulations.

3.1.3 Feedback Hypothesis

In environmental economics, the feedback hypothesis argues that the association between economic expansion and environmental quality is bidirectional. It posits that the environment and the economy are interconnected through a dynamic process in which each affects the other over time. For instance, economic activity can result in resource depletion or pollution (economic growth → environmental deterioration), while declining environmental conditions may subsequently affect economic output, health, and productivity (environmental deterioration → slower economic growth). This creates a feedback loop instead of a unidirectional causal chain (M. Ahmed & Azam, 2016).

3.1.4 Neutrality Hypothesis

The neutrality hypothesis posits that both energy consumption and economic growth are independent, implying that neither drives nor hinders the other. Policy initiatives that target energy consumption (conservation or expansion) are not expected to substantially affect economic performance. Hence, energy conservation policies and strategies can be implemented readily when this hypothesis holds true for a nation (Hasanov et al., 2017).

3.1.5 Conservation Hypothesis

The conservation hypothesis discusses the relationship between energy consumption and economic growth and assumes that a unidirectional causality runs from economic growth to energy consumption (Y → EC). It posits that economic growth is the key determinant of energy consumption and an increase in income levels leads to an increase in energy consumption. This hypothesis stresses that energy conservation policies do not have a negative impact on economic growth (Ozturk, 2010).

3.1.6 Economic Growth Hypothesis:

The Growth Hypothesis posits that a unidirectional causal relationship exists from energy consumption to economic growth (EC → Y). It suggests that limitations on energy utilization may negatively impact economic growth, while enhancements in energy use may foster economic growth. It states that energy consumption significantly influences economic growth, both directly and indirectly in the production process. Hence, formulating energy conservation policies have an adverse impact on economic growth (Ozturk, 2010).

3.1.7 Pollution Haven Hypothesis

The pollution haven hypothesis asserts that multinational companies from developed nations often relocate their polluting industries to developing countries with lenient environmental rules and regulations and low compliance costs. According to the PHH, strict regulations in industrialized nations increases production costs for pollution-intensive industries, motivating them to seek "havens" in countries where regulations are not strictly implemented. These nations often welcome such investments with the expectation of economic development, sometimes intentionally maintaining lax environmental standards to attract foreign direct investment (FDI) (Walter & Ugelow, 1979).

3.1.8 Pollution Halo Hypothesis

The pollution halo hypothesis posits that FDI can help to improve the environmental quality of host nations. In contrast to the pollution haven hypothesis, which asserts that multinational corporations relocate polluting operations to nations with relaxed environmental regulations, the pollution halo hypothesis asserts that firms from developed countries transfer environmentally friendly technologies and better management practices, when investing internationally. These techniques not only mitigate pollution at their facilities but also have the potential to raise the standards of local enterprises through competitiveness, collaborations, and workforce mobility. Consequently, foreign direct investment can reduce resource consumption, mitigate emissions, and enhance the overall environmental performance of the host economy (Akbulut & Yereli, 2023).

3.1.9 IPAT, ImPACT, IPBAT, and STIRPAT Models

IPAT Identity

The IPAT identity serves as a well-established framework for analyzing the impact of human activities on the environment (Harrison & Pearce, 2000; Stern, 1992). IPAT emerged out of the Ehrlich-Holdren/Commoner debate in the early 1970s about the fundamental driving forces behind human-induced environmental impacts. Ehrlich & Holdren (1971)made the case for the substantial contribution of population growth to ecological disruption. They noted the exponential nature of population growth and warned that failure to control our number would ultimately lead to ecological and social collapse. Commoner (1992, 1971; Commoner et al., 1971) challenged this interpretation. Focusing on the United States, he stressed that the surge in environmental impacts after World War II could not be solely attributed to population growth. He laid the blame for the environmental crisis at the feet of modern production technologies, which are out of step with natural processes. Commoner et al. (1971; Commoner, 1971) using the I = PAT formula as an equation in which known values of I, P, and A are used to solve for T [T = I/(PA)] demonstrated that in the United States since World War II, the levels of emission of certain pollutants have risen far more rapidly than have population and affluence. This provided the empirical basis for his argument that technology was the most important driving force behind environmental deterioration (York et al., 2002).

IPAT continues to serve as a comprehensive framework for examining the factors influencing environmental change (Harrison, 1993; Raskin, 1995; York et al., 2002). The IPAT model demonstrates that environmental impact (I) is correlated with population (P), affluence (A), and innovation (T), represented in the following general form:

$$I = \alpha P^x A^y T^z \mu \qquad (3.2)$$

where I, P, A and T denote environmental impact, population, affluence, and technological level respectively. Model coefficient is represented by α; and the estimated coefficients of P, A, and T are presented by x, y, and z respectively. μ represents the error term. It outlines those environmental impacts (I) result from the combined effect of three primary driving forces: population (P), per capita consumption or production (affluence (A)), and technology (T). IPAT is a mathematical identity and has typically been used as an accounting equation, in which known values of I, P and A are used to solve for T (Commoner, 1992, 1971; Ehrlich & Ehrlich, 1991; Ehrlich & Holdren, 1972; Harrison, 1993; Raskin, 1995). Affluence is typically operationalized as per capita gross domestic product (GDP), so that

$$PA = P\left(\frac{GDP}{P}\right) = GDP \qquad (3.3)$$

Thus, by definition,

$$T = I/(PA) \text{ or } T = I/(GDP) \qquad (3.4)$$

so that T is the impact per unit of economic activity.

ImPACT Model

Waggoner & Ausubel (2002) have used IPAT as a starting point for assessing potential action and policy levers to alter impacts. They reconceptualize the IPAT identity, renaming it ImPACT, by dividing T into consumption per unit of GDP as 'C' and effect per unit of consumption as 'T', making I = PACT. For example, an analysis of carbon dioxide (CO2) emissions using the traditional IPAT identity would indicate that total emissions (I) are the product of population (P), per capita GDP (A), and CO2 emissions per unit of GDP (T). In contrast, the ImPACT model predicts total CO2 emissions to be equal to the product of population, per capita GDP (A), energy utilization per unit GDP (C), and CO2 emissions per unit of energy consumption (T). The principal purpose of the ImPACT model is to determine the variables that can be altered to minimize the impact and the key variables that influence each factor.

York et al. (2003a) also used IPAT model and found that the key to understanding the relative importance of each driving force (P, A, and T) is to assess the rate and range of potential change in each of the drivers. Elsewhere, we introduced the concept plasticity as a measure of the range and potential for changes in population, affluence, and technology impacts. Plasticity is a tool that recognizes that drivers generate impacts at different scales and at different rates (York et al., 2002). Plasticity comprises two elements: (1) the potential range and variability of each driving force (P, A, and T); and (2) the rate at which each factor can change. The first element highlights the potential breadth of change while the second highlights the potential speed of change. The concept of plasticity makes clear that the important question for researchers and policy makers, then, is which factors can be most easily and effectively changed.

IPBAT Model

Schulze (2002) suggests including Behavior (B) into I = PAT, resulting in I = PBAT which, similar to ImPACT, is an attempt to identify additional factors that affect impacts. He argues that individuals have various effective methods, including altering their behavior, reducing affluence, or employing more efficient technologies to mitigate environmental impact. However, Schulze's methodology has faced criticisms. Diesendorf (2002) posits that certain aspects are inherently integrated into each factor on the right side of the equation I = PAT. Consequently, B can only encompass those behavioral aspects that are not already represented in P, A and T; hence, B is challenging to define precisely.

The key strengths of IPAT and ImPACT are their grounding in ecological principles, their clear and parsimonious specifications, and their utility for illustrating how changes in driving forces can alter impacts. The key limitation of IPAT and ImPACT lies in their structure as accounting equations (i.e. mathematical identities). Because they do not permit hypothesis testing since the values of known terms establish the value of the missing factors.

STIRPAT Model

To address the constraints of these models, York et al. (2003a) formulated a stochastic version of IPAT model, named STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology), to examine the disproportionate effect of population on environment. Unlike IPAT and ImPACT, the STIRPAT model is not an accounting equation; rather it is a stochastic model that can be used to empirically test hypotheses. The specification of the STIRPAT model is:

$$I_i = a\,P_i^b A_i^c\,T_i^d\,e_i \tag{3.5}$$

The model keeps the multiplicative logic of the equation I = PAT, treating P, A, and T as the determinants of I. The constant 'a' scales the model, 'b,' 'c,' and 'd' are the exponents of P, A, and T, that must be estimated and 'e' is the error term (IPAT's proportionality assumption sets $a = b = b = d = e = 1$). The subscript 'i' indicates that these quantities (I, P, A, T, and e) vary across observational units. An additive regression model in which all variables are in logarithmic form facilitates estimation and hypothesis testing. After taking logarithms, the model takes the following form:

$$lnI = a + b\ lnP + c\ lnA + d\ lnT + e \tag{3.6}$$

Eq.3.6 presents the linear relationship between population, affluence, and technology.

Furthermore, York et al. (2003a) introduced the idea of ecological elasticity (EE) to analyze the environmental issues. EE denotes the responsiveness of environmental impacts due to modifications in any of the key factors. Hence, we can compute the EE of any key factors. The term population elasticity of impact (EEIP) denotes the responsiveness of an environmental impact to variations in population size. Affluence elasticity of impact (EEIA) denotes the responsiveness of an environmental impact to variations in affluence. The coefficients b and c in model (2) are respectively the EEIP and EEIA.

3.1.10 Kaya Identity

Kaya identity was first proposed by Professor Yoichi Kaya (Kaya, 1989) on Intergovernmental Panel on Climate Change (IPCC) in 1990. It is a decomposition method that shows the level of energy related CO2 emissions due to the following factors: (a) Population, (b) Gross Domestic Product per capita, (c) Energy Intensity (Energy supply per unit of GDP), and (d) Carbon Intensity (CO2 emissions per unit of total primary energy supply. The Kaya identity is expressed as follows.

$$C = \frac{C}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P \tag{3.7}$$

Where, C, E, GDP, and P denote CO2 Emissions, energy utilization, GDP, and Population respectively. Population growth and economic growth are the main factors which influence

GHG emission trends. The GDP per capita is the best description of economic growth (Tavakoli, 2018). The next important GHG emission driver is “Energy Intensity” as it measures energy efficiency, or provides the amount of economic output that can be generated by one standardized unit of energy used. The higher energy efficiency the lower are associated GHG emissions. The carbon intensity of energy supply is the most important diver of energy related GHG emissions in the country as it shows the low carbon energy transition trends and the increasing share of renewables is the major reason of decrease of carbon intensity of energy consumption.

3.1.11 Tapio Decoupling

In 2005, based on the concept of elasticity, Tapio (2005) used the CO_2 emissions of the transportation industry in European countries as the research data indices. The exponential simulation of economic growth and CO_2 emissions was conducted. Tapio defined decoupling as an elasticity value less than 1. This elasticity value accurately described the state existing between traffic volume and economic growth. According to the definition of elasticity in the economics community, Tapio believed that decoupling referred to the degree of change in transportation volume when *GDP* changed by one percentage point over a period of time. Based on the definition of decoupling, Tapio produced a set of index system called Tapio decoupling index system, as shown in table 3.1. The equation is as follows:

$$r_{v,GDP} = (\%\Delta V|V)/(\%\Delta GDP|GDP) \tag{3.8}$$

where *r* is the elasticity value that indicates the degree of change in traffic volume with *GDP* growth, and *V* represents the traffic volume. The equation of decoupling elasticity between the CO_2 emissions generated by the transportation industry can be expressed as:

$$m_{CO2,r} = (\%\Delta CO2|CO2)/(\%\Delta V|V) \tag{3.9}$$

Tapio obtained the CO_2 decoupling equation by multiplying the two equations, which can be expressed as:

$$t_{CO2,GDP} = (\%\Delta CO2|CO2)/(\%\Delta GDP|GDP) \tag{3.10}$$

where tCO_2, GDP represents that CO_2 emissions will show different development trends with the growth of the national economy. Through this set of index system, it can be described whether CO_2 is decoupled and the degree of decoupling. In the Tapio CO_2 decoupling index system, the critical value can be expressed as three elasticity values of 0, 0.8, and 1.2, so as to divide the decoupling interval amongst CO_2 emissions and GDP. According to the judgement, the CO_2 decoupling status and degree should conform to the actual economic situation.

Table 3.1 Tapio Decoupling Index System.

Decoupling status		**Decoupling index**		
		ΔCO_2	ΔGDP	Elasticity t
Negative Decoupling	Weak negative decoupling	< 0	< 0	0 < t < 0.8
	Strong negative decoupling	> 0	< 0	< 0
	Negative decoupling of growth	> 0	> 0	> 1.2
Decoupling	Recessive decoupling	< 0	< 0	> 1.2
	Strong decoupling	> 0	> 0	< 0
	Weak decoupling	> 0	> 0	0 < t < 0.8
Connectivity	Declining connection	< 0	< 0	0.8 < t < 1.2
	Growth connectivity	> 0	> 0	0.8 < t < 1.2

3.1.12 Jevons Paradox

First articulated by William Stanley Jevons in 1865, in his book, ‘The Coal Question’, the paradox was observed when improvements in the efficiency of coal-powered steam engines made coal use cheaper, leading to even greater overall coal consumption across industries, instead of reducing demand. The Jevons paradox is closely related to the notion of “rebound effects,” which refer to the tendency for expected gains from increased efficiency to be partly or wholly offset by behavioural or other systemic responses.

3.1.13 Urban Environment Transition Theory

Urban environmental transition theory posits that cities undergo a series of environmental issues during their development (Jacobi et al., 2010). Initially, the priority environmental challenges are related to the 'brown' agenda, encompassing water supply, sewage, and sanitation issues. As cities industrialise, they are face issues related to the 'grey' agenda or those related with industrial and automotive pollution. The post-industrial societies face 'green' agenda challenges including greenhouse gas emissions, ozone-depletion, non-point-source pollution and increasing municipal waste. This transition in impact type is accompanied by a change in scale (from local to global), time (from immediate to delayed impacts), and nature (from health-threatening to ecosystem-threatening) (Marcotullio & Lee, 2003).

3.1.14 Ecological Modernization Theory

Ecological modernisation theory (EMT) is a major concept in environmental sociology and policy research, positing that society can address environmental challenges while holding onto modern capitalist or industrial systems. Formulated in the early 1980s by academics named, Joseph Huber and Arthur P. J. Mol, EMT asserts that environmental sustainability can be achieved through systematic eco-innovation, which entails the adoption of cleaner technologies, improved management practices, and more sustainable methods of production and consumption across society. EMT posits that government policy, market competition, and societal forces can stimulate innovations, prompting sectors to incorporate environmental considerations and develop new opportunities based on sustainability.

The theoretical perspectives discussed in this chapter provide the basis for understanding the relationship between energy consumption, economic growth, and emissions in the QUAD countries. The Environmental Kuznets Curve (EKC) hypothesis, growth theory, the STIRPAT model, and other theories guide the empirical framework developed in this study to examine the energy–growth–emissions nexus and the influence of rural and urban populations on emissions. The empirical models are therefore developed to examine the theoretical relationships presented in this section.

3.2 Empirical literature

The effects of climate change are evident and can be observed everywhere around the globe. Countries globally are implementing strategies towards clean energy use and green technology (Amri et al., 2019), to reduce GHG emissions and facilitate climate change mitigation along with balancing economic growth (Qin & Ozturk, 2021). Many academicians have studied this nexus of energy use, Innovation, and emissions (Shahbaz et al., 2019; Shahbaz & Sinha, 2019; N. Zhang et al., 2016); mainly focusing on the issues and determinants of Global warming (Ladan, 2018; Major et al., 2018; Sanchez Rodriguez et al., 2018). Numerous academicians opine that CO2 emissions and a country's GDP move hand in hand as the nation's economy expands and contracts (Doda, 2014). (Jotzo et al., 2012) conducted a study to investigate the reason behind this rapid upsurge in CO2 emissions. Their findings suggested that the primary underlying factors responsible for this were growth in energy intensity, elevated GDP growth rates, and an increase in the carbon intensity of the related energy mix. The level of CO2 emissions rapidly increases when a nation experiences an economic expansion (Heutel, 2012; Shahiduzzaman & Layton, 2015), the primary reason being that as the per capita income of the country increases, the demand for products by the consumer surges. This leads to more industrial production and increased energy consumption, contributing to air pollution, as highlighted by Eng & Wong (2017).

3.2.1 Environmental Kuznets Curve (EKC)

Economic growth, often measured by a nation's GDP, has a complex relationship with CO_2 emissions that is well-documented in the literature. This association between economic growth and CO_2 emissions is tested particularly through the lens of the EKC hypothesis (Kuznets, 1955). The EKC hypothesis suggests an inverted U-shaped relationship between income levels and environmental degradation: in the early phases of economic development, growth tends to worsen environmental outcomes because of rise in industrial activities (scale effect). However, as countries progress economically, they often adopt cleaner technologies and implement environmental regulations (technique effect), which helps reduce emissions (Stern, 1998).

Panayotou, (1993); Suri & Chapman, (1998) were among the pioneering researchers to empirically establish the EKC hypothesis among variables such as energy consumption and GDP for both developed and emerging economies. Subsequently, other researchers sought to validate the EKC hypothesis across different regions and contexts. Aldy, (2005) established the EKC in the United States using OLS regression, while Mazzanti et al. (2007) found mixed evidence for the EKC in their study, highlighting sectoral variations in Italy. Dinda (2009) tested the presence of EKC hypothesis on panel of 88 nations between 1960-1990 and found that EKC is valid only for the developed nations while developing nations depict a linear positive income-emission relationship. Jalil & Mahmud (2009) conducted their study in case of China and employed ARDL model from 1975 to 2005. They found that CO2 emissions are majorly determined by income and energy use hence, validating the EKC hypothesis. Alike results were found by Arouri et al. (2012) for Middle East and North African (MENA) nations from 1981 to 2005. K. Ahmed & Long (2012) in their study used ARDL bound testing approach and found that an inverted U-shaped relationship exists among emissions and economic growth. Further asserting that economic growth is an important variable that explains environmental pollution in Pakistan. Esteve & Tamarit (2012) introduced a more sophisticated methodological framework by using threshold cointegration techniques to analyse the association between per capita emissions and income in Spain. Their findings underscored the non-linear nature of this relationship, and the existence of an Environmental Kuznets Curve for Spain. On the contrary, Ozcan (2013) studied 12 Middle East countries from 1990 to 2008. The study observed a U-shaped relationship in five nations, an inverted U-shaped relationship in three nations, and no causal relationship between Co2 emissions and income in the remaining four countries. Cho et al. (2014) conducted a panel study on OECD countries, considering total GHG remissions including methane and nitrous oxide. The results of fully modified OLS (FMOLS) model confirmed the presence of a quadratic (inverted U-shaped) relationship among emissions and GDP over the long run. Similarly, Apergis & Ozturk (2015) used the Generalized Method of Moments (GMM) to confirm the EKC hypothesis in Asian countries, contributing further empirical support from a regional perspective. Chen et al. (2016)

studied the economy-energy-environment (E3) nexus for 188 countries by using panel cointegration and Vector Error Correction Model (VECM) for the period 1993-2010. They found that there exist long-run relationships between economic growth, energy consumption, and carbon dioxide emissions for all the countries. Apergis et al. (2017) applied Fully Modified Ordinary Least Square (FMOLS) to empirically validate the EKC hypothesis in the United States, supporting the existence of inverted U-shaped curve and thereby validating the EKC hypothesis. Similarly, Alejandro & Anastacio (2017) applied Pedroni cointegration and FMOLS technique, validating the EKC hypothesis in North America. Hanafy & El-Aasar (2018) investigated the existence of the EKC in Egypt by employing ARDL bound testing approach. The results depicted that EKC does not exist for GHG emissions in both short and long-term. However, Sinha & Shahbaz (2018) confirmed the existence of inverted U-shaped relationship in India with turning point at per capita income of USD 2937.77. Destek & Sarkodie (2019) studied the association between economic growth and environment using Augmented Mean Group (AMG) estimator and heterogenous panel causality method. The authors identified that an inverted U-shaped association existence in Mexico, Philippines, Singapore, and south Africa demonstrating that economic growth initially leads to increased emissions before eventually decreasing, and a U-shaped relationship in India, China, South Korea, Thailand, and Turkey. Similarly, Rana & Sharma (2019) found the existence of EKC hypothesis along with Pollution Haven Hypothesis in case of India. A novel approach in identifying the presence of EKC hypothesis by considering total factor productivity as a measure of income was introduced by Amri et al. (2019). The study used the Autoregressive Distributed Lag (ARDL) model and found that EKC does not hold true in Tunisia. Similar results were observed by Dogan & Inglesi-Lotz (2020) who found that in the in Europe nations, the EKC did not hold when industrial share was used as a proxy for economic growth. However, the EKC is established when aggregate GDP growth is considered for the analysis. Akram et al. (2020) employed fixed effect panel Quantile Regression (PQR) and panel OLS on 66 developing countries, highlighting that energy efficiency is an important factor in the formation of EKC hypothesis. Mujtaba et al. (2020) studied 25 upper middle-income countries from 1985 to 2014 and observed a negative association among economic growth and emission levels. Tenaw & Beyene (2021) applied second generation panel data techniques, namely cross-sectional dependence test, CIPS, PMG, and CCE-PMG in their study confirming the robustness of their results. Their empirical analysis considered HDI as a proxy for economic growth and confirmed that an inverted U-shaped EKC curve is present in 20 Sub-Saharan African (SSA) nations from 1990 to 2015. Dong et al. (2020) used Logarithmic Mean Divisia Index (LMDI) method and found that economic growth and population growth were the two main drivers of CO2 emissions in low-income countries. Akadırı et al. (2021) tested the EKC hypothesis in case of BRICS (Brazil, Russia, India, China, and South Africa) countries over the period of 1995-2018. They concluded that an inverted U-shaped relationship exists between economic growth and emissions in the long-run the BRICS nations (Naseem et al., 2022). Likewise, Thio et al. (2022) verified the STIRPAT model using the panel quantile regression approach for the top 10 carbon emitter countries namely, China, USA, India, Russia, Japan, Germany, South Korea, Canada, Mexico, and South Africa. They observed that in all the countries income per capita significantly increases environmental pollution, establishing the EKC hypothesis. Jena et al. (2022) employed CO2 emissions and ecological footprint as proxies for environmental deterioration to determine the EKC hypothesis in China, India, and Japan. Their study found that in case of CO2 emissions, an inverted U-shaped relationship exists for China, while U-shaped relationship is found for India and Japan. Similarly in the case of ecological footprint, it was observed that an inverted U-shaped relationship exists for Japan, while U-shaped relationship exists for India and China. Mahmood (2022) analyses the association amongst consumption-based CO2 emissions, exports, imports, and FDI in case of GCC countries using a Spatial Durbin Model for the period 1990–2019. The study confirmed the validity of EKC hypothesis in both territory-based CO2 emissions and consumption-based CO2 emissions. Further Mahmood (2023) extended this analysis to Latin America, examining trade, FDI, and emissions using spatial econometrics. The study empirically tested the pollution heaven and EKC hypothesis for the period 1970–2019 and documented that the Latin American region lies in the 1st stage of EKC. Liu et al. (2023) confirmed the validity of the inverted U-shaped EKC hypothesis in the emerging Asian economies such as India, China, Japan, and Russia. Dlamini et al. (2024) employed Generalized Mean of Moments (GMM) on 48 Sub Saharan African countries, confirming the existence of EKC hypothesis between income and CO2 emissions. Pata et al. (2024) analyzed the role of human capital in reducing emissions across EU nations using the Fourier ADL approach. The results depicted that human capital helps in reduction of emissions, hence confirming the presence of EKC hypothesis. Wu & Wan (2024) employed LMDI along with Tapio Decoupling Index (DI) from 2000 to 2020 for the USA, Japan, Germany, China, India, and Russia. They found that economic growth predominantly contributed to increased carbon emissions, depicting that the decoupling efforts made by developing countries are weaker than those of developed countries. Zhu et al. (2024) examined the impact of green finance, fintech and mineral resources on environmental sustainability in the E7 nations namely Brazil, China, India, Indonesia, Mexico, Russia, and Turkey from 1998 to 2022 using nonlinear ARDL (NARDL) model. The results confirmed the

EKC hypothesis, linking green finance and fintech to improved environmental sustainability. Ximei et al. (2025) studied the Asia-Pacific Economic Cooperation (APEC) economies for the period 1991–2020 by utilizing advanced panel data estimation techniques along with causality tests and focused on the SDG-13. The empirical analyses reveal that information & communication technology (ICT), economic globalization, renewable energy consumption, and green financial development foster environmental sustainability, supporting the EKC hypothesis. Other than the traditional U-shaped and an inverted U-shaped relationship between emission and growth, some studies found N-shaped association among the variables. J. Zhang (2021) observed an N-shaped association amongst per capita GDP and carbon dioxide emissions, highlighting the positive influence of energy utilization on CO2 emissions in China in the long-horizon. Likewise, Mahmood et al. (2021) confirmed the N-shaped relationship in Egypt's energy consumption patterns over a period from 1965 to 2019. Al Numan et al. (2025) in their study also found that economic growth can eventually reduce Ecological footprint through structural transformation and technology adoption and confirmed the presence of N-shaped EKC curve.

3.2.2 Energy Use

Energy consumption and emissions are closely linked, with various factors influencing their relationship across different sectors such as transportation, industry, and economic growth. The nature and source of energy play a pivotal role in this linkage. Broadly, energy sources can be categorized into traditional (fossil-based) and renewable alternatives. The global dependence on fossil fuels particularly coal, oil, and natural gas has been a dominant contributor to carbon emissions. Consequently, a transition toward cleaner, renewable energy sources is considered vital for reducing emissions while maintaining economic development.

In the case of the United States, Soytas et al. (2007) examined the long-run dynamic relationship among CO2 emissions, income, and energy consumption. Their findings suggest that energy consumption Granger causes CO2 emissions over the long-run, implying that changes in energy use significantly impact emission levels. In France Ang (2007) identified causality running from economic growth to both CO2 emissions and energy consumption for the period 1960–2000. Ang (2008) further analyzed Malaysia from 1971 to 1999. The results indicated that a unidirectional causality runs from economic growth to energy consumption in both short-run and long-run. Soytas & Sari (2009) report a unidirectional causal from carbon emissions to energy consumption in Turkey for the period between 1960 and 2000. His finding is particularly noteworthy, suggesting that emission levels themselves may influence energy demand. In Tunisian, Chebbi (2010) investigated the sector-specific causal relationship between energy consumption, income, and CO2 emissions. The empirical evidence indicated that energy consumption influences economic growth differently across sectors, reflecting the heterogeneous nature of energy-growth linkages. Chang (2010) examined the causal relationship between economic growth, energy utilization, and CO2 emissions in China. The findings revealed that energy utilization stimulates CO2 emissions. Additionally, electricity use was found to be positively associated with coal consumption and showed bidirectional causality with CO_2 emissions, suggesting a feedback mechanism. Similar results were observed for South Africa by Menyah & Wolde-Rufael (2010), they studied the long and short run relationship amongst variables using bound test and found that one-directional causality runs from energy utilization to CO2 emissions. Using multivariate cointegration analysis, Hatzigeorgiou et al. (2011) explored the association amongst CO2 emissions, GDP, and energy intensity in Greece during the period 1977–2007. They discovered that there are unidirectional causalities running from GDP to energy intensity and from GDP to CO_2 emission, along with a bidirectional causality between CO_2 emissions and energy intensity. Alam et al. (2011) investigated the relationship among energy consumption, GDP, and energy pollutants in India. Their empirical research demonstrated the bidirectional causal relationship between energy utilization and CO_2 emissions. In the case of China, Jalil & Feridun (2011) examined the effects of GDP, energy use, and financial development on carbon emissions. Their findings indicated that all three factors negatively affect environmental quality. A positive correlation amongst energy utilization and economic expansion with CO_2 emissions was also established by Bojanic (2012), further confirming this relationship. Shahbaz et al. (2013) investigated Indonesia and observed similar patterns, emphasizing the detrimental environmental impact of rising energy consumption amid economic growth. Mercan & Karakaya (2015) analyzed the association between energy use and economic growth concerning CO_2 emissions for eleven OECD nations from 1970 to 2011. In their study, cointegration was identified between energy consumption (EC) and economic growth. Abubakar Siddique et al. (2016) studied the influence of energy use and urbanization on CO_2 emissions in South Asia from 1983 to 2013 and revealed a bidirectional causality between CO_2 emissions and energy use. In the case of developed nation like the United States, Dogan & Turkekul (2016) employed the ARDL model and found bidirectional causality between energy use and CO_2 emissions. Similarly, Wang et al. (2018) examined the impact of earnings and energy use on CO_2 emissions through the ARDL framework. The researcher observed that both income and energy use per capita lead to a rise in CO_2 emission. In Pakistan, M. K. Khan et al. (2019) tested the relationship between energy consumption, globalization, and CO_2 emissions from 1971 to 2016. They found that political and economic globalization along with energy consumption were positively associated with CO2 emissions. Shastri et al. (2020) examined the nonlinear relationship among economic growth, renewable energy consumption, and non-renewable energy consumption by applying NARDL in case of India. The results supported the growth hypothesis and depicted that a unidirectional causal relationship runs from non-renewable and renewable energy consumption to economic growth. Tetteh & Baidoo (2022) introduced advanced methodologies, including neural network autoregression (NNAR) and Markov switching models, to study the nexus of globalization index, energy consumption, and emissions. Their findings augmented the view that energy use and global integration contributed to the environmental deterioration. Most recently, Dharmapriya et al. (2024) conducted a comprehensive study across 48 Asian countries. Their analysis revealed that energy consumption remains a central factor driving CO_2 emissions in the region, underscoring the urgent need for energy transition strategies.

3.2.3 Renewable Energy

Renewable energy, derived from natural and replenishable resources like solar radiation, wind currents, hydropower, geothermal heat, and biomass, is increasingly recognized as an international effort to address climate change (Doğan et al., 2021, 2022; Kartal, 2022, 2023). The shift toward renewable energy is driven by the urgent need to reduce greenhouse gas emissions, achieve energy security, and support sustainable economic development.

Varun et al. (2009) pointed out that increased use of alternative energy is typically negatively related with the degree of CO2 emissions. However, the influence of non-conventional energy on economic growth remains inconclusive, with outcomes varying across nations and timeframes. In their analysis of G7 countries, Sadorsky (2009) applied panel vector error correction model (VECM) to examine non-conventional energy consumption, CO2 emissions, and oil prices during the period 1980-2005. The study found that in long horizon, CO2 emissions, and GDP per capita are two major factors behind renewable energy growth per capita. Similarly, Apergis et al. (2010) examine the causal association amongst CO2 emissions, renewable energy, nuclear energy, and GDP across 19 developed and developing nations for the period 1984–2007. Their findings demonstrated a long-run positive association among CO_2 emissions and non-conventional energy consumption, though the results from the panel Granger causality tests indicated that non-conventional energy consumption does not reduce CO2 emissions in the short-run. Menyah & Wolde-Rufael (2010) investigated the causal association among CO2 emissions, non-conventional and nuclear energy consumption, and real GDP for the US from 1960 to 2007, affirming the role of nuclear energy in emissions reduction. Interestingly, no causal association was found between non-conventional energy consumption and CO_2 emissions, though emissions did influence renewable energy use. Silva et al. (2012) examined the causal relationship between GDP, CO2 emissions, and renewable energy sources (used for electricity generation only) in Denmark, Portugal, Spain, and the US over the period 1960–2004. Their results concluded that initially for all countries except the US, increase in the share of renewable energy sources have a negative impact on economic growth but positive impact on CO2 emissions reduction. In Latin American and Caribbean countries, Al-mulali et al. (2015) studied the effect of GDP, renewable energy utilization, and financial development (FD) on CO2 emission from 1980 to 2010 using the FMOLS and VECM approach. The results revealed that non-conventional energy has no significant long-run impact on CO2 emissions. On the contrary, Cansino et al. (2015) used LMDI approach to deduce that renewable energy sources help in reduction of CO2 emissions in Spain during the period 1995-

2009. Irandoust (2016) employed VAR model to investigate the relationship between renewable energy, economic growth, and CO2 emissions in four Nordic countries. The author observed that the use of renewable energy improves environmental well-being. Similar results were obtained by Bilgili et al. (2016) for 17OECD countries by employing DOLS and FMOLS techniques over the period 1977-2010. In case of BRICS economies, Danish et al. (2019) employed the second-generation approach to test the link amidst environmental degradation, GDP, natural resources, and renewable energy. The findings revealed that renewable energy use helped in CO2 emissions reduction. S. A. R. Khan et al. (2020) in their study employed dynamic common correlated effect (DCCE) model andidentified renewable energy consumption helps to reduce GHG emissions in Nordic countries. Many studies have documented similar results between renewable energy consumption and co2 emissions in the case of Australia (Z. Ahmed & Le, 2021; Rahman & Vu, 2020), E7 countries (Gyamfi et al., 2021), and ASEAN countries (Anwar et al., 2021). (Murshed et al., 2021) examined South Asian countries like Bangladesh, India, Pakistan, and Sri Lanka from 1990 to 2016. The study focused on identifying the relationship between environmental policies, economic progress, renewable energy use, non-renewable energy usage, technology, and ecological footprint by validating the EKC and pollution haven hypothesis. The results revealed that renewable energy use and environmental regulations jointly reduce the ecological footprints and validated the existence of EKC and pollution haven hypothesis. R. Sharma et al. (2021) examined the effects of renewable energy, population density, life expectancy, income, and other demographic variables on the ecological footprint during a period of 25 years, from 1990 to 2015 for eight South and Southeast Asian countries. The study employed Cross-Sectional ARDL (CS-ARDL) approach indicating that renewable energy significantly mitigated environmental degradation.

Similarly, Iqbal et al. (2021) concluded that the utilization of renewable energies and the advancement of environmentally oriented technological innovations contribute to the advancement of environmental sustainability. Y. Wang et al. (2021) examined the relationship between natural resources and environmental degradation in Pakistan between 1990 and 2018. The analysis employed ARDL and found that green energy negatively affects environmental degradation in both short and long term. Similar results were observed by A. Amin et al. (2022) in case of China. Recent contributions from Adebayo et al. (2023),Miao et al. (2022), and Zafar et al. (2021) asserted that the utilization of renewable energies and the conservation of natural resources contribute significantly to the mitigation of ecological deterioration. Gyamfi et al. (2022) found that technological innovation along with renewable energy use helps to reduce environmental degradation. In case of G-20 nations, Aneja et al. (2024) found that renewable energy plays a significant role in sustaining the environmental conditions. N. Amin et al. (2023) advanced their study by using second generational panel methodologies to overcome the problem of multicollinearity. Based on the empirical findings, they observed that both green technological Innovation and renewable energy use reduces CO2 emissions in selected south Asian economies. In case of Nigeria and the United States Idoko et al. (2024) found that both the nations benefit environmentally from renewable energy use. Ghorbal & Ben Youssef (2024) used ARDL model on annual dataset from 1980 to 2018. The results revealed that South Korea should continue to promote renewable energies and facilitate the use of foreign patents, particularly those relating to renewable energies. This will lead to a reduction in its carbon emissions while benefiting its economic growth. Shu et al. (2024) employed the STIRPAT model on quarterly data of China and found that renewable energy mitigates ghg emissions in both short run and long run. In a recent study, Borowiec & Papież (2024) through DCCE-MG modelling, explored the role of globalization in emissions convergence. Their findings indicated that while stricter environmental policies and globalization facilitate emissions convergence in developing countries, renewable energy and industrialization had limited influence on this convergence process. To understand the impact of increasing use of non-conventional energy and forest area on the GHG emissions, Yazd et al. (2024) employed advanced Machine Learning (ML) and Deep learning (DL) approaches and found that increase in both non-conventional energy consumption and forest areas significantly contributes to the decline of GHG emissions.

3.2.4 Non-Renewable Energy

The role of energy in economic development is undeniably significant, yet the environmental costs related with the consumption of conventional energy sources remain a major concern. Conventional fuels such as petroleum, coal, and gasoline are widely acknowledged as primary contributors to environmental degradation, particularly in industrialized economies (Kartal et al., 2023; Usman & Balsalobre-Lorente, 2022). Historical researchers underscore the growth-enabling potential of non-renewable energy, while simultaneously emphasizing its role on increasing GHG emissions.

Vaona (2012) used VAR model over an extensive historical dataset from 1861 to 2000 for Italy and examined the relationship between energy consumption of non-renewable energy sources and output. The results confirmed bidirectional causality between non-renewable energy consumption and economic output, implying that non-renewable energy consumption promotes economic growth. Hanif et al. (2019) studied the impact of foreign direct investment (FDI), fossil fuel use, and economic development on carbon emissions in emerging economies in Asia. They argued that increased FDI inflows into China would lead to greater energy consumption and, hence, higher CO2 emissions. This finding is in contrast to findings of De Beule et al. (2022). Yang et al. (2021) also observed that use of traditional energy source such as oil and coal leads to an increase in CO2 emissions. Supporting this, Raihan & Mainul Bari (2024) explored the consequences of increase in economic outgrowth, conventional fuel, and renewable energy utilization on China's CO2 emissions. The study utilized an ARDL model to analyze annual data from 1965 to 2022, and found the presence of long-term cointegration among the variables. The empirical results show that a 1% increase in conventional fuel use leads to 4.97% rise in CO_2 emissions, while economic growth alone contributes 0.58% to emissions growth over the long term.

3.2.5 Urbanization

In the last four decades, world has witnessed a strong growth in urbanization across the globe. Urbanization is a critical driver of economic development, often regarded as a key indicator of a nation's development status B. Li & Yao (2009). However, while urbanization can catalyze industrial expansion and improve living standards, it can have several negative consequences on the environment. These include, but are not limited to, heightened levels of air and water pollution, greater vehicular and industrial emissions, increased solid waste generation, and a surge in greenhouse gas emissions. As a result, the intricate nexus between urbanization, energy consumption, and carbon dioxide emissions has been a subject of considerable academic research.

Jones (1991) was among the earliest scholars to explore this relationship using cross-sectional data. Their findings indicated a strong correlation amongst energy use per capita and urban population, moreover increase in urban population increased energy utilization and transport energy. Similarly, Parikh & Shukla (1995) analyzed data from 1965 to 1987 across several developing countries and reported that the GHG emission and energy consumption were positively correlated with the urbanization level. Further, York et al. (2003b) substantiated this finding in their study by revealing that urbanization has a positive effect on energy use and CO2 emissions. In China, Y. Liu (2009) used econometric tools such as ARDL and factor decomposition model on data from 1978 to 2008. The analysis confirmed a one-way causality running from urbanization to energy utilization in both short and long run. Mishra et al. (2009) found a positive correlation between CO2 emissions and urban population in Tonga, French, and Polynesia, but an adverse association in Samoa. Using the STIRPAT model on a panel of 99 high, middle, and low-income nations, Poumanyvong & Kaneko (2010) conducted their analysis between 1975 and 2005. The findings revealed that urbanization decreases energy use in low-income nations, while it increases in middle and high-income nations. Donglan et al. (2010) applied LMDI analysis and found that energy intensity helps reduce the level of carbon dioxide emission but income leads to increase in the emission in both urban and rural areas in China. They further highlighted that increase in urban populations was an important contributor to carbon dioxide emission. On the same line results were obtained by Parshall et al. (2010) in the United States. Feng et al. (2011) used grey model to compare the association amidst energy use, consumption expenditure, and CO2 emissions for different lifestyles. The result depicted that energy-related CO_2 emissions were more intense in urban than rural lifestyles in China. S. S. Sharma (2011) analyzed 69 countries from 1985-2005 and found that urbanization has a negative impact on carbon dioxide emission across high, middle, and low-income nations, suggesting that better urban planning may mitigate environmental harm.

Further insights were offered by Hossain (2011), who used time series data from 1971 to 2007 on newly industrialized nations. He found that urbanization was associated with improved environmental quality in the long-run. Martínez-Zarzoso & Maruotti (2011) in their study analyzed developing countries from 1975 to 2003. The empirical evidence found that the association between emissions and urbanization is stronger in less urbanized areas, which aligns with the view that higher environmental impact seen in less developed regions. X. Dong & Yuan (2011) used the SVAR approach by Blanchard and Quah to explore the long-run impact of urbanization on GHG emission in case of China. Based on their findings, they documented that the urbanization level approximately contributes to 18% of the change in CO2 emissions and in the short run delays in urban development contributes to temporary emission reduction. Similarly, Liu et al. (2011) applied input-output method to examine the impact of increased urban and rural household energy consumption on carbon emissions in China. The results depicted that the household energy use was responsible for more than 40% of China's primary energy-based CO_2 emissions between 1992 and 2007. Although Geng et al. (2011) found the same results in China, they highlighted coal combustion as the leading cause of emission. Moreover, the carbon intensity in the future was not high and the emissions were anticipated to improve with time. Madlener & Sunak (2011) argued that the role of urbanization in increasing the demand of energy depends on the mechanism of urbanization within different sectors and development level of the country. In Tunisia, Shahbaz & Lean (2012) found that urbanization had both long run and a short run causal relationship with energy consumption over the period of 1971-2008. Y. Fan & Xia (2012) found similar results in China and predicted that energy demand will reach 4.7 billion tons of coal equivalent in 2020. In the case of UAE, Shahbaz et al. (2014) used ARDL model and found that positive association exists between urbanization and CO_2 emissions from 1975 to 2011. Y. J. Zhang et al. (2014) studied the association between economic growth, industrialization, urbanization, and CO_2 emissions in China by using the ARDL approach. The results confirmed a long-term association between urbanization and energy emission. Al-Mulali & Ozturk (2015) noted that in MENA nations, urbanization along with energy use and trade drives the ecological footprint. Time-series and Panel data studies by Kasman & Duman, (2015); Q. Wang et al., (2016); Y. Wang et al., (2016) revealed that urbanization significantly increases both CO_2 emissions and energy consumption. Dogan & Turkekul (2016) employed ARDL model in their study and found that bidirectional causality between urbanisation and GDP in the United States. Bekhet & Othman (2017) in their research, found that in case of Malaysia, unidirectional causality runs from urbanization to CO_2 emissions in the short-term and a two-way causality amid CO_2 emissions and urbanization in the long-term. While in case of 17 countries in the South and Southeast Asian region Behera & Dash (2017) used a simple panel cointegration test to find if there exists a long-run relationship among urbanisation and CO_2 emissions. The results found that CO_2 emissions are associated with urbanization in all groups of countries. Yazdi & Dariani (2019) studied 18 Asian countries using PMG model from 1980 to 2014 and found a bidirectional causality between urbanization and Co_2 emissions. Salahuddin et al. (2019) applied ARDL model on annual dataset from 1984 to 2016 and obtained similar results in case of South Africa. Samreen & Majeed (2020) found that, increase in urban population increases the level of industrial production which leads to greater levels of air pollution. In the case of APEC countries Z. Wang et al. (2020) observed similar results from 1990 to 2014. However, Shaheen et al. (2020) found that in Pakistan, urbanization and industrialization have no significant impact on environmental quality. Anwar et al. (2020) used fixed effect model in nine east Asian countries from 1980 to 2017 and examined the association between urbanization, CO2 emissions, and economic growth. The findings confirmed a strong positive correlation between urbanization and CO_2 emissions. Mills et al. (2019) applied the Toda and Yamamoto granger causality test and found similar relationship in case of the United States and China from 1980 to 2017. Abbasi et al. (2020) in their study, noted that in the long-run urbanization and energy consumption negatively affect environmental quality across several Asian countries such as, Bangladesh, China, India, Indonesia, Malaysia, Nepal, Pakistan, Sri Lanka. Further, Hongxing et al. (2021) considered 81 economies of Belt and Road Initiative (BRI) corridor, which is an economic corridor having interaction among 138 relevant countries to increase economic development. The study employed Westerlund and PMG models and confirmed that energy utilization, urbanization, trade, and CO2 emissions are the key determinants of economic growth in these countries. Armeanu et al. (2021) in their study, examined the multidimensional association between GDP, energy, CO2 emissions, and urbanization across different income groups from 1990 to 2014 by employing the Granger causality test. The empirical analysis revealed that lower middle-income economies support the conservation hypothesis while, the upper and middle-income economies exhibit a feedback hypothesis among the variables. Azam et al. (2022) employed CS-ARDL, PMG, and Dumritch-Hurlin granger causality techniques to examine the relationship between urbanization, GDP per capita, income, energy consumption, and CO2 emissions. The results revealed that urbanization, GDP per capita, income, and energy use, drives CO2 emissions in SAARC countries. Moreover, the results confirmed a bidirectional relationship between CO2 and urbanization. Kayani et al. (2023) studied the top ten most polluted economies of the world and found that in these countries, an increase in urbanization and economic growth, results in increasing carbon emissions. Shu et al. (2024) employed the STIRPAT model on quarterly data and found that in both short run and long run, urbanization accelerates GHG emissions in China. Q. Wang et al. (2024) studied Shandong province of China using input-output method and found that the emissions of urban residents were thrice that of rural residents. However, in a recent study by Dlamini et al. (2024), it was observed that in Sub Saharan Africa, urbanization has a minimal impact on the carbon emissions. Dharmapriya et al. (2024) extended this evidence by confirming the long-run environmental impact of urbanization across 42 Asian nations.

3.2.6 Innovation

Technological innovation has increasingly emerged as a critical factor influencing the dynamic relationship between energy use, GDP, and environmental sustainability. A wide body of empirical literature has explored how advancements in technology, especially those related to clean energy and emissions-reducing solutions can mitigate environmental degradation, depending on their nature and implementation. One of the earliest studies by Ausubel (1991) pointed out the necessity of technical innovation as it relates to climate change given that it can preserve our climate and proliferate new inventions, in many forms, across various sectors of any typical economy. Dechezleprêtre et al. (2011) observed some patented innovations relating to climate-related technology. It was observed that innovation in climate change was highly done in selected OECD countries, such as the USA, Germany, and Japan, underscoring the efforts made by developed countries to mitigate carbon emissions. Similarly, Z. Wang & Wang (2012) observed that patent driven energy innovations stimulate economic activity and leads to the development of better energy technologies. For instance, improved solar technologies have drastically reduced environmental damage. Tang & Tan (2013) used patent data as a proxy for technical innovation to study the causal association between CO2 emissions, growth, and clean energy in Malaysia over the period 1970–2009. The results based on ARDL approach shows that technological innovation is significant in mitigating the usage of fossil fuels.

Fei et al. (2014) extended this analysis to explore the causal relationship between technological innovation, CO2 emissions, growth, and clean energy in New Zealand and Norway over the period 1971–2010. The results based on ARDL approach show that technological innovation plays a significant role in the clean energy-growth nexus. Sohag et al. (2015) investigated the influence of technological innovation on energy consumption in Malaysia. They discovered that increasing GDP per capita and trade openness affects technological innovation resulting in a rebound impact on energy use. H. Khan et al. (2015) investigated how the CO2 emission responds to different shocks in the US economy, and observed that the CO2 emissions decline when an expected or unexpected technological shock occurs. Similarly, Irandoust (2016) applied VAR model across four Nordic countries and found that technological innovation played a positive role in linking renewable energy to economic growth. Ali et al. (2016), argued that increased innovation designed to combat the climate change will ultimately lead to an increased cost to the environment. Moreover, Santra (2017) observed a statistically insignificant but negative correlation between innovation and carbon emissions in some countries. H. Fan & Hossain (2018) Conducted an analysis of technological innovation, trade openness, CO2, and GDP in China and India from 1974 to 2016 utilizing the ARDL bounds test approach and Toda-Yamamoto Granger causality test. They reported that over the long term, innovation is not a significant factor in India's economic growth, and in the short run, both innovation and trade openness are not an important factors for India's economic expansion. Hashmi & Alam (2019) advanced the STIRPAT model by developing a model to analyze the influence of environmental regulation and innovation on the carbon emission reduction during the period 1999–2014. The study found that a 1% increase in environmentally friendly patent reduced carbon emissions by 0.017%, and a 1% increase in environmental tax revenue per capita reduced carbon emissions by 0.03% for OECD countries. Du et al. (2019) employed panel threshold model on 71 economies from 1996 to 2012. They found that green technological innovations do not significantly reduce CO2 emissions for the nations with income levels below the threshold while the mitigation effect becomes significant for those with income levels above the threshold. However, the threshold occurs at an extremely high-income level. At the same time, many academicians found that innovation intensity has a negative yet significant relationship with climate change crises. This relationship further highlights the fact that the countries who invested in R&D, innovation can combat climate change (Afrifa et al., 2020; Töbelmann & Wendler, 2020). Ahmad et al. (2020) examined the influence of natural reserves, technological patents, and economic development on the ecological footprint in 20 emerging countries from 1984 to 2016. The Westerlund panel cointegration and cross-sectional autoregressive distributed lag (CS-ARDL) model established that technological innovations are negatively correlated with ecological footprint. However, the nations are increasing the consumption of energy and natural resources in order to maximize their economic growth, which in turn will rise the GHG emissions (Adebayo et al., 2020). Hence, many studies substantiated the role of green Innovation in mitigating climate change and achieving green economic growth. Furthermore, by generating negative externalities from increased intense production, technological advancements can raise carbon emissions; on the other hand, by encouraging the development of clean energy technologies, these technological advancements can assist in reducing environmental deterioration (W. Li et al., 2021). Cheng et al. (2021) employed panel quantile regression to examine the direct and moderating impact of technological innovation on CO2 emissions in OECD nations from 1996 to 2015. The findings show that technological innovation reduces CO2 emissions across all quantiles. Iqbal et al. (2021) employed the CS-ARDL model to posit that renewable energy use along with environmentally oriented technological innovations contribute to environmental sustainability. This underscores the significance of using advanced methods to tackle the issues of GHG emissions (Dwivedi et al., 2022). Khurshid et al. (2022) examined the role of eco-patents and trademarks in rising carbon dioxide emissions using data from 2000 to 2018 of western and southern Europe. The empirical analysis revealed that trademarks and eco-patents decrease carbon dioxide emission in both the regions. Oyebanji et al. (2022) reported similar findings for Spain, attributing environment related patents with minimization of emissions. Lin & Ma (2022b) studied a different approach on how innovation impacts emissions in 30 provinces of China from 2008 to 2017. Their findings revealed that foreign technology import helps reduce CO2 emissions in low-emission areas, however foreign and domestic technologies lead to a rise in CO2 emissions and carbon intensity in high-emission regions. Additional study of Lin & Ma (2022a) explored the impact of the urban innovation environment on the effect of green technological innovations on CO2 emissions by studying 264 prefecture-level cities from 2006 to 2017 in China. The results found that the impact of green technology innovations is different in different types of cities. On a similar note, Gao et al. (2022) studied 30 provincial administrative areas in China from 2008 to 2020 emphasizing the dual (direct and indirect) benefits of green innovation on emissions. The results concluded that the direct and indirect impact of green technology innovation on carbon emission reduction is significant in the eastern-central area, but insignificant in the western region. N. Amin et al. (2023) employed advanced second generational panel methodologies to overcome the problem of cross-sectional dependence and heterogeneity. Based on the empirical findings, their analysis confirmed that green technological innovation reduces CO2 emissions in selected south Asian economies. Mahmood et al. (2023) investigated the effect of patents on CO2 emissions in MENA region using Spatial econometric model. The results found that although patents help in achieving environmental sustainability in MENA region, the same cannot be said in case of domestic economies as patents leads to an increase CO2 emission. In case of G-20 nations, Aneja et al. (2024) studied the period 1992-2018 by employing CS-ARDL model. The findings concluded that green technological innovation significantly improves the environmental conditions. Abbas et al. (2024) used Q-ARDL, CS-ARDL, and Grangers non-causality approach on panel of 118 Chinese cities and found that investing in R&D and green technological innovation can substantially increase environmental sustainability. Pata et al. (2024) studied EU member countries over the period 1974–2019 using Fourier-ADL approach. The study found that environmental patents effectively reduce CO2 emission in Germany, but has no significant effect on emission in France and the Netherlands. Ghorbal & Ben Youssef (2024) in their study distinguished between domestic and foreign patents in South Korea. The authors observed that home patents depicted a positive impact on CO2 emissions while, foreign patents depicted a negative impact on the emissions. Raihan et al. (2025) studied the impact of technological innovation, population, and fossil fuel consumption on emissions of UK and found that all these factors lead to decline in emissions in both short run and long run.

3.3 Research Gaps

The challenge of climate change requires a nuanced understanding of the factors driving CO2 emissions. In the recent decades, this has become one of the most debated topics by the academicians around the world, and has served as a significant motivation for the present research. This study examines the impact of various macroeconomic and socioeconomic variables on the CO2 emissions of QUAD nations. Based on the literature survey, following gaps are identified:

3.3.1 Contextual Gap: QUAD nations are underrepresented in the literature.

While significant research has been conducted on key factors influencing emissions, existing studies predominantly focus on developed countries, with limited focus on the unique dynamics of QUAD nations. Despite the growing significance of QUAD countries in the global economy, the role of GDP, energy consumption, urban and rural population in driving CO2 emissions remains underexplored. Given the distinctive economic structures, policy environments, and institutional frameworks across QUAD nations, there is a need for a more detailed investigation into how different macroeconomic factors influences emission in these economies.

3.3.2 Theoretical Gap: Role of socioeconomic factors.

Prior studies have mainly focused on the relationship between economic growth and emissions by testing the presence of EKC hypothesis. There is a significant lack of literature explaining the importance of other socio and macroeconomic variables such as, urban and rural population, population density, energy consumption, and trade volume on the emission levels.

This gap further necessitates the investigation into how these factors influence the emissions of QUAD nations.

3.3.3 Methodological Gap: Monotony in techniques.

Most of the existing studies on emissions have employed VAR, VECM, and ARDL methodology to find the impact of different variables on the level of emissions. In the present study, two stage least square (2SLS) methodology was employed to study the relationship among variables, SVAR model to study the endogenous model, and provided visual representation of the EKC for the QUAD nations.

3.3.4 Evidence Gap: EKC hypothesis of Japan.

The existing studies in the literature which have explored and reported the existence of EKC hypothesis in case of Japan have taken the dataset from 1990 onwards. However, this study tried to examine the EKC hypothesis using historical data spanning from 1970 to 2021 and found that EKC does not exists in case of Japan. Hence, providing new insights in the literature.

3.4 Conceptual Framework

The conceptual framework presents a summary of the variables and their interrelationships within the context of the study. Figure 3.3 provides an overview of the macroeconomic and socioeconomic variables used in this study. Here, CO2 emissions serve as the dependent variable, while other macroeconomic and socioeconomic variables serve as theindependent variable. This framework aims to illustrate how the CO2 emissions of a particular nation are influenced by the other variables.

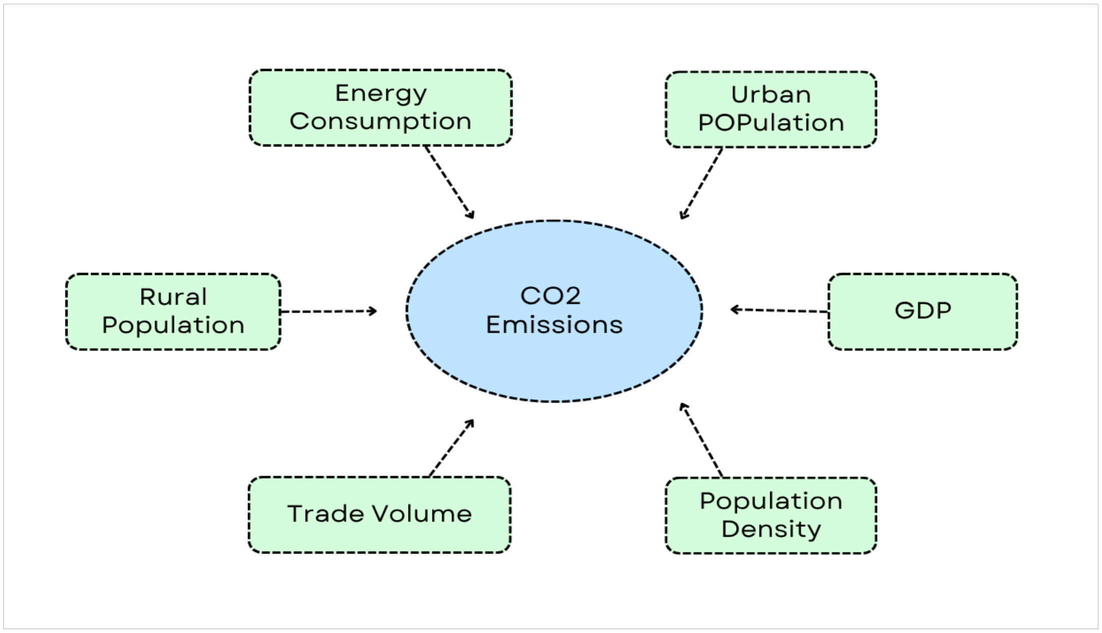


Figure 3.2 Conceptual Framework.
Source: Authors own compilation.

3.5 Summary of Chapter

The third chapter reviews the theoretical and empirical studies available on Economic growth, emissions, and energy use. It provides a foundation by discussing the foundational theories such as the EKC hypothesis, IPAT, STIRPAT, and others. The chapter explores empirical literature that examines the energy-growth-emission nexus, focusing on both positive and negative conclusions as observed in several contexts. A detailed discussion on how variables such as economic growth, renewable energy, non-renewable energy, total energy use, urbanisation, and technological progress impact the emission level is included. The chapter concludes by identifying the existing research gaps, such as the need for a deeper examination of country-specific factors.

CHAPTER 4

Methodology

Research is a careful and organized way of asking questions to gain knowledge, find patterns, and understand complicated issues in economics. It includes formulation of research questions, data collection and analysis, hypothesis testing, and the derivation of conclusions that contribute both to theoretical development and practical application. Guided by the theoretical relationships discussed in the previous chapter, this chapter outlines the research methodology utilized to explain the association between energy use, CO_2 emissions, and economic growth while identifying key determinants of CO_2 emissions in QUAD nations. The methodological framework has been carefully constructed to capture the complex and evolving interactions among energy use, emissions, economic growth, and other relevant macroeconomic indicators. The study employs time series data from 1970-2021, sourced from multiple reliable databases, ensuring credibility in the analysis. Given the diverse economic and institutional structures within the QUAD nations, the methodology incorporates rigorous econometric techniques.

4.1 Data

This section presents a summary of the data utilized in this study. It describes the sample size, time-period covered, and the variables chosen for the study, including their sources and methods of measurement. The dataset is structured as time series data, indicating that it analyses information over a specific duration. This approach is especially advantageous as it enables researchers to observe trends and patterns over time, helping to understand how variables develop and influence each other throughout the study period. In economics, there are three types of data structures for empirical analysis namely, time-series, cross-sectional, and panel data.

a. **Time-Series data**: Time-Series data comprises observations on a single entity, collected systematically over uniform time intervals, such as daily stock prices, monthly unemployment rates, or annual GDP statistics. Each data point is chronologically recorded, allowing analysts to investigate temporal trends, cycles, seasonal variations, and irregular fluctuations in the data.

b. **Cross-Sectional data**: Cross-Sectional data gathers information on various entities at a specific point in time, leading to the comparison of variables across units. This type of data facilitates research focused on diversity among units rather than temporal evolution of the variables.

c. **Panel data**: Panel data combines both time-series and cross-sectional data by collecting repeated observations on many variables over time. This type of dataset enables researchers to assess both temporal evolution within entities and differences among them.

4.1.1 Sample Size

The sample for this study consists of QUAD nations including three developed and one developing nation. These countries represent a unique and influential group in the global energy-emission-growth nexus, given their substantial contribution in global energy consumption, GHG emissions, and economic growth. The QUADs combined and individual efforts to mitigate climate change, along with their geopolitical influence, makes them essential for the discussion. By focusing on this group of countries, the study identifies variations in emission levels and economic performance, helping to understand how different macroeconomic and socio-economic factors influence the emission levels. The selection of these economies is further justified by their collective actions and policies have a far-reaching implication for global sustainability, making them important for understanding the interaction between energy, emission, and economic growth.

4.1.2 Time Period

The study spans a 51-years from 1970 to 2021, using annual data. This timeframe is selected to encompass major economic revolutions, endemic, policy changes, and financial crises that have shaped carbon dioxide emissions and economic growth in QUAD countries. This time-frame includes important events such as the 1977 oil crisis, 1991 economic reforms, 1997 Asian financial crisis, the 2008 sub-prime crisis, and the novel COVID-19 pandemic in 2019, each of which had varying impacts on emissions and economic stability across the QUAD nations. Using annual datasets enables a systematic examination of long-term trends across the Quad economies, providing a robust foundation to analyse the interrelationship between economic growth and emission dynamics.

4.1.3 Variables used in the Study

This study examines the nexus between emission, energy consumption, and economic growth in the QUAD economies from 1970 to 2021. To conduct a comprehensive empirical analysis, the study identifies a set of key variables, including emissions, GDP, energy consumption, urban population, rural population, trade volume, and population density. These variables have been selected based on their theoretical and empirical relevance in the existing literature on emission and growth dynamics. The data for the given variables have been sourced from various databases such as the World Development Indicators, the Our World in Data database, the OECD statistics, the IMF, and macrotrends statistics. The list of the variables, along with their data sources and definition, is given in Table 4.1.

The variables used in the study are defined as follows:

i. **Gross Domestic Product (GDP):** GDP is a key indicator of a country's economic performance, reflecting the total market value of all final goods and services produced within its borders during a specific period. It acts as an important indicator of economic growth, market size, and overall economic activity, thereby influencing investment decisions, policy development, and macroeconomic analysis. In this study, GDP is calculated using the expenditure approach, which calculates GDP as the sum of total spending within an economy. The formula is given as:

$$GDP = C + I + G + (X\text{-}M) \tag{4.1}$$

Where, C is Consumption expenditure (spending by households on goods and services), I is Investment expenditure (business investments in capital goods, including machinery, infrastructure, and inventories), G is Government expenditure (spending by the government on public goods and services, such as education, healthcare, and defence), X is Exports (goods and services sold to foreign markets), and M is Imports (goods and services purchased from foreign markets).

The term (X-M) represents net exports, which account for the balance of trade. A positive value indicates a trade surplus, while a negative value indicates a trade deficit. For this study, GDP is measured at constant 2015 prices in USD millions, ensuring that economic output is analyzed without the effects of inflation, allowing for meaningful comparisons over time.

ii. **Carbon dioxide (CO2) Emissions**: CO2 is the primary greenhouse gas released as a result of human activity. It is closely linked to economic growth and energy use. As economies expand and energy consumption increases, especially from fossil fuels, CO2 emissions tend to rise due to higher industrial activity, transportation, and energy production. This relationship indicates that economic growth often leads to greater emissions, contributing to environmental challenges like climate change. The aggregate data for CO2 emissions provides a comprehensive analysis of nation's environmental condition and facilitate cross-country comparisons. The data is collected from OWID database.

iii. **Energy Consumption**: Energy consumption refers to the amount of energy used by households, industries, and governments to support economic activities and daily life. Rise in energy consumption, especially from non-renewable sources often leads to increased CO2 emissions and environmental degradation. Therefore, efficient energy use and the transition to cleaner energy sources are important for sustainable development.

iv. **Population Density**: Population density refers to the quantity of individuals living within one square kilo meter of land area. Population density is calculated by dividing the mid-year population by the land area in square kilo meter. Population is defined as de facto, which encompasses all residents irrespective of citizenship. However, individuals seeking refuge who have not established permanent residency in the host nation are generally considered citizens of their country of origin. The land area of a country refers to its total area, excluding regions occupied by inland water bodies, national claims to continental shelf, and exclusive economic zones.

v. **Trade volume**: Trade volume refers to the total quantity or value of goods and services exchanged between countries during a specific period. It is an important indicator of global economic activity and integration. It is calculated as sum of total exports and imports of a nation. It can be measured in monetary terms (such as US dollars) or physical quantities (such as tons or units). The formula for trade volume is:

$$Trade\ Volume = Total\ Exports + Total\ Imports \qquad (4.2)$$

This calculation provides a comprehensive view of a country's engagement in international trade, reflecting the scale of its trade activities.

vi. **Urban Population**: Urban population comprises of individuals living in regions designated as urban by national statistical offices, according to criteria such as population density, infrastructure, and administrative regulations. It is calculated using total population data from the World Bank and urban-rural ratios from the United Nations World Urbanization Prospects. The rapid growth of cities globally signifies a notable demographic transition from rural to urban settings. This generally happens at the same time as economies shift from agriculture-based economy to industry, technology, and service-based economy.

vii. **Rural population**: Rural population refers to individuals residing in areas designated as rural according to the national statistical offices. It is typically calculated as the difference between total population and urban population. It is calculated using total population estimates from the World Bank and rural ratios obtained from the United Nations World Urbanization Prospects. This method offers a practical estimate by determining the midyear nonurban population however, it fails to provide a precise measurement due to differing definitions across nations. Thus, rural population statistics should be regarded as approximations of individuals residing beyond the officially defined urban regions.

Table 4.1 Variables Description.

Symbol	Variable	Define	Unit	Source
GDP	Gross Domestic Product	Constant 2015 US$.	USD	WDI
UR	Urban Population	Urban population refers to people living in urban areas as defined by national statistical offices.	Numbers	WDI
EC	Energy Consumption	Primary energy consumption per capita.	kWh/person	OWID
CO_2	CO2 emissions	Total carbon-dioxide emissions excluding LULUCF.	Mt CO_2 eq.	WDI
Ru	Rural Population	Rural population refers to people living in rural areas as defined by national statistical offices.	Numbers	WDI
TV	Trade Volume	Sum of exports and imports	USD/tons	WDI
PD	Population Density	people per sq. km of land area		WDI

4.2 Methodology

This section outlines the statistical techniques and tests used to analyse the dataset and assess the validity of the research findings. The methodology addresses the key assumptions inherent in time-series data models, ensuring that the empirical analysis remains robust and reliable.

Time series data regression models make several assumptions about the residuals, such as homoscedasticity, no autocorrelation, stationarity, and normality. This section emphasizes the importance of performing diagnostic tests to identify potential violations of these assumptions, as ignoring such issues could lead to biased, inconsistent, or inefficient estimates. The tests discussed in this section cover a range of diagnostic concerns, including heteroscedasticity**,** autocorrelation**,** stationarity, and the normality of residuals. Each test is carefully selected based on its relevance to the study and the specific nature of the data.

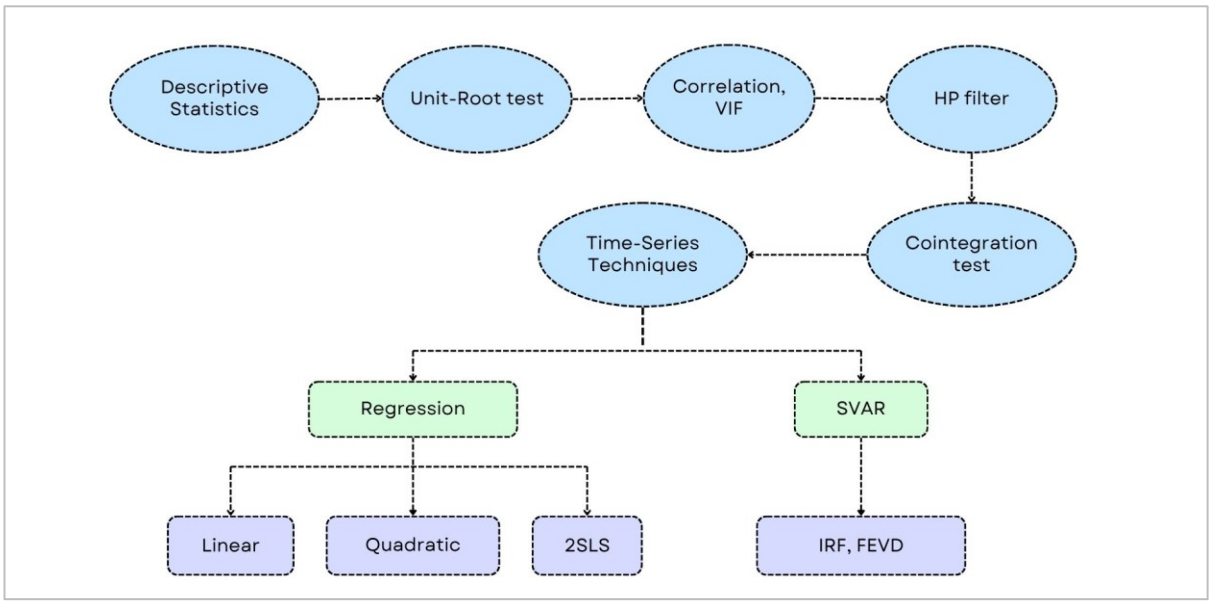


Figure 4.1 Methodological Framework
Source: Authors own compilation

The section not only presents the mathematical formulations of each test but also explains their practical application within the context of the research. By applying these tests, the user ensures that the underlying assumptions of the time series data models are satisfied and that the results are not driven by methodological shortcomings. This methodological framework given in figure 4.1 forms the foundation for the empirical analysis and guarantees that the study's conclusions are both reliable and scientifically rigorous.

4.2.1 Descriptive Statistics

Descriptive statistics play a vital role in describing and summarizing the fundamental characteristics of a dataset. Researchers can determine the central values around which data points are concentrated by analysing the measures of central tendency, such as the mean and median. The standard deviation further reveals the extent of variation within the dataset, highlighting he dispersion of the observations. Skewness provides information about the symmetry of the data distribution, while kurtosis offers insight into its shape by considering the sharpness of the peak and the thickness of the tails. The Jarque-Bera test leverages both skewness and kurtosis to assess whether the dataset follows a normal distribution. These statistical measures play are essential for identifying patterns and evaluating the appropriateness of the data for further econometric modelling and testing of hypothesis.

a) **Mean:** The mean or arithmetic average, serves as a fundamental measure of central tendency by indicating the average value of a dataset. It is calculated by taking the sum of all observations and dividing it by the number of observations. The mean indicates the magnitude of the data and is beneficial in normally distributed data.

   Mathematically, the mean of a dataset is calculated as follows:

   For a population:

$$\bar{\mu} = \frac{\sum_{i=1}^{N} X_i}{N} \tag{4.3}$$

   Here, $\bar{\mu}$ denotes the population mean, X_i represents individual observations, and *N* is the total number of observations in the population.

   For a sample:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{4.4}$$

Here, $\bar{X}$ represents the sample mean, X_i denotes individual observations, and n is the number of observations in the sample. The mean is often employed in statistical analysis; however, it is sensitive to outliers and extreme values, which may significantly influence its accuracy in datasets that are highly skewed or contain significant anomalies.

b) **Median:** The median represents the central value of a dataset when organized in either ascending or descending order. As a measure of central tendency, the median is particularly advantageous in distributions that are skewed, since it is less influenced by outliers. By dividing the dataset into two equal parts, the median ensures that half the observations fall below and half above this central value. The formula for calculating the median based upon whether the number of observations (n) is odd or even:

If n is odd, the median is calculated as:

$$Median = X_{\frac{n+1}{2}} \tag{4.5}$$

If n is even, the median is calculated as:

$$Median = \frac{X_{\frac{n}{2}} + X_{\frac{n}{2}+1}}{2} \tag{4.6}$$

Compared to the mean, the median remains unaffected by outliers and extreme values, making it a reliable measure of central tendency, particularly for datasets that exhibit skewed distributions.

c) **Standard Deviation:** The standard deviation quantifies the degree of dispersion of individual data points from the mean. It offers insight into the variability of a dataset, where higher values denote greater dispersion and lower values indicate that the datapoints are more closely clustered around mean. Standard deviation is crucial for evaluating data consistency and is extensively utilized in statistical inference and testing of hypothesis. The standard deviation is calculated using the following formulas:

For a population:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(X_i-\mu)^2}{N}} \tag{4.7}$$

Here, σ represents the population standard deviation, X_i denotes individual observations, μ is the population mean, and N is the total number of observations.

For a sample:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(X_i-\bar{X})^2}{n-1}} \tag{4.8}$$

Here, s represents the sample standard deviation, Xi denotes individual observations, $\bar{X}$ is the sample mean, and n is the number of observations in the sample.

d) **Skewness:** It measures the asymmetry of the distribution, indicating whether the data points are evenly distributed around the mean. Mathematically, it is defined as:

$$Skewness = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x}_i)^3}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2\right)^{\frac{3}{2}}} \tag{4.9}$$

Here, x_i is the individual residuals, $\bar{x}_i$ is the mean of the residuals, and n is the number of observations.

A skewness value close to zero suggests a symmetrical distribution, whereas positive skewness signifies a longer tail on the right side, and negative skewness suggests a longer tail on the left side.

e) **Kurtosis:** Kurtosis is a statistical measure used to describe the distribution of observed data around the mean. It is used to identify the tails and sharpness of the distribution. It is mathematically expressed as:

$$Kurtosis = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^2} \tag{4.10}$$

A kurtosis value of 3 indicates a mesokurtic distribution, which has the same tail thickness and peak as a normal distribution. Distributions with kurtosis greater than 3 are classified as leptokurtic; this exhibit pronounced peaks and heavy tails, reflecting a higher frequency of extreme values. In contrast, distributions with kurtosis less than 3 are termed platykurtic and are characterized by flatter peaks and lighter tails, meaning fewer outliers occur. Calculating kurtosis helps researchers to determine the frequency of extreme values in a dataset compared to expectations under normal distribution.

f) **Jarque-Bera (JB) Test**: The Jarque-Bera test determines whether a given dataset exhibits skewness and kurtosis consistent with a normal distribution. It tests the null hypothesis that the data are normally distributed. Mathematically, JB test statistic is calculated as:

$$JB = \frac{n}{6}\left(S^2 + \frac{1}{4}(K-3)^2\right) \tag{4.11}$$

Where n is the sample size, S is the sample skewness, and K is the sample Kurtosis.

4.2.2 Unit Root Test

Unit root test is one of the most essential econometric analyses in case of both time-series and panel data. This test statistics is used to ascertain the stationarity or non-stationarity of a time-series, it further helps in the selection of appropriate econometric model. A series with a unit root signifies a non-stationary process, indicating that its statistical features, including mean and variance change over time. It also implies that shocks to the series produce a permanent effect, compared to a stationary series where shocks only have a temporary impact. Moreover, the Unit root tests are divided into two generations, first-generation tests and second-generation tests. In this study we have taken only first-generation unit root test as we have time-series data which does not have a problem of cross-sectional dependence.

a. **First-Generation Unit Root Tests:** The first-generation unit-root tests are statistical techniques employed to determine if a time series is stationary or has a unit root, indicating non-stationarity. It assumes that individual time series are independent of each other. The key assumption is that of uncorrelated error terms across these series. Having stationarity is important in time series analysis as non-stationary series can lead to biased estimations and spurious regression results. First-generation unit-root tests include, the Dickey-Fuller, Augmented Dickey-Fuller, and Phillips-Perron tests.

i. **Dickey-Fuller:** The Dickey-Fuller test is a statistical method used to check for the presence of unit root in a time series, indicating that the series is non-stationary. the null hypothesis of DF test implies the existence of a unit root against the alternative hypothesis that indicates the series is stationary. The test assumes the time series to be autoregressive of order 1. It is calculated as:

$$\Delta y_t = \delta y_{t-1} + \mu_t \tag{4.13}$$

Where, Δy_t is the difference between consecutive observations, $y_{t-1}$is the lagged series, and $\mu_t$is the error term.

ii. **Augmented Dickey-Fuller (ADF) Test:** The Augmented Dickey-Fuller (ADF) test is an extension of the fundamental Dickey-Fuller test. It is extensively employed to check for the existence of unit-root in a series, signifying its non-stationary nature. Compared to the original Dickey-Fuller test, ADF test adjusts for higher-order serial correlation by incorporating lagged differences of the dependent variable in the regression model. The null hypothesis of the ADF test posits that the time series has a unit root i.e., $\gamma = 0$. The ADF equation for a time series y_t is specified as:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \, \Delta y_{t-i} + \epsilon_t \tag{4.14}$$

Where, Δyt is the first difference of the series; yt, α is the intercept term; βt is a time trend; γ is the coefficient of the lagged value of yt, which is tested for a unit root (i.e., $\gamma = 0$ indicates a unit root); ϵt is the error term; and p is the number of lags included to account for autocorrelation.

iii. **Phillips-Perron (PP) Test:** The Phillips-Perron (PP) test is also one of the most frequently employed first-generation unit root test. While it shares the same objective as the Augmented Dickey-Fuller (ADF) test, the two differ primarily in their approach to handling serial correlation and heteroscedasticity in the error terms. The ADF test employs a parametric method by including lagged differences of the dependent variable to correct for serial correlation. In contrast, the PP test uses a non-parametric approach to adjust the test statistics, making it robust to a wider range of error structures without explicitly specifying the number of lagged terms. This non-parametric correction allows the PP test to maintain validity in the presence of autocorrelation and heteroscedasticity. The null hypothesis of the PP test posits that the series is non-stationary or has a unit root. The PP test is calculated as follows:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \epsilon_t \tag{4.15}$$

Both ADF and PP test statistics can lead to biased results when applied to panel data with cross-sectional dependence.

b. **Second- generation unit root test:** The second-generation unit root test addresses the limitation of first-generation test by considering the problem of cross-sectional dependence in the panel dataset. Unlike the first-generation unit-root tests, these adjust for correlation between units therefore providing more accurate and reliable stationarity results. These test include, Cross-sectional Im, Pesaran, and Shin (CIPS) test and Cross-sectional Augmented Dickey-Fuller (CADF)Test.

4.2.3 Correlation and VIF

a. **Correlation:** This statistical technique measures the strength and direction of the linear relationship between two or more variables. It reveals the extent to which the variables change together, whether an increases in one variable corresponds to an increases or decreases in another variable. The coefficient of correlation (r) ranges from -1 to +1, with values close to 1 denoting a strong positive relationship, values close to -1 indicating a strong negative relationship, and values around 0 reflect little to no linear association. The Pearson correlation coefficient is the most frequently employed measure of linear association among the two variables. The sample correlation coefficient (r) between two variables X and Y is calculated as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{4.16}$$

Where, n is the sample size, $\bar{X}$ and $\bar{Y}$ are the sample means of X and Y respectively. The population correlation coefficient (r) between two variables X and Y is calculated as:

$$\rho = \frac{Cov(X,Y)}{\sigma_X \sigma_Y} \tag{4.17}$$

Where, Cov(X, Y) is the covariance between X and Y, σ_X and σ_Y are the standard deviation coefficient for X and Y respectively.

b. **Variance Inflation Factor (VIF):** The Variance Inflation Factor (VIF) is a measure of statistical analysis used to identify multicollinearity in the regression analysis. The problem of multicollinearity arises when two or more independent variables within a regression model exhibit high correlation, leading to spurious regression. The value of VIF measures the degree to which the variance of a regression coefficient is elevated due to the presence of multicollinearity.

A VIF value of 1 indicates no correlation among the independent variables, the VIF value between 1 and 5 indicates moderate correlation. And a VIF value of more than 5 or in some cases 10 indicate very high collinearity in the dataset which is not suitable to conduct regression analysis. Mathematically, VIF is calculated as:

$$VIF = \frac{1}{1-R_j^2} \tag{4.18}$$

In this equation, R_j^2 represents the coefficient of determination obtained by regressing the i^{th} independent variable against all other independent variables included in the regression model.

4.2.4 *Hodrick Prescott and Principal Component Analysis*

a. **Hodrick-Prescott (HP):** HP filter was developed by Hodrick & Prescott (1997). This is one of the mostly widely used methods in literature (Ravn & Uhlig, 2002). The mechanics of HP filter are illustrated with the help of an example.

Let the time series $\{y\}_{t=0}^{T}$ is composed of the long-term trend τ_t and cyclical movement ct. The HP filter separates the cyclical part from the trend by solving the following optimization problem,

$$\min_{\tau_1 \ldots \tau_t} \sum_{t=1}^{T} (y_t - {\tau_t}^t)^2 + \lambda \sum_{t=2}^{T-1} [(\tau_{t+1} - \tau_t)(\tau_t - \tau_{t-1})]^2 \tag{4.19}$$

where λ is the smoothing parameter, its value is 100 for annual data.

This technique provides us an avenue to observe if the emissions are procyclical, countercyclical, or acyclical to output. Emissions are procyclical if the cross-correlation between cyclical components of emissions and output is positive, acyclical if zero and countercyclical if negative (Doda, 2014).

b. **Principal Component Analysis (PCA):** PCA is a statistical technique used in multivariate analysis to reduce dimensionality. In time series analysis, PCA transforms the original correlated variables into a set of uncorrelated components called the principal components. It helps with interpretation and visualization of complex dataset by reducing noise and by addressing the problem of multicollinearity thereby enhancing model performance and robustness. Mathematically, it is calculated as follows:

$$PC_k = x_k.w \tag{4.20}$$

Here, k is the number of observations in a sample, x_k represents the vector of original feature values for the k-th observation in the dataset, and w represents the selected eigenvector.

4.2.5 Cointegration Test

Cointegration tests are used to examine if a long-term equilibrium relationship exists between the time series variables. While individual series may exhibit trends or random walks, a linear combination of these series may be stationary. This indicates that the variables move together over the long-term, despite deviations in the short-term. Testing for cointegration is an important step in econometric analysis, as it helps to avoid biased regression results that arise from using non-stationary data. The presence of cointegration indicates a steady link between the dependent and independent variables across time. Common methods for testing cointegration in time series include the Engle-Granger test, Pedroni test, and the Johansen test.

a. **Pedroni Cointegration Test:** The Pedroni test is primarily applied on panel dataset and is an extension of the traditional Engle-Granger cointegration approach. It allows for variations in intercepts and slope coefficients across individual cross-sectional units.

Pedroni developed seven test statistics that can be categorized as group statistics (within dimension) and panel statistics (between dimension). The null hypothesis of Pedroni test states that no cointegration exists in the dataset. To estimate the presence of cointegration among variables, majority rule is applied wherein more than 3 statistics among the seven available should reject the null hypothesis. Also, Pedroni examines the stationarity of the residuals $\epsilon_{it}$to test for cointegration. Consider the following panel regression model:

$$y_{it} = \alpha_i + \beta_i x_{it} + \epsilon_{it} \tag{4.21}$$

Where, y_{it} is the dependent variable and x_{it} is the independent variable, α_i allows for individual fixed effects, β_i represents the slope coefficients, and $\epsilon_{it}$is the residual term.

b. **Johansen Cointegration test**: This concept was first given by (Engle & Granger, 1987) and extended by Johansen (1990). Since the Johansen & Juselius (1990), cointegration methodology is well recognized in the literature, a brief explanation of this methodology is given as:

$$\Delta Y_t = A_0 + \Pi Y_{t-p} + \sum_{i=1}^{p} A \Delta Y_{t-i} + \eta_t \tag{4.22}$$

In this framework, Y_t denotes a vector of endogenous I (1) variables, A_0 represents a vector of constant terms, A is a matrix of coefficients, η_t is a vector of residuals, and p indicates the lag length. All variables in Equation (1) are considered potentially endogenous. The long-run equilibrium relationship among Y_t is determined by the rank of Π (denoted as r). If r is zero, the variables in their level form do not exhibit any cointegration relationship and Equation (1) can be reformulated as a VAR model of p order. If 0 < r < n, then there exists n × r matrices of α and β such that:

$$\Pi = \alpha\beta' \tag{4.23}$$

Here, α measures the strength of the cointegration relationship, while β is known as the cointegration vector.

4.2.6 Econometric Models

a. **Analysis of Variance (ANOVA)**: ANOVA is a statistical method employed to compare the means of three or more groups to ascertain whether at least one group mean significantly differs from the others. It examines the variability both within and between groups. The null hypothesis of ANOVA states that all group means are equal. It is calculated as follows:

$$F = \frac{MS_{between}}{MS_{within}} \tag{4.24}$$

Where, F-statistic is the ANOVA coefficient, $MS_{between}$ depicts the mean sum of squares between groups, and MS_{within} represents the mean sum of squares within groups.

b. **Structural Vector Autoregressive (SVAR) Model**: SVAR allows for the analysis of dynamic interaction without assuming a predetermined causal direction that facilitates to uncover the underlying causal relationship between variables. Blanchard & Quah (1989) proposed an innovative methodology for identifying the parameters of a SVAR model. Their methodology entails imposing restrictions on the long-term effects of shocks on endogenous variables, specifically constraining the response of certain variables to specific shocks over extended horizons. This long-run restriction is consistent with the concept of long-term neutrality, which asserts that permanent changes in nominal variables have no influence on the real variables in the long run. Compared to Single-Equation Models, the SVAR framework offers notable advantages by enabling the inclusion of additional identifying assumptions to structure contemporaneous relationships among endogenous variables. These identifying restrictions can be informed by economic theory, institutional frameworks, and other contextual constraints (Köse & Ünal, 2021). The SVAR specification is as follows:

$$Ay_t = a_0 + B(L)y_{t-1} + \varepsilon_t \tag{4.25}$$

where A denotes a 4 × 4 matrix, B(L) stands for a polynomial matrix constructed using the lag operator L. The polynomial's order, denoted as p, is selected based on a lag length criterion. The vector y_t comprises the endogenous variables. The vector $\varepsilon_t$captures the structural shocks in the system.

i. **Impulse Response Function:** The Impulse Response Function (IRF) demonstrates how the current and future values of each variable dynamically react to a one-unit shift in a given structural shock, assuming that all other shocks are set to zero. In models like Vector Autoregressions (VAR), IRFs are employed to evaluate the dynamic interactions among variables, allowing researchers to measure both short-term and long-term response to innovations. This framework is essential for understanding and illustrating the interdependencies within the time-series model.

ii. **Forecast Error Variance Decomposition**: The Forecast Error Variance Decomposition (FEVD) is a statistical method used in the time-series econometrics, specifically with VAR models to measure how much structural shocks contribute to the forecast error variance of a particular variable over time. FEVD offers valuable insights into the dynamic interactions among variables, enabling a deeper understanding of the transmission mechanisms of shocks in a multiple variable framework.

c. **Vector Error Correction Model (VECM)**: A Vector Error Correction Model (VECM) is an advanced statistical model used to analyse and predict both short-run fluctuations and long-run relationships among integrated time series. It extends the Vector Autoregressive (VAR) model by including an error correction term that captures how deviations from the long-run equilibrium are adjusted over time. This adjustment term represents the speed at which variables return to equilibrium after a disturbance. While the model explains the short-term dynamics through the inclusion of lagged differences of the variables. The formula for VECM is:

$$\Delta x_t = \Pi x_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta x_{t-i} + c + \varepsilon_t \qquad (4.26)$$

Here, $\Delta x_t$is the vector of first differences of the k endogenous variables at time t, x_{t-1} is the vector of the levels of variables with one period lag, Π is the k × k matrix capturing the long-run relationships among the variables, Γ_i are the coefficient matrices capturing short-term dynamics for lag i, c is a vector of constants, and $\varepsilon_t$is the vector of error terms, assumed to be white noise.

d. **Regression**:

i. **Linear Regression**: Linear regression is a statistical modelling technique that identifies the linear relationship between a response (dependent) variable and one or more independent variables by fitting a straight-line equation. The technique determines the line that best fits the given dataset by minimizing the sum of squared differences between observed and predicted values. To provide reliable and robust results, linear regression relies on several assumptions such as Homoscedasticity, linearity, normality of residuals, independence of errors, and no perfect multicollinearity among variables. It also helps with prediction and trend analysis. The regression equation is:

$$Y = a + bX \tag{4.27}$$

Where, Y is the dependent variable, a is the intercept, X is the dependent variable, and b represents the slope of the independent variable.

ii. **Quadratic Regression**: Quadratic regression is a statistical technique used to identify curved or parabolic relationships among variables. The model fits a second-degree polynomial equation to the dataset, allowing it to capture nonlinear trends. The quadratic regression assumes that the residuals are homoscedastic and normally distributed. This model allows the regression to represent curves such as U-shaped or inverted U-shaped patterns in the data. Mathematically, it is represented as:

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 \tag{4.28}$$

Here, Y is the dependent variable, β_0 is the intercept, β_1 is the linear coefficient with respect to independent variable (X), and β_2 is the quadratic coefficient with respect to variable X.

iii. **Two-Stage Least Square:** Two-stage least squares (2SLS) is a regression methodology employed to mitigate endogeneity in econometric models, wherein one or more explanatory variables exhibit correlation with the error term, resulting in bias in ordinary least squares (OLS) estimations. Endogeneity can occur due to omitted variables, measurement error, or simultaneous causation between variables. It involves two steps:

Stage 1: The endogenous variable (X_1) is regressed on the instrumental variables ($Z_1, Z_2, ..$) i.e., variables that are correlated with the endogenous regressors yet uncorrelated with the error term. This step yields forecast values of the endogenous variable ($\hat{X}_1$) that is free from endogeneity bias.

$$X_1 = \pi_0 + \pi_1 Z_1 + \pi_2 Z_2 + \cdots + \upsilon \quad (4.29)$$

Stage 2: Here, the initial regression model is calculated by substituting the endogenous variable with their forecasted value obtained from the first stage. This provides consistent and fair coefficient estimates. Y is the dependent variable. $Y = \beta_0 + \beta_1 \hat{X}_1 + \beta_2 Z_2 + \epsilon$

(4.30)

4.3 Summary of Chapter

This chapter presents the research methodology, providing a comprehensive overview of the dataset, variables, and econometric techniques employed to analyse the nexus between energy consumption, CO2 emissions, and economic growth in QUAD nations. In section 4.1, the data was thoroughly examined, including the sample size, time-period (1970–2021) of the study, and key macroeconomic and socio-economic variables. These variables include GDP, CO2 emissions, total energy consumption, urban and rural population, ecological innovation, trade volume, population density, renewable energy consumption, energy intensity, and temperature, along with their respective definitions and sources. In section 4.2 the methodological approach was discussed, starting with the preliminary tests such as descriptive statistics, correlation analysis, and unit root tests to confirm the robustness of the data. The analysis subsequently utilizes the cointegration test to identify the existence of long-term relationship among emissions; the Structural Vector Autoregressive (SVAR) model and two-stage least square regression model to examine the association among variables; and the quadratic regression to investigate the presence of a curved relationship between economic growth and CO_2 emissions. This chapter establishes a robust groundwork for empirical analysis by carefully defining the data and methodology, which will be examined in greater detail in the following chapter.

CHAPTER 5

Empirical Results

5.1 Trend Analysis

Trend analysis is a crucial research tool for recognizing and understanding patterns, trajectories, and variations in key factors over time. It enables researchers to examine historical and present data in order to monitor the trajectory of a variable and discover new shifts within a dataset. This method facilitates robust forecasting and comparison across time periods.

5.1.1 *CO2 Emissions per capita*

The bar chart depicts the global and QUADs per capita CO_2 emissions for 2023. Per capita emissions indicate the average CO_2 emitted by an individual, highlighting significant emission differences among countries.

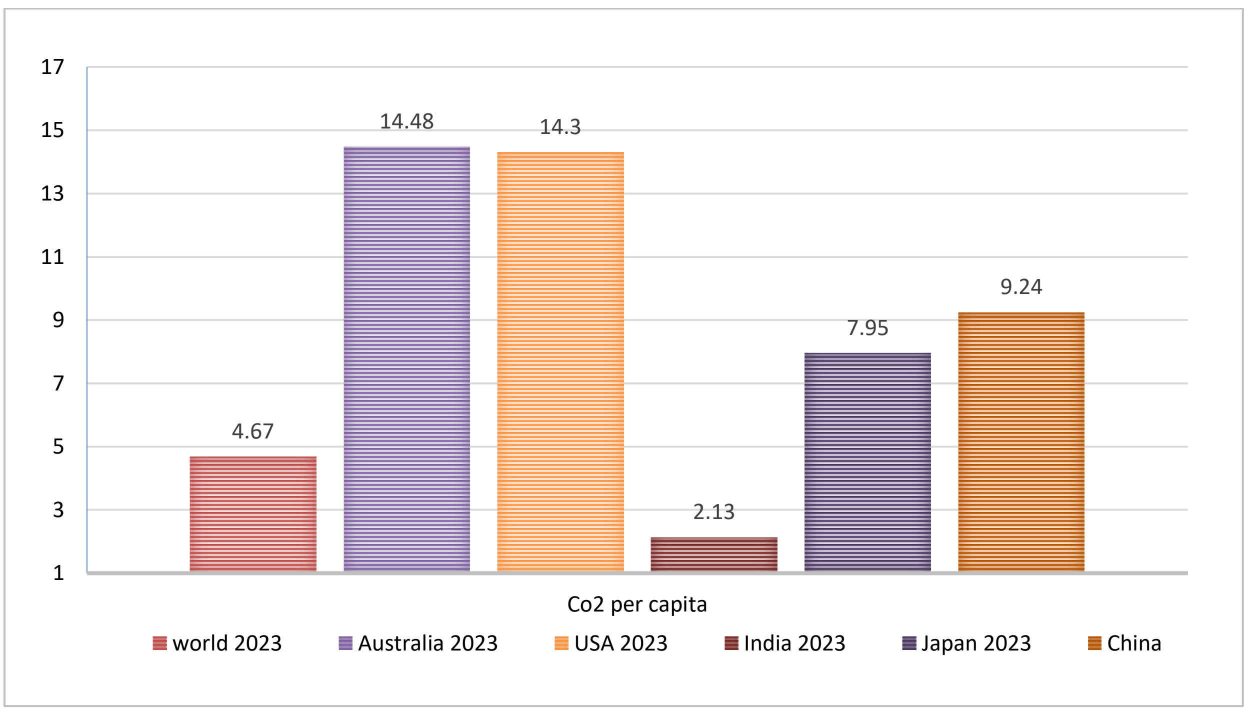


Figure 5.1 CO2 emissions per capita-2023.
Source: Computed by the authors.

As per the figure above, Australia and the USA have remarkably high per capita emissions, with 14.48 tons and 14.3 tons respectively. These statistics significantly surpass both the global average per capita emissions (4.67) and the emissions of the other countries included. This underscores the carbon-intensive characteristics of their economies, extensive reliance on fossil fuels, and comparatively elevated living standards, which lead to increased energy use per capita. China's CO2 emissions per capita reached 9.24 tons, this value is significantly above the world average of 4.6 tonnes. This reflects its rapid industrial growth, massive energy consumption predominantly based on coal, and large infrastructure development. Despite efforts to reduce pollution, China's high per capita CO_2 emissions underscore the environmental impact of its sustained economic expansion and highlight its critical role in global climate strategies. In the case of Japan, depicted in brown color, it registers a moderately elevated emission per capita at 7.95 tons, about twice the global average. This illustrates Japan's energy consumption and industrial progress, along with enhanced energy efficiency and reduced dependence on coal. Lastly, India's per capita emissions are substantially lower at 2.13 tons per capita, indicating that despite growing population and modernization, the average carbon footprint of an individual remains minimal. Hence, the figure highlights significant disparities in CO_2 emission intensity, which reveals the fact that high-income, industrialized nations are majorly responsible for global carbon emissions. It underscores the importance of major nations to implement decarbonization initiatives, while allowing low emitters such as India to develop sustainably.

5.1.2 *CO2 Emissions and Urban-Rural Population*

The figure below illustrates the relationship between CO_2 emissions, urban population, and rural population in India, Japan, the United States of America, and Australia from 1970 to

2021, highlighting key trends in economic growth and population structure across these four economies.

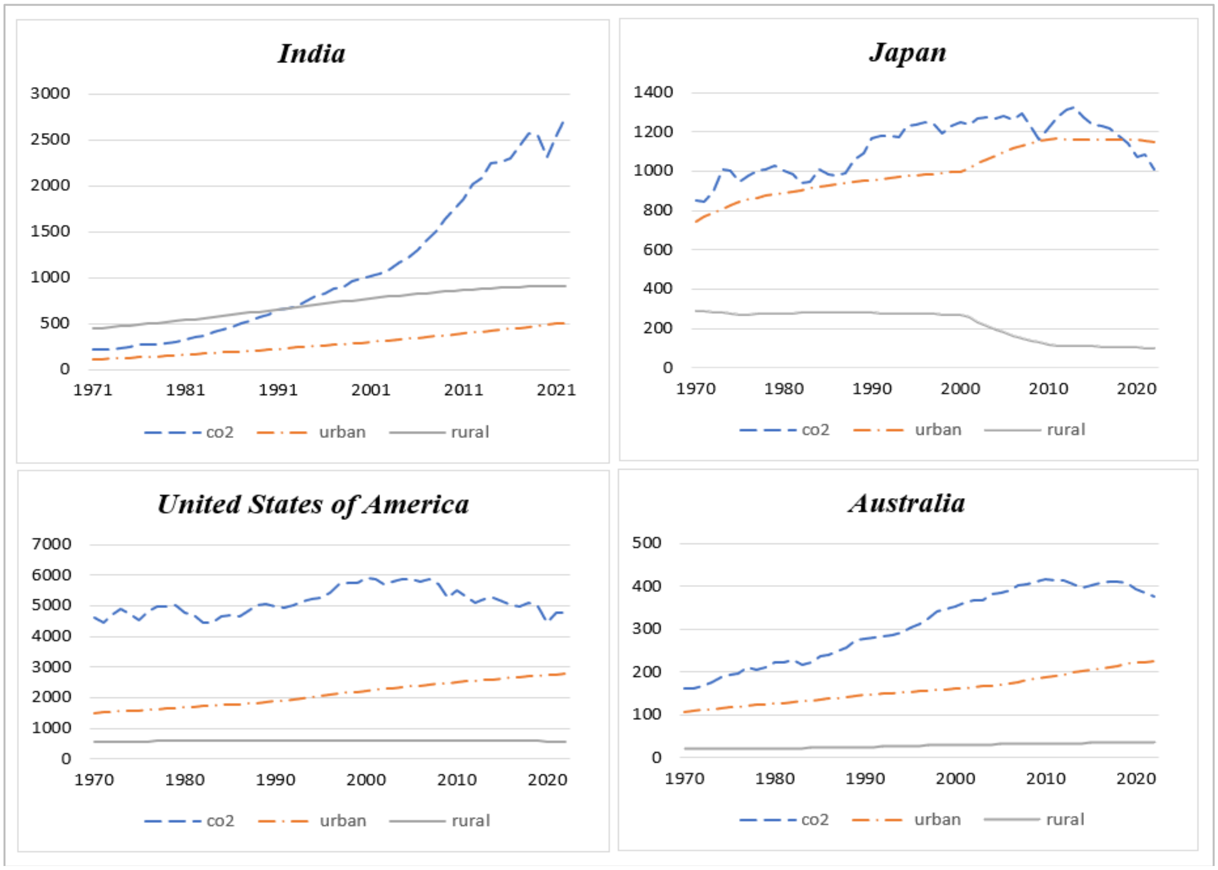


Figure 5.2 Trend of CO2 emissions, urban, and rural population of QUAD nations.
Source: Computed by the authors.

India's graph illustrates a significant and continuous increase in CO_2 emissions from 1971 to 2021, reflecting tremendous industrialization, population growth, and urban development over the last fifty years. Urban population statistics indicate a consistent increase, however they remain significantly lower than CO_2 levels, while rural population growth continues to progress gradually and consistently. The significant rise in emissions, especially post-1990, indicates economic liberalization and extensive utilization of fossil fuels. Despite a substantial rise in rural population, urban population growth rate surpasses the rural, indicating the continuous demographic transitions towards urban areas. The trend patterns in Japan depicted that CO_2 emissions and urban population increased until the early 2000s, and later started to decrease while urban population stabilized. however, the rural population continually declined throughout the entire time. The decoupling of emissions from urban population growth after 2005 indicates inclusion of effective measures, such as the introduction of eco-friendly technologies and a stabilization in energy-intensive sectors. Japan demonstrates the characteristics of a mature economy with an aging rural population, sustainable urban planning, and rigorous environmental regulations that promotes emission reductions while maintaining urban population. The United States exhibits consistently high CO_2 emissions over the five decades, reaching a peak in the 2000s before experiencing a minor decline. The urban population consistently increases at a moderate pace, in contrast to CO_2 emissions, but the rural population stays largely stagnant. This decline in emissions after 2010 demonstrates the effects of environmental regulations. however, consistent urbanization reflects ongoing population trends favoring urban living, and stable rural population indicates that the majority of the demographic shifts are occurring in urban areas aligning with global patterns in developed countries.

5.1.3 *CO2 Emissions and GDP*

The figure below illustrates the relationship between CO_2 emissions and GDP for India, Japan, the United States of America, and Australia from 1970 to 2021, highlighting key trends in economic growth and carbon emissions across these four economies. India's data indicates a robust positive link between CO_2 emissions and GDP from 1971 to 2021. Both indicators exhibit a significant increase, particularly post-1990, indicates rapid economic expansion driven by industrialization, technical progress, and urban development. The simultaneous expansion indicates that India's economic growth is intricately linked with fossil fuel consumption and emissions. Despite recent sustainability initiatives, advancements in decoupling emissions from GDP remain limited, making India's growth trajectory significantly dependent on carbon-intensive industries.

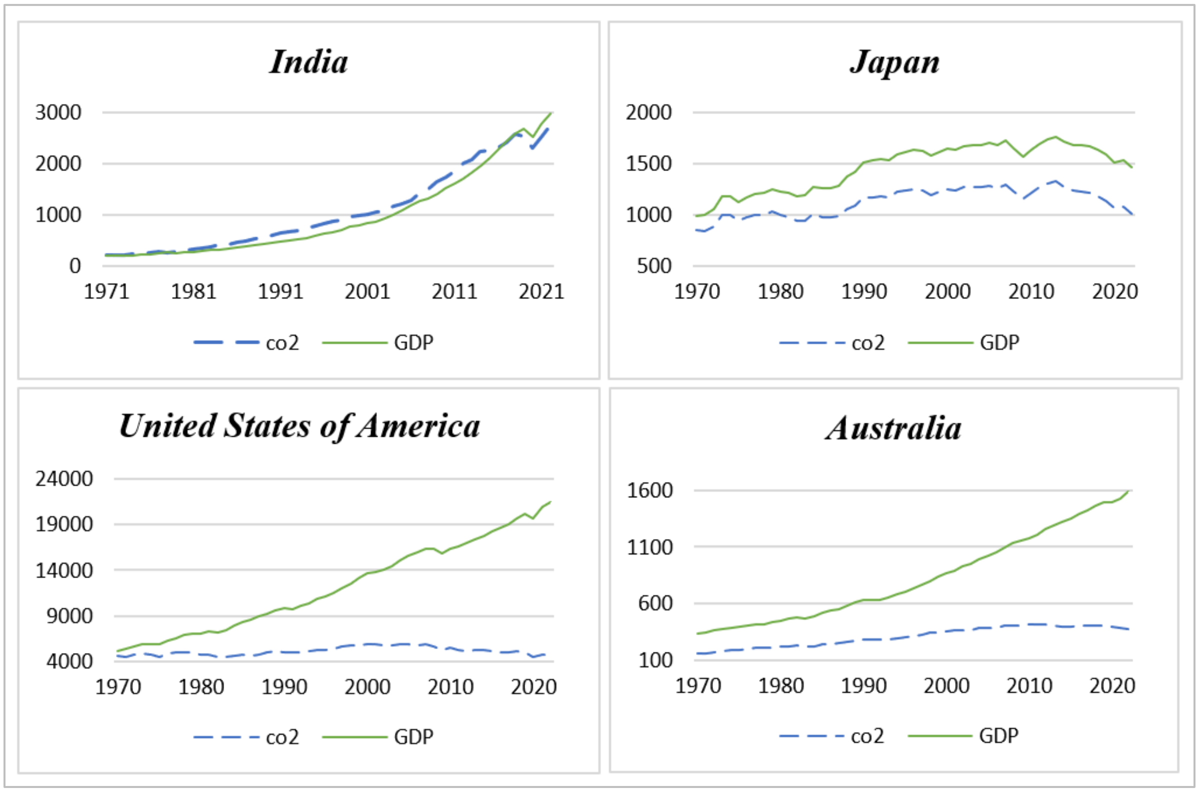


Figure 5.3 Trend of CO2 emissions and GDP of QUAD nations.
Source: Computed by the authors.

In case of Japan, it demonstrates a divergence between GDP and CO_2 emissions after the year 2000. GDP rises until the early 2000s and then declines slightly, while, CO_2 emissions rise and subsequently decrease. This pattern indicates effective decoupling, likely due to technological innovation, strict regulation, and adoption of cleaner energy sources. Japan's developed economy benefits from environmental regulations that facilitate sustained prosperity while reducing environmental damage. In the United States, GDP demonstrates continuous expansion from 1970 to 2020, but CO_2 emissions remain relatively stable. This decoupling underscore significant structural transformations towards the integration of modern environment friendly technology. The graph of Australia indicates consistent GDP growth throughout the time period, while CO_2 emissions rise at a reduced pace. Following the year 2010, emissions exhibit a marginal decline, despite the ongoing increase in GDP. This trend illustrates Australia's recent investments in renewable energy, carbon reduction strategies, and economic diversification. The constrained increase in emissions relative to substantial GDP growth signifies gradual decoupling, suggesting that economic advancement can coexist with enhanced environmental results.

5.1.4 *CO2 Emissions and Energy Consumption*

The figure below illustrates the relationship between CO_2 emissions and energy consumption in QUAD countries from 1970 to 2021, highlighting key patterns in energy consumption and carbon emissions across these four nations.

India's data indicates a fast, concurrent increase in energy consumption and CO_2 emissions from 1971 to 2021. Both curves exhibit significant acceleration after the early 1990s, signifying industrialization, urbanization, and the expansion of infrastructure. The parallel paths indicate that economic growth was predominantly led by fossil fuels, with elevated energy consumption directly correlating to rising emissions. This pattern is a characteristic of developing nations where the energy mix is predominantly carbon-intensive and initiatives for renewable energy adoption are being implemented. Japan's figure illustrates an increase in energy consumption and CO_2 emissions until the early 2000s, succeeded by a gradual decline in both measures. The synchronous movement of these lines indicates a successful transition towards energy efficient and low-carbon technologies. The rise in Japan's economic growth in the early years contributed to increasing energy demand. However, stabilized energy consumption and reduced emissions reflect its mature economic structure.

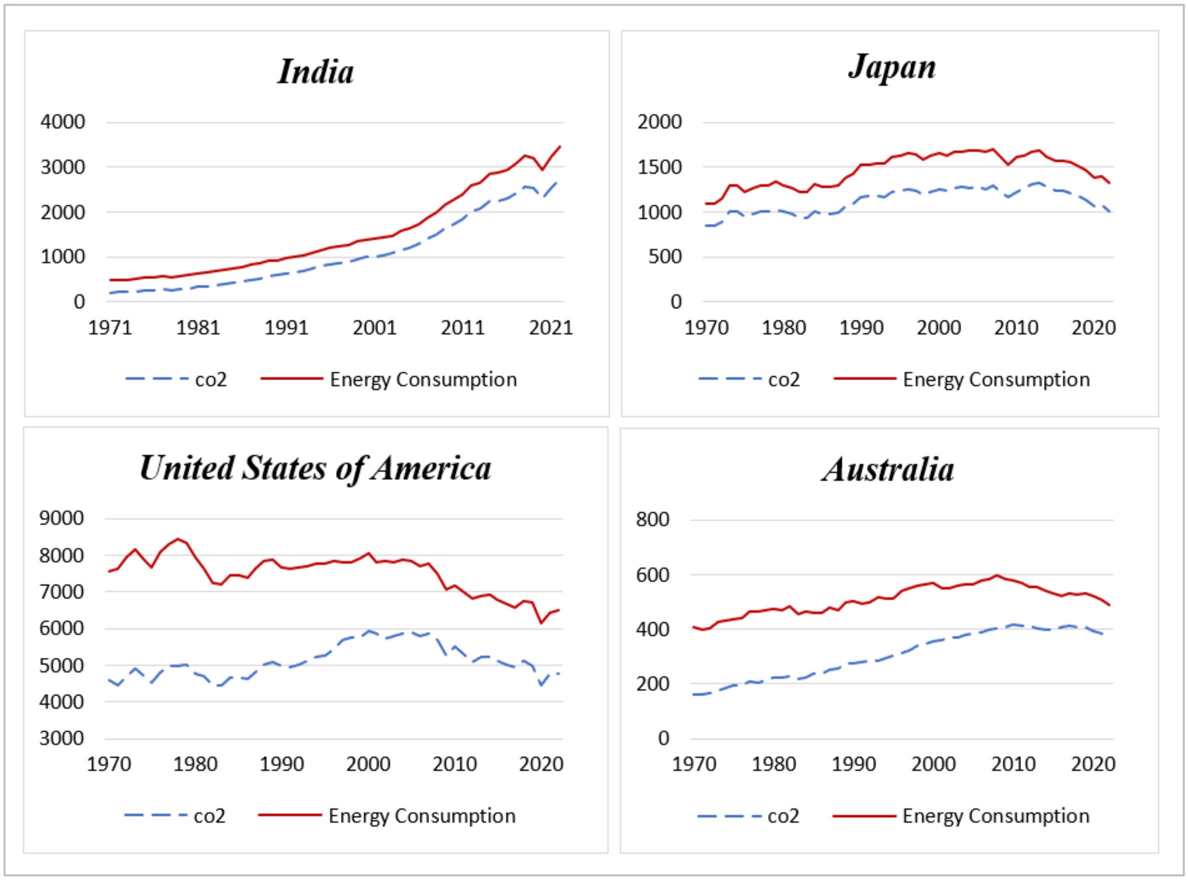


Figure 5.4 Trend of CO2 emissions and energy consumption of QUAD nations.
Source: Computed by the authors.

The United States of America demonstrates a distinct pattern, here energy consumption varies but ultimately decreases in early 2000s, while CO_2 emissions exhibit a similar downward trajectory. This decoupling can be attributed to advancements in energy efficiency, transitions towards non-conventional fuel, and regulatory measures. Australia's graph indicates a gradual increase in energy usage from 1970, reaching a peak in 2010, followed by a slight decline. CO_2 emissions reflected this trend, but at a slower pace. The co-movement of emissions and energy consumption illustrates Australia's dependence on fossil fuels, particularly coal, for energy generation. The recent decline in both indices indicates initial effects of renewable energy implementation and emission reduction strategies. However, the lag between energy consumption and emissions suggests a necessity for more extensive decarbonization initiatives to provide substantial long-term environmental advantages.

5.2 Descriptive Statistics (All Variables)

Table 5.1 summarizes descriptive statistics that explains the distributional characteristics of the key variables such as, CO2, GDP, EC, PD, RU, UR, and TV. Natural-logarithmic (ln) transformations were applied to all variables observed from 1970 to 2022. This transformation is commonly used to linearize relationships and stabilize variances, making the statistical analyses more robust.

Table 5.1 Descriptive statistics of Australia.

Variables	lnGDP	lnCO2	lnEC	lnUR	lnRU	lnTV	lnPD
Mean	27.339	5.689	8.528	16.559	14.811	25.996	0.865
Median	27.323	5.745	8.544	16.553	14.836	26.037	0.863
Maximum	28.092	6.028	8.691	16.929	15.076	27.218	1.218
Minimum	26.539	5.077	8.291	16.167	14.509	24.659	0.487
Std. Dev	0.479	0.302	0.105	0.212	0.194	0.854	0.209
Skewness	-0.022	-0.477	-0.485	0.063	-0.125	-0.049	0.033
Kurtosis	1.667	1.870	2.328	1.990	1.469	1.548	1.904
Jb Stat.	3.923 (0.14)	4.831 (0.08)***	3.074 (0.21)	2.284 (0.31)	5.312 (0.07)***	4.673 (0.09)***	2.659 (0.26)
Sum	1448.986	301.522	452.033	877.669	785.026	1377.794	45.891

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The summary comprises of metrics including the mean, standard deviation, skewness, kurtosis, and the Jarque-Bera test, each providing significant insights into data features and distribution patterns. The mean provides a central measure by dividing the sum of all observations by the total number of observations, therefore reflecting the value around which the data points cluster. The descriptive statistics for Australia reflect how key variables have behaved across observations. The mean value gives an overview of the central tendencies, with GDP (lnGDP) having the highest mean at 27.33, followed by trade volume (lnTV) at 25.99, urban population (lnUR) at 16.55, rural population (lnRU) 14.81, CO_2 emissions (lnCO2) at 5.68, energy consumption (lnEC) at 8.53, and population density (lnPD) having lowest mean at 0.865. All the variables have median values close to their mean value, indicating a symmetric distribution pattern. Standard deviation statistic depicts the amount of variability or dispersion in each variable's values around its mean. Here, the standard deviation statistics reveal that all the variables are tightly clustered around their mean, reflecting low dispersion in the dataset. The Jarque-Bera statistic tests the normality of the dataset by considering the value of skewness and kurtosis together. A significant JB probability depicts that the data does not follow a normal distribution. Our results accept the null hypothesis of JB test which states that data is normally distributed, given the p-value of all the variables are more than 0.05.

The descriptive statistics for India reflect how key variables have behaved across observations. The mean value gives a general picture of the central tendencies, with GDP (LnGDP) having the highest mean at 27.27, followed by trade volume (lnTV) at 25.72, rural population (lnRU) 20.35, urban population (lnUR) at 19.36, CO_2 emissions (lnCO2) at 6.69, and population density (lnPD) having lowest mean at 5.769. All the variables have median values close to their mean value, indicating a symmetric distribution pattern. Standard deviations reveal the amount of dispersion in each variable's values around its mean. Here, the Standard deviation statistics depict that all the variables are tightly clustered around their mean, reflecting low dispersion in the dataset except for trade volume and environmental innovation. The Jarque-Bera statistic tests the normality of the dataset. Our results accept the null hypothesis of JB test which states that data is normally distributed, given the p-value of all the variables are more than 0.05.

Table 5.2 Descriptive statistics of India.

Variables	lnGDP	lnCO2	lnEC	lnUR	lnRU	lnTV	lnPD
Mean	27.270	6.691	5.985	19.366	20.353	25.729	5.769
Median	27.206	6.751	5.919	19.400	20.398	25.591	5.807
Maximum	28.726	7.916	6.568	20.052	20.633	27.948	6.172
Minimum	26.039	5.367	5.605	18.530	19.917	23.636	5.234
Std. Dev	0.848	0.809	0.300	0.447	0.230	1.458	0.288
Skewness	0.178	-0.087	0.531	-0.212	-0.408	0.109	-0.292
Kurtosis	1.732	1.739	1.942	1.883	1.810	1.510	1.810
Jb Stat.	3.755 (0.15)	3.508 (0.17)	4.870 (0.08)***	3.091 (0.21)	4.509 (0.10)	4.909 (0.08)***	3.809 (0.14)
Sum	1418.070	347.968	311.231	1007.051	1058.381	1337.947	300.028

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The descriptive statistics for Japan reflect how key variables have behaved across observations. The mean value gives a general picture of the central tendencies, with GDP (lnGDP) having the highest mean at 28.81, followed by trade volume (lnTV) at 27.29, urban population (lnUR)

18.41, rural population (lnRU) at 16.83, energy consumption (lnEC) at 8.121, CO2 emissions (lnCO2) at 7.02, and population density (lnPD) having lowest mean at 5.81. All the variables have median values either similar or close to their mean value, indicating a symmetric distribution pattern. Standard deviations reveal the amount of dispersion in each variable's values around its mean. Here, the Standard deviation statistics depict that all the variables are tightly clustered around their mean, reflecting low dispersion in the dataset. The Jarque-Bera statistic tests the normality of the dataset. Our results reject the null hypothesis of JB test which states that data is normally distributed, given the p-values are less than 0.05 for variables such as GDP, population density, and rural population. However, rest all other variables follow a normal distribution with p-value more than 0.05.

Table 5.3 Descriptive statistics of Japan.

Variables	lnGDP	lnCO2	lnEC	lnUR	lnRU	lnTV	lnPD
Mean	28.812	7.020	8.121	18.415	16.836	27.296	5.813
Median	28.986	7.068	8.128	18.403	17.122	27.448	5.841
Maximum	29.153	7.190	8.315	18.572	17.185	28.221	5.861
Minimum	28.009	6.741	7.816	18.123	16.124	25.924	5.641
Std. Dev	0.343	0.123	0.142	0.128	0.411	0.675	0.058
Skewness	-0.922	-0.511	-0.229	-0.295	-0.759	-0.343	-1.364
Kurtosis	2.462	2.060	1.902	2.118	1.758	1.867	3.789
Jb Stat.	8.157 (0.01)*	4.264 (0.11)	3.122 (0.20)	2.488 (0.28)	8.494 (0.01)*	3.874 (0.14)	17.831 (0.00)*
Sum	308.100	372.063	430.463	976.030	892.328	1446.710	308.100

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The descriptive statistics for the United States of America reflect how key variables have behaved across observations. The mean value gives a general picture of the central tendencies, with GDP (lnGDP) having the highest mean at 30.04, followed by trade volume (lnTV) at 28.02, urban population (lnUr) 19.14, rural population (lnRu) at 17.89, energy consumption (lnEC) at 8.921, CO2 emissions (lnCO2) at 8.53, and population density (lnPD) having lowest mean at 3.372. All the variables have median values either similar or close to their mean value, indicating a symmetric distribution pattern. Standard deviations reveal the amount of dispersion in each variable's values around its mean. Here, the Standard deviation statistics depict that all the variables are tightly clustered around their mean, reflecting low dispersion in the dataset except for trade volume.

Table 5.4 Descriptive statistics of the USA.

Variables	**lnGDP**	**lnCO2**	**lnEC**	**lnUR**	**lnRU**	**lnTV**	**lnPD**
Mean	30.047	8.537	8.921	19.148	17.894	28.020	3.372
Median	30.075	8.521	8.945	19.158	17.898	28.260	3.381
Maximum	30.694	8.687	9.040	19.441	17.937	29.420	3.597
Minimum	29.274	8.400	8.722	18.832	17.806	25.498	3.108
Std. Dev	0.429	0.086	0.073	0.195	0.029	1.133	0.153
Skewness	-0.214	0.278	-0.817	-0.055	-1.007	-0.601	-0.106
Kurtosis	1.726	2.004	2.857	1.600	3.737	2.284	1.673
Jb Stat.	3.988 (0.13)	2.874 (0.23)	5.943 (0.05)**	4.352 (0.11)	10.172 (0.00)*	4.323 (0.11)	3.984 (0.13)
Sum	1592.535	452.498	472.815	1485.093	948.392	1485.093	1592.535

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The Jarque-Bera statistic tests the normality of the dataset. Our results reject the null hypothesis of JB test which states that data is normally distributed, given the p-values are less than 0.05 for variables such as energy consumption and rural population. It is important to highlight that both the variables have kurtosis value near 3 and skewness near 0, which depicts normality in the dataset. However, all other variables follow a normal distribution with p-value more than 0.05.

5.3 Unit-Root Tests

Table 5.5, 5.6, 5.7, and 5.8 presents the unit-root test results for all the four nations using the Augmented Dickey Fuller (ADF) and Philips Perron (PP), all of which are first-generation unit root tests. These tests are used to assess the stationarity of variables in time-series data settings, as the time series regression may show a very high fit due to spurious relationship. The Augmented Dickey-Fuller (ADF) test is an extension of the fundamental Dickey-Fuller test, ADF test adjusts for higher-order serial correlation by incorporating lagged differences of the dependent variable in the regression model. It tests the null hypothesis which posits that the time series has a unit root against the alternate hypothesis which states that time-series has no unit root. While both ADF and PP test have similar objective, the PP test uses a non-parametric approach to adjust the test statistics, making it robust to a wider range of error structures without explicitly specifying the number of lagged terms. This non-parametric correction allows the PP test to maintain validity in the presence of autocorrelation and heteroscedasticity. It tests the null hypothesis of non-stationary series against the alternate hypothesis which states that time-series is stationary.

The findings from the ADF and PP tests for the United States of America are presented in Table 5.5. It reveals that all variables like lnGDP, lnCO2, lnEC, lnTV, lnUR, lnRU, and lnPD, reject the null hypothesis of a unit root for ADF and PP test at either 1% or 5% significance levels ($p < 0.01$, $p < 0.05$). This indicates that variables are stationary at different levels of integration, confirming that they do not contain a unit root.

Table 5.5 Unit-Root test results of the USA.

Variables	ADF level	1st level	2nd level	I()	Pp level	1st level	2nd level	I()
lnCO2	-1.639 (0.45)	-3.446 (0.01)*		I(1)	-1.557 (0.49)	-7.168 (0.00)*		I(1)
lnGDP	-1.679 (0.43)	-5.988 (0.00)*		I(1)	-2.037 (0.27)	-5.893 (0.00)*		I(1)
LnUR	-0.94 (0.76)	-1.976 (0.29)	-4.776 (0.00)*	I(2)	-0.911 (0.77)	-1.455 (0.54)	-4.669 (0.00)*	I(2)
lnRU	-1.237 (0.65)	-1.668 (0.44)	-5.734 (0.00)*	I(2)	-2.644 (0.09)	-1.691 (0.42)	-5.735 (0.00)*	I(2)
lnEC	-0.660 (0.84)	-6.417 (0.00)*		I(1)	-0.773 (0.81)	-6.382 (0.00)*		I(1)
lnPD	-1.228 (0.65)	-1.613 (0.46)	-5.898 (0.00)*	I(2)	-2.398 (0.14)	-1.679 (0.43)	-5.802 (0.00)*	I(2)
lnTV	-4.525 (0.00)*			I(0)	-9.374 (0.00)*			I(0)

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The findings from the ADF, and PP tests for Australia are presented in Table 5.6. It reveals that except for lnCO2, all variables are stationary at first difference. lnCO2 rejects the null hypothesis of a unit root for ADF and PP test at either 1% or 5% significance levels ($p < 0.01$, $p < 0.05$), indicating that variables are integrated at level. Hence, this signifies that variables are stationary at level and first difference, confirming that they do not contain a unit root.

Table 5.6 Unit-Root test results of Australia.

Variables	ADF level	1st level	I()	PP level	1st level	I()
lnCO2	-3.588 (0.00)*		I(0)	-3.241 (0.02)**		I(0)
lnGDP	-0.871 (0.78)	-6.345 (0.00)*	I(1)	-0.883 (0.78)	-6.299 (0.00)*	I(1)
lnUR	0.526 (0.98)	-5.562 (0.00)*	I(1)	-0.859 (0.79)	-5.543 (0.00)*	I(1)
lnRU	-0.490 (0.88)	-3.031 (0.03)**	I(1)	-0.892 (0.78)	-3.157 (0.02)**	I(1)
lnEC	-2.177 (0.21)	-6.903 (0.00)*	I(1)	-2.166 (0.22)	-7.026 (0.00)*	I(1)
lnPD	0.120 (0.96)	-6.298 (0.00)*	I(1)	-1.137 (0.69)	-6.298 (0.00)*	I(1)
lnTV	-1.137 (0.69)	-6.155 (0.00)*	I(1)	-1.072 (0.71)	-6.616 (0.00)*	I(1)

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The findings from the ADF, and PP tests for India are presented in Table 5.7. It reveals that variables reject the null hypothesis of a unit root for ADF and PP test at either 1% or 5% significance levels ($p < 0.01$, $p < 0.05$). Here, all the variables confirm stationarity at either base or first difference except for lnCO2, indicating that variables are stationary at different levels of integration, confirming that they do not contain a unit root.

Table 5.7 Unit-Root test results of India.

Variables	ADF level	1st level	2nd level	I()	Pp level	1st level	I()
lnCO2	-0.827 (0.80)	-2.123 (0.23)	-3.304 (0.02)**	I(2)	-0.827 (0.80)	-6.368 (0.00)*	I(1)
lnGDP	1.618 (0.99)	-7.548 (0.00)*		I(1)	1.870 (0.99)	-7.548 (0.00)*	I(1)
lnUR	-2.986 (0.04)**			I(0)	-13.920 (0.00)*		I(0)
lnRU	-3.890 (0.00)*			I(0)	-5.300 (0.00)*		I(0)
lnEC	1.684 (0.99)	-6.448 (0.00)*		I(1)	1.690 (0.99)	-6.447 (0.00)*	I(1)
lnPD	-4.113 (0.00)*			I(0)	-7.908 (0.00)*		I(0)
lnTV	0.142 (0.96)	-5.791 (0.00)*		I(1)	0.059 (0.95)	-5.780 (0.00)*	I(1)

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The findings from the ADF and PP tests presented in Table 5.8 reveals that variables reject the null hypothesis of a unit root at either the 1% or 5% significance levels ($p < 0.01$, $p < 0.05$). It is important to highlight that we have I(2) series for urban and rural population, while other variables depict stationarity at either level or first difference for both ADF and PP test. This indicates that variables are stationary at mixed levels of integration, confirming that they do not contain a unit root.

Table 5.8 Unit-Root test results of Japan.

Variables	ADF level	1st level	2nd level	I()	Pp level	1st level	2nd level	I()
lnCO2	-2.169 (0.21)	-5.586 (0.00)*		I(1)	-2.169 (0.21)	-5.554 (0.00)*		I(1)
lnGDP	-5.742 (0.00)*			I(0)	-5.742 (0.00)*			I(0)
lnUR	-1.053 (0.75)	-2.048 (0.26)	-5.866 (0.00)*	I(2)	-3.132 (0.03)**			I(0)
lnRU	-0.474 (0.88)	-1.949 (0.30)	-5.014 (0.00)*	I(2)	0.414 (0.98)	-1.705 (0.42)	-5.043 (0.00)*	I(2)
lnEC	-2.202 (0.20)	-6.716 (0.00)*		I(1)	-2.176 (0.21)	-6.727 (0.00)*		I(1)
lnPD	-1.870 (0.34)	-3.855 (0.00)*		I(1)	-11.017 (0.00)*			I(0)
lnTV	-2.104 (0.24)	-7.591 (0.00)*		I(1)	-4.402 (0.00)*			I(0)

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

5.4 Correlation

The correlation matrix of QUAD countries is presented in Table 5.9. It highlights the strength and direction of relationships among CO_2 emissions (lnco2), GDP (lnGDP), energy consumption (lnec), urban population (lnur), rural population (lnru), population density (lnPD), and trade volume (lnTV).

Table 5.9 Correlation matrix of QUAD countries.

	lnCO2	lnGDP	lnEC	lnUR	lnRU	lnTV	lnPD
				USA			
	lnCO2	lnGDP	lnEC	lnUR	lnRU	lnTV	lnPD
lnCO2	1.00						
lnGDP	0.530*	1.00					
lnEC	0.257***	-0.654*	1.00				
lnUR	0.496*	0.995*	-0.693*	1.00			
lnRU	0.288**	0.190	0.118	0.128	1.00		
lnTV	0.555*	0.997*	-0.606*	0.974*	0.337**	1.00	
lnPD	0.494*	0.985*	-0.692*	0.160*	0.160	0.980*	1.00
				India			
lnCO2	1.00						
lnGDP	0.992*	1.00					
lnEC	0.968*	0.986*	1.00				
lnUR	0.996*	0.987*	0.955*	1.00			
lnRU	0.988*	0.970*	0.923*	0.993*	1.00		
lnTV	0.987*	0.992*	0.973*	0.982*	0.971*	1.00	
lnPD	0.995*	0.982*	0.943*	0.998*	0.998*	0.980*	1.00
				JAPAN			
lnCO2	1.00						
lnGDP	0.859*	1.00					
lnEC	0.926*	0.802*	1.00				
lnUR	0.777*	0.935*	0.643*	1.00			
lnRU	-0.459*	-0.651*	-0.236*	-0.856*	1.00		
lnTV	0.813*	0.964*	0.703*	0.982*	-0.815*	1.00	
lnPD	0.862*	0.975*	0.833*	0.894*	-0.539*	0.905*	1.00
				AUSTRALIA			
lnCO2	1.00						
lnGDP	0.967*	1.00					
lnEC	0.925*	0.810*	1.00				
lnUR	0.945*	0.992*	0.764*	1.00			
lnRU	0.973*	0.992*	0.835*	0.974*	1.00		
lnTV	0.972*	0.997*	0.827*	0.985*	0.996*	1.00	
lnPD	0.952*	0.995*	0.777*	0.999*	0.981*	0.989*	1.00

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

Generally, the variables are considered highly correlated if the correlation coefficient value is more than 0.5 or in some cases more than 0.8. Table 5.9 indicates that in the USA, the correlation matrix reveals a positive correlation between CO2 emissions and GDP (0.53), trade volume (0.56), and urban population (0.50), indicating that higher economic activity, trade integration, and urbanization are associated with rising emissions. In contrast, energy consumption (lnec) exhibits a negative correlation with GDP (–0.65), urbanization (–0.69), population density (-0.69), and trade volume (-0.61) suggesting possible efficiency improvements or shifts in energy use as the economy grows and urbanizes. Additionally, GDP is almost perfectly correlated with population density (1.00), urban population (1.00), and trade volume (0.99), underlining the close link between economic growth, population concentration, and international trade. Rural population (lnru), however, shows only weak associations with other variables, indicating its limited role in influencing national emission trends compared to urban factors. Similarly, in case of India the results reveal extremely high positive correlations across most variables, with coefficients close to 1.00. CO_2 emissions are strongly correlated with GDP (0.99), energy consumption (0.97), urban population (1.00), rural population (0.99), population density (1.00), and trade volume (0.99), indicating that India's rapid economic expansion, increasing energy demand, rising trade, and demographic changes are closely tied to rising emissions. Similarly, GDP shows strong associations with energy consumption (0.99), urban and rural populations (0.99 and 0.97, respectively), and trade (0.99), underscoring the interconnected nature of growth, energy use, and demographic dynamics. Population density also shares near-perfect correlations with both emissions and urbanization, highlighting the role of demographic pressures in intensifying environmental challenges. Compared to the USA, where correlations were more varied, India's uniformly high coefficients suggest that economic growth, demographic expansion, and energy consumption move in tandem, collectively driving environmental outcomes. Likewise, in Japan the correlation matrix suggests a positive correlation between CO2 emissions and GDP (0.85), energy consumption (0.92), urban population (0.77), trade volume (0.81), and population density (0.95), indicating that higher economic activity, trade integration, and urbanization are associated with rising emissions. In contrast, rural population exhibits negative correlation with GDP (-0.65), emissions (-0.46), energy consumption (-0.24), and urbanization (-0.86). Additionally, GDP is almost perfectly correlated with population density (0.98), urban population (0.94), trade volume (0.81), and energy consumption (0.80) highlighting the close association between economic growth, population concentration, rising energy demand, and international trade. Lastly, in the case of Australia, Lastly, in the case of Australia, the results reveal extremely high positive correlations across most variables, with coefficients close to 1.00. GDP shows strong associations with energy consumption (0.81), urban and rural populations (0.99 each respectively), and trade volume (0.99), underscoring the interconnected nature of growth, energy use, and demographic dynamics. Similarly, CO_2 emissions are strongly correlated with GDP (0.96), energy consumption (0.92), urban population (0.94), rural population (0.97), population density (0.95), and trade volume (0.97), indicating that Australia's rapid economic expansion, increasing energy demand, rising trade, and demographic changes are closely tied to rising emissions. Population density also shares near-perfect correlations with both GDP and urbanization, highlighting the role of demographic pressures in intensifying environmental challenges.

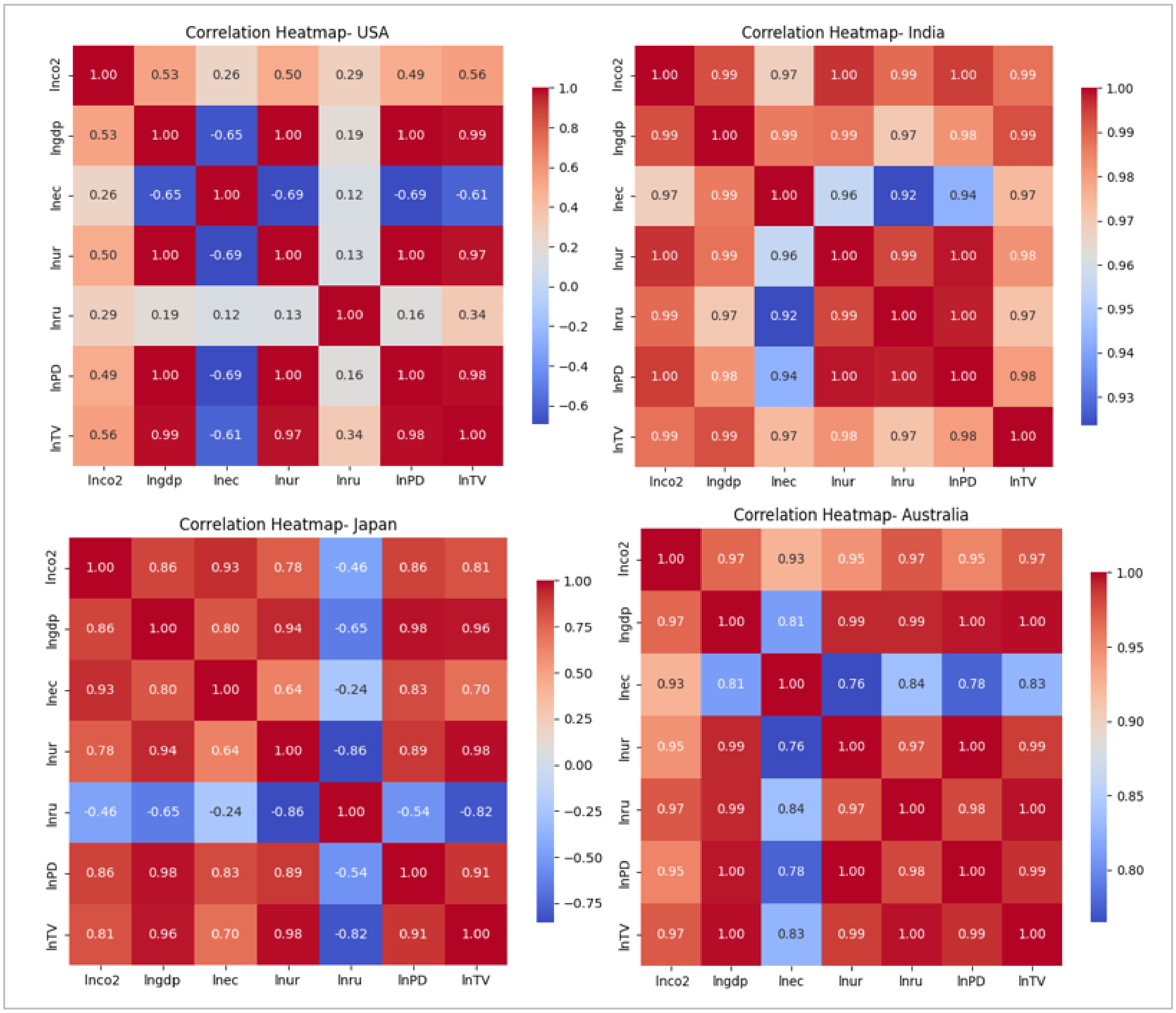


Figure 5.5 Correlation heatmap of QUAD countries.
Source: Computed by the authors.

Fig 5.5 represents correlation heatmap which is a graphical way of presenting data where individual values are represented as colours within a matrix, making it easy to spot patterns and relationships in complex datasets. The correlation heatmap visually represents the strength and direction of linear relationships among seven key variables such as, lnco2, lnGDP, lnec, lnur, lnru, lnPD, and lnTV. Each cell in the grid shows the correlation coefficient between a pair of variables, the value of coefficient ranges from -1 to 1. Positive coefficients indicate variables move together, while negative coefficients imply that they move in opposite directions. Warm colours like red signify strong positive correlations, whereas cooler blue shades denote negative relationships.

5.5 Objective 1

For objective 1, we tried to analyze the relationship among energy use and economic growth and CO2 emission levels in QUAD nations. In order to achieve this objective, we employed HP filter on the dataset of variables such as CO2 emissions (lnCO2), Trade Volume (lntrade), GDP (lnGDP), and Fossil Fuel consumption (lnff) for the time span from 1970 to 2020. Following hypothesis were tested using various econometrics techniques:

a) H_0: No cycle exists in CO_2 emissions and GDP.

b) H_0: No significant correlation between GDP and carbon dioxide emissions.

c) H_0: The CO_2 emission cycle cannot be explained by the GDP cycle.

5.5.1 *HP filter*

The results of the HP filter's application on GDP, CO_2 emissions, fossil fuel consumption, and Trade volume indicate the existence of a significant cyclical component in these variables. Thus, the null of no cycles in GDP and CO_2 emissions is not accepted, implying that GDP, and CO_2 emissions exhibit significant cycles. To further validate this, Pearson's correlation coefficients were computed between the cyclical components of GDP and CO_2 emissions. The analysis confirmed a statistically significant positive correlation, indicating that GDP and CO_2 emissions are procyclical in nature, which is consistent with the earlier findings of (Sarwar et al., 2021). Figure 5.6 visually represents this by superimposing the cyclical components of GDP and CO_2 emissions for the QUAD countries.

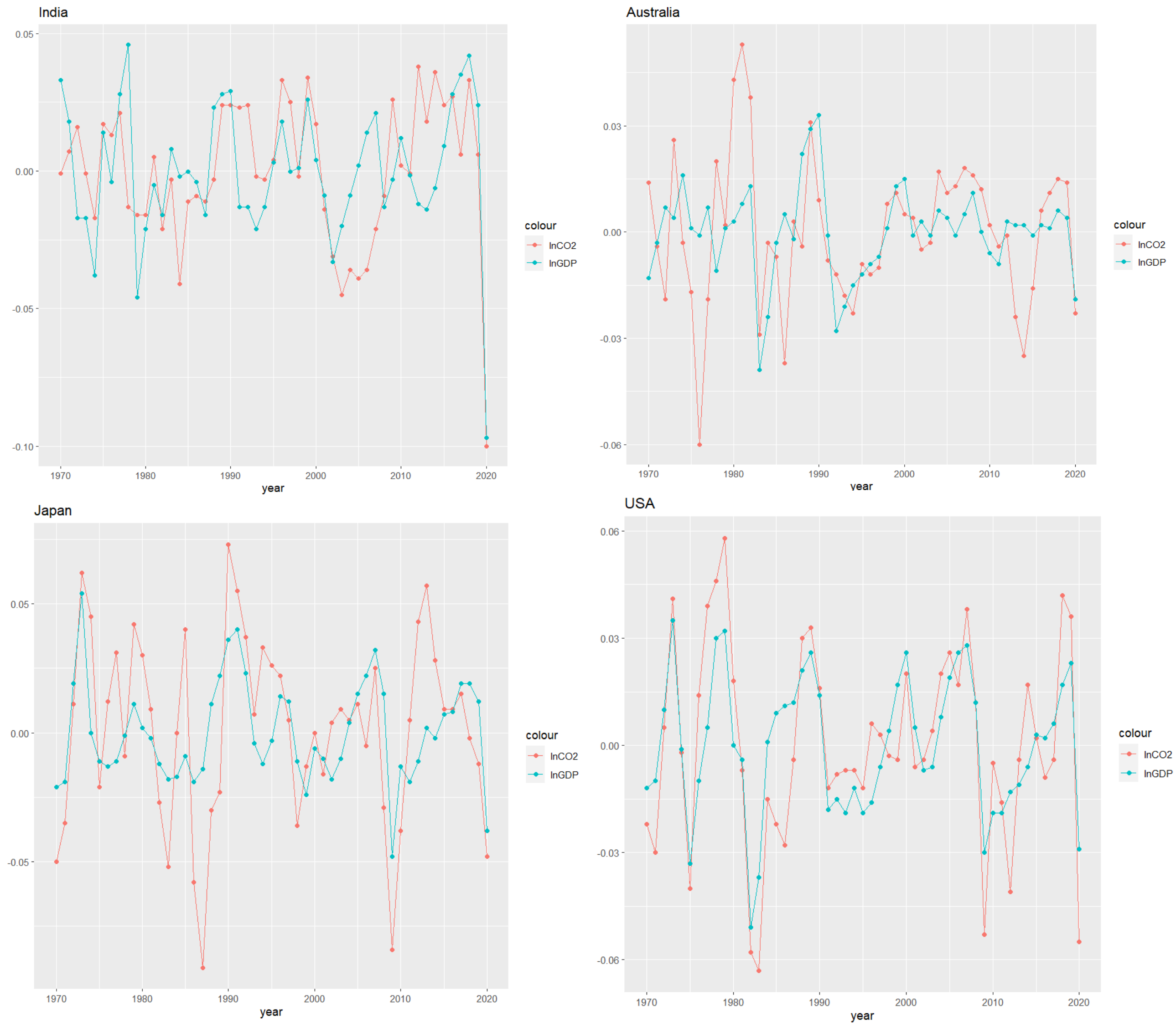


Figure 5.6 Co-Movement of CO2 emissions and GDP cycles.
Source: Computed by the authors.

Figure 5.7 superimposes the cyclical components of CO_2 emissions and fossil fuel consumption. The analysis reveals distinct patterns for different countries within the QUAD group. In the case of the USA and India, a strong procyclical relationship exists between CO_2 emissions and fossil fuel consumption. Notably, for the United States, the cyclical component of fossil fuel consumption almost perfectly coincides with that of CO_2 emissions, suggesting a nearly one-to-one correspondence between these variables over the business cycle. For Japan and Australia, while the cyclical components do not perfectly overlap, they closely track each other and also display a procyclical relationship. This suggests that fossil fuel consumption and CO_2 emissions move in tandem during different phases of the economic cycle in these countries as well.

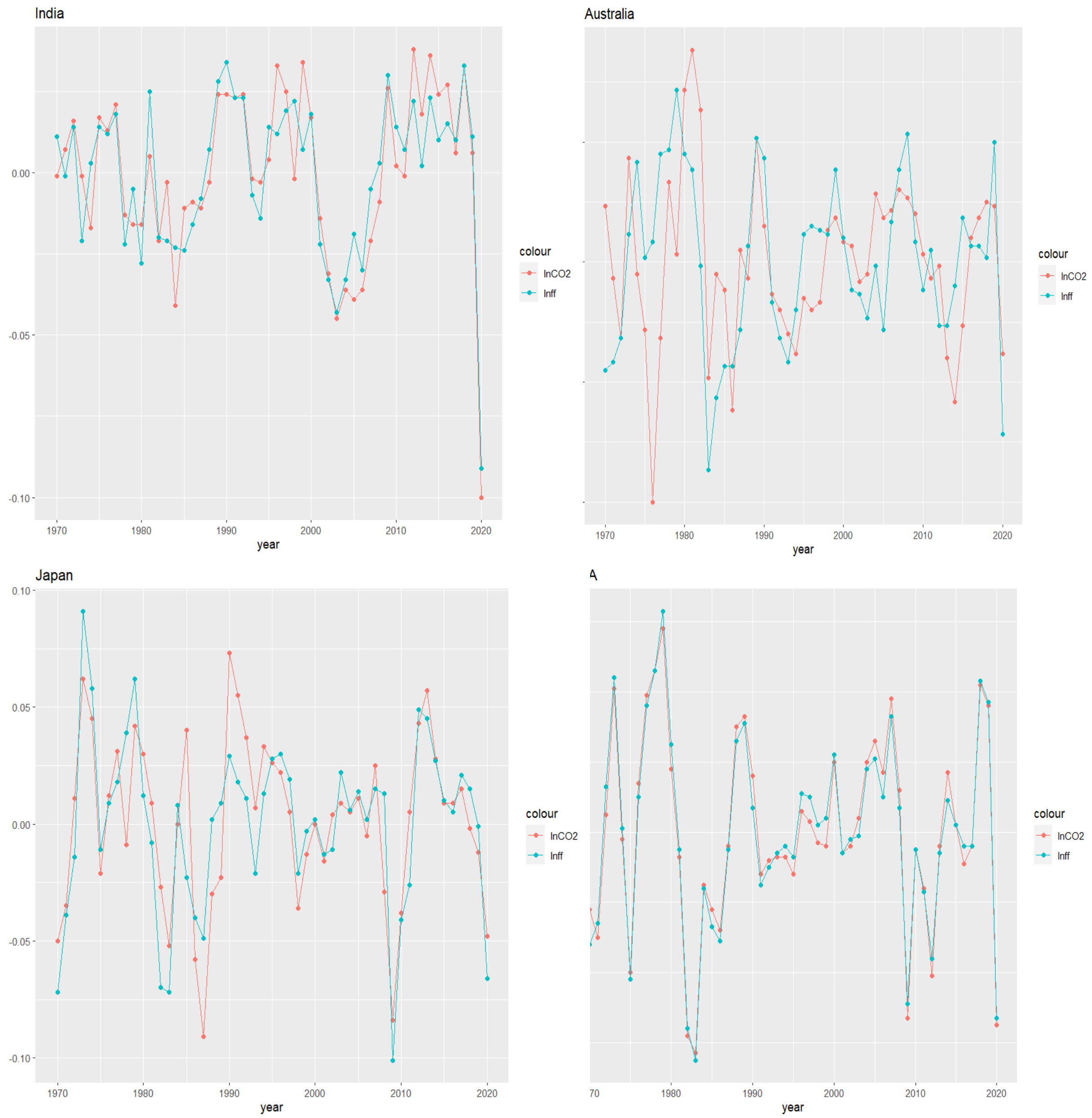


Figure 5.7 Co-Movement of CO2 emissions and fossil fuel consumption cycles.
Source: Computed by the authors.

In Figure 5.8, we superimposed CO_2 emissions and trade cyclical components and found that CO_2 emissions and trade components both are procyclical in nature. However, the peak and trough in case of trade component are more pronounced in comparison to the CO_2 emission component for all the QUAD countries individually.

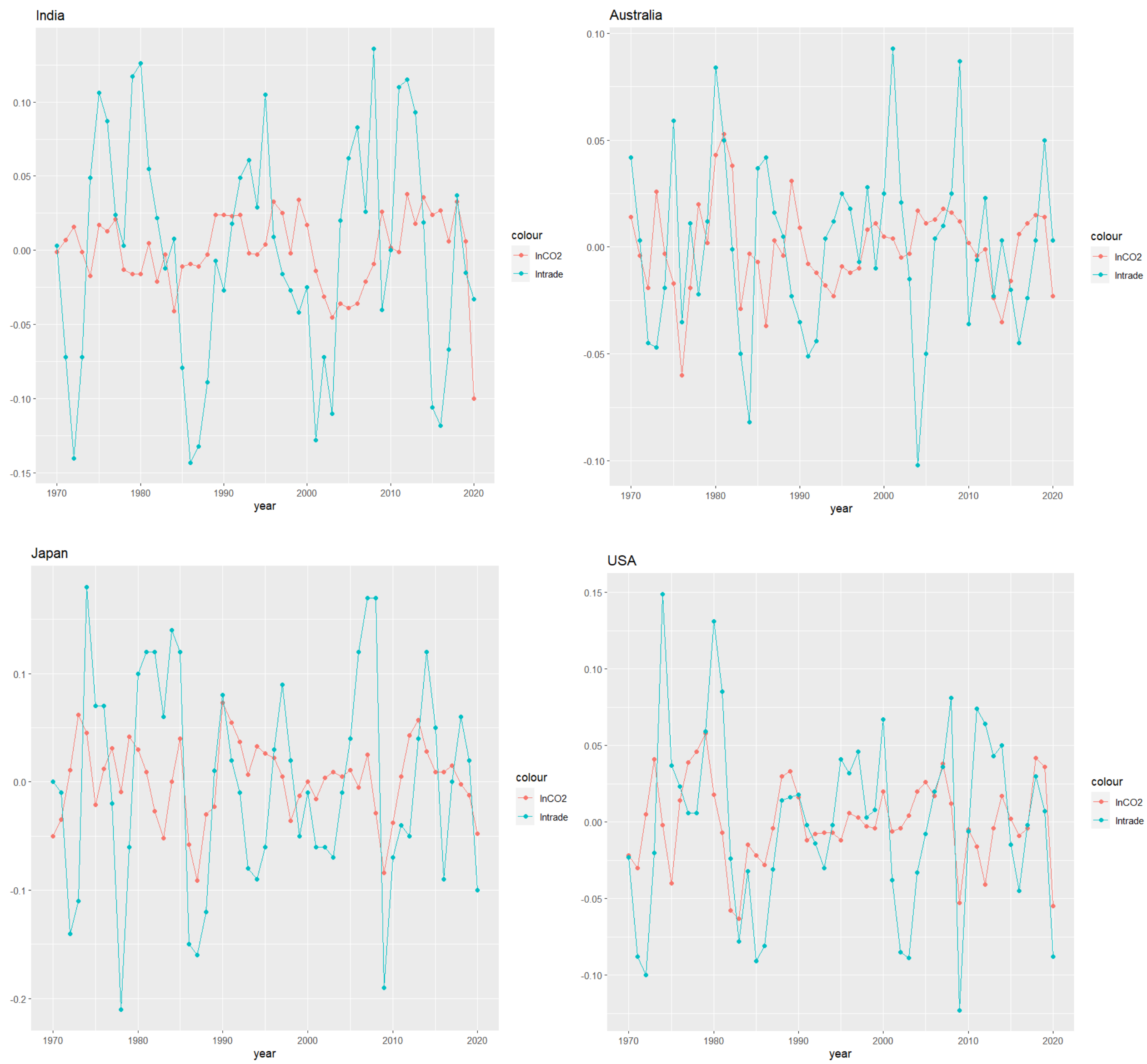


Figure 5.8 Co-Movement of CO2 emissions and trade cycles.
Source: Computed by the authors.

5.5.2 *Correlation*

In order to statistically establish the presence of procyclical behaviour and positive relationship in the given variables, we estimated the Pearson correlation coefficient of GDP, fossil fuel consumption, and Trade with the CO_2 emissions. The estimations are recorded in Figure 5.9 below. CO_2 emissions have positive correlation with GDP, fossil fuel consumption, and trade volume in the case of QUAD countries.

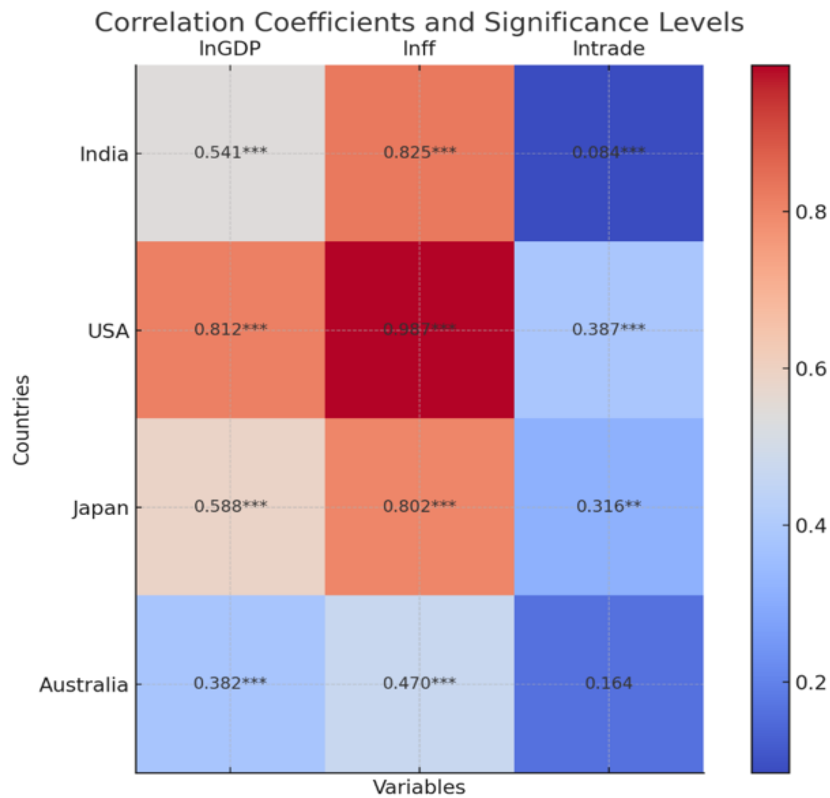


Figure 5.9 Pearson correlation of GDP, fossil fuel, and Trade with CO2 emissions.
Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

In the case of India, the correlation of CO_2 emission with GDP, fossil fuel consumption, and Trade were 0.54, 0.82, and 0.08, respectively. It is also important to note that these correlation coefficients are statistically significant at a 1% significance level. Similarly, in the case of the

USA, the correlation of CO_2 emissions with GDP, fossil fuel consumption, and Trade were 0.81, 0.98, and 0.38, respectively. Likewise, we got similar results for Japan and Australia. In the case of Australia, only the correlation between CO_2 emissions and Trade is not statistically significant at a 5% significance level. Thus, the null of no correlation between GDP and CO_2 emissions is not accepted. The relationship among variables with CO_2emissions as the dependent variable is tested using the regression analysis technique. Regression analysis provides statistical measures to evaluate the model's goodness of fit.

Table 5.10: Regression analysis result.

Country	**Variable**	**Coeff**	**Std. error**	**t-stat**	**p-value**	**Collinearity Statistics**	
India	lnGDP	0.063	0.083	0.757	0.452	Tolerance:0.67 VIF :1.49	R^2=0.78 df=50
	Lnff	0.952	0.087	10.869	0.00*	Tolerance: 0.66 VIF :1.506	
	lntrade	-0.028	0.022	-1.228	0.225	Tolerance: 0.936 VIF :1.068	
USA	lnGDP	0.090	0.056	1.612	0.113	Tolerance:0.324 VIF :3.088	R^2=0.94 df=50
	Lnff	0.940	0.042	22.087	0.000*	Tolerance:0.28 VIF :3.571	
	lntrade	0.001	0.012	0.123	0.902	Tolerance:0.777 VIF :1.283	
Japan	lnGDP	0.116	0.206	0.564	0.574	Tolerance:0.546 VIF :1.073	R^2=0.65 df=50
	Lnff	0.712	0.107	6.614	0.000*	Tolerance:0.566 VIF :1.766	
	lntrade	0.062	0.031	1.943	0.057*	Tolerance:0.932 VIF :1.833	
Australia	lnGDP	0.249	0.256	0.971	0.336	Tolerance:0.631 VIF :1.585	R^2=0.24 df=50
	Lnff	0.356	0.160	2.222	0.031**	Tolerance:0.614 VIF :1.63	
	lntrade	0.039	0.066	0.596	0.553	Tolerance:0.962 VIF :1.04	

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

The results from the estimation are recorded in Table 5.10 respectively. Overall, the findings indicate that fossil fuel consumption has a significant positive relationship with CO_2emissions in all the QUAD countries. Conversely, the association between carbon dioxide emissions and GDP does not exhibit significant statistical evidence in QUAD countries. Similarly, the association between CO_2 emissions and trade does not demonstrate statistically significant results across the countries.

5.5.3 *SVAR*

The analysis of the long-run restriction matrix aids in comprehending the fundamental association among the parameters in the long-term. The matrices are calculated for the QUAD countries over the period of 1970-2020 using the recursive long-run restrictions in the model. Here in this model, we focused on the interaction of CO_2 emissions with the other variables over the long run. During the estimation of the basic VAR model, the lags selected were based on the AIC lag selection criterion for all the QUAD countries individually. The lags selected for India, USA, Japan, and Australia were 4, 4, 1, and 2, respectively. The result matrices for all the QUAD countries are given in matrix below.

Estimated identified long run impact matrix for India:

$$\begin{bmatrix} variables \\ lnCO2_t \\ lnff_t \\ lnGDP_t \\ lntrade_t \end{bmatrix} \begin{bmatrix} lnCO2 & lnff & lnGDP & lntrade \\ 0.048 & 0 & 0 & 0 \\ 0.036 & 0.003 & 0 & 0 \\ 0.011 & 0.003 & 0.008 & 0 \\ 0.009 & 0.028 & -0.039 & 0.082 \end{bmatrix}$$

Estimated identified long run impact matrix for the USA:

$$\begin{bmatrix} variables \\ lnCO2_t \\ lnff_t \\ lnGDP_t \\ lntrade_t \end{bmatrix} \begin{bmatrix} lnCO2 & lnff & lnGDP & lntrade \\ 0.032 & 0 & 0 & 0 \\ 0.015 & 0.010 & 0 & 0 \\ 0.033 & -0.002 & 0.003 & 0 \\ 0.023 & -0.027 & 0.003 & 0.039 \end{bmatrix}$$

Estimated identified long run impact matrix for Japan:

$$\begin{bmatrix} variables \\ lnCO2_t \\ lnff_t \\ lnGDP_t \\ lntrade_t \end{bmatrix} \begin{bmatrix} lnCO2 & lnff & lnGDP & lntrade \\ 0.052 & 0 & 0 & 0 \\ 0.038 & 0.024 & 0 & 0 \\ 0.012 & 0.002 & 0.028 & 0 \\ 0.017 & -0.050 & 0.032 & 0.104 \end{bmatrix}$$

Estimated identified long run impact matrix for Australia:

$$\begin{bmatrix} variables \\ lnCO2_t \\ lnff_t \\ lnGDP_t \\ lntrade_t \end{bmatrix} \begin{bmatrix} lnCO2 & lnff & lnGDP & lntrade \\ 0.024 & 0 & 0 & 0 \\ 0.006 & 0.025 & 0 & 0 \\ 0.007 & 0.004 & 0.012 & 0 \\ -0.0004 & 0.023 & -0.009 & 0.032 \end{bmatrix}$$

In the case of India, it was observed that all three variables positively impacted CO_2 emissions, indicating that increase in fossil fuel consumption, economic growth, and trade leads to rise in emission levels. Notably, the impact of fossil fuel (ff) and GDP on CO_2 emissions were 0.03 and 0.01, respectively, which were significantly greater when compared to the influence of Trade (0.009) on CO_2 emissions. These findings suggest that country's energy composition plays a more prominent role in determining its carbon emissions. Similarly, in the case of the USA, a positive influence of all the variables on the CO_2 emissions was observed, with GDP having the largest impact (0.033), followed by trade (0.023) and fossil fuel consumption (0.015) on the CO2 emissions. The finding implies that economic expansion remains an important determinant of emissions. Likewise, in the case of Japan, all the variables depicted a positive impact on the emissions. The impact of ff, GDP, and Trade on CO_2 emissions were 0.038, 0.012, and 0.017, respectively. The relatively larger impact of fossil fuel consumption indicates that energy use is a key determinant of CO2 emissions, while the positive impact of GDP and trade suggest that economic expansion and trade activities also contribute to environmental degradation. Correspondingly, in the case of Australia, ff and GDP depicted a positive influence on CO_2 emissions. The impact of ff and GDP were 0.006 and 0.007 respectively. However, trade variable depicted low yet negative (-0.0004) impact on the emissions. This finding suggests that while economic growth and fossil fuel consumption increases emissions, trade is associated with relatively cleaner production, thereby having a limited influence on overall CO2 emissions.

5.5.4 *Structural Impulse Response Function (IRF)*

In order to trace the response of a dependent variable to shocks arising in the independent parameters in the model, IRF is used. The graphs of IRF of fossil fuel, trade, and GDP due to one innovation shock in CO_2emissions for ten periods for all the QUAD countries are given below. Figure 5.10, 5.11, 5.12, and 5.13 represents IRF in the case of India, the USA, Japan, and Australia. It shows the response of CO_2emissions, GDP, ff, and trade due to one innovation shock in CO2 emissions, GDP, ff, and trade for ten periods. Here, shock 1 is CO2 emissions, shock 2 is ff, shock 3 is GDP, and shock 4 is trade volume.

In panel A of fig 5.10, the impulse response of CO_2 emissions indicates no contemporaneous effect due to a shock in ff for the initial three periods. Subsequently, the response turns negative until the sixth period, followed by positive response for future periods. In contrast, a shock in

GDP produces a positive contemporaneous response of CO_2 emissions for 3 periods. This response becomes negative up to the eighth period, followed by a positive response till 10 periods. Lastly, CO2 emissions illustrate a negative response to a shock in trade volume till 5 periods, followed by a positive response till future periods. In panel B, a one standard deviation shock in CO2 emissions and GDP depicts a positive contemporaneous response of ff for up to four periods. This effect is followed by negative response till nine periods and changes to positive for future periods. Similarly, a shock in trade produces a negative contemporaneous for two periods, followed by a brief positive response for 1 period. The response then becomes negative up to the fifth period, turning positive until the ninth period, and eventually dies out.

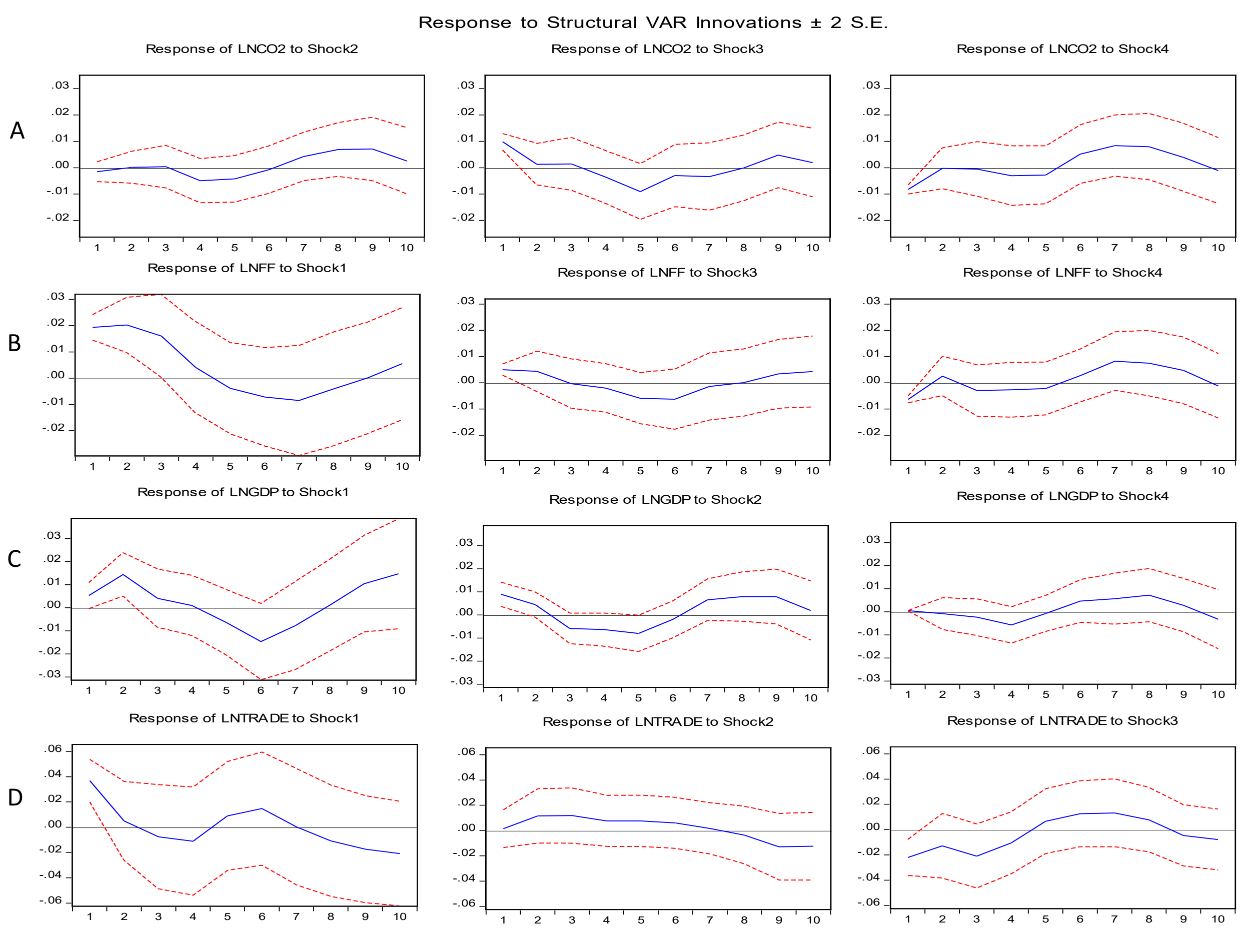


Figure 5.10 Structural Impulse Response Function with one innovation shock in CO_2emissions for India.
Source: Computed by the authors.

In panel C, a shock in emissions and ff lead to an initially positive response of GDP, which subsequently turns negative for eight periods, the response eventually becomes positive for future periods. However, a shock in trade volume results in a negative contemporaneous impact on GDP for the first five periods. This is followed by a positive response lasting for nine periods, after which the effect becomes negative in the future periods. Lastly, panel D represents the response of trade volume due to one innovation shock in emissions, ff, and GDP. The shock in emission depicts a positive response for two periods which becomes negative till four periods. The response then becomes positive for seven periods and negative for future periods.

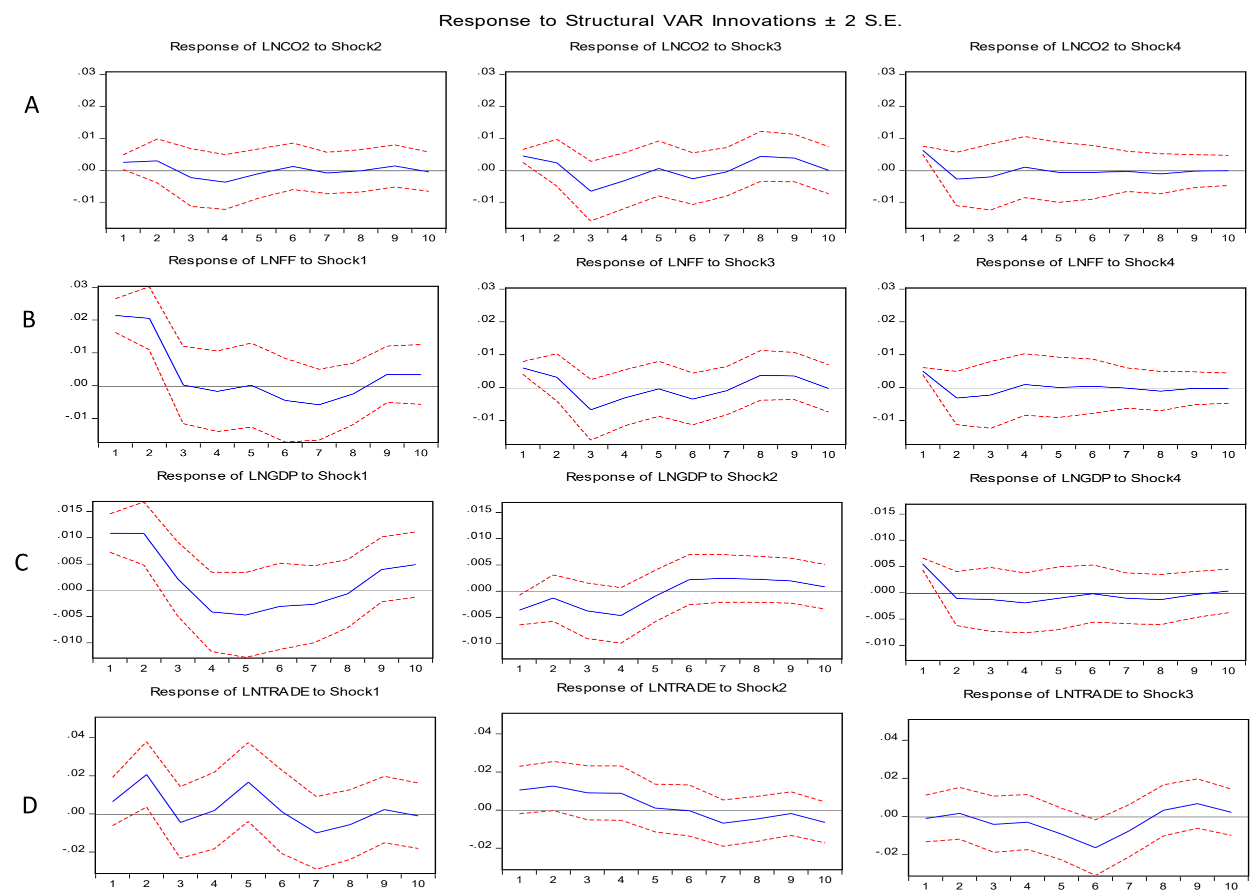


Figure 5.11 Structural Impulse Response Function with one innovation shock in CO_2emissions for the USA.
Source: Computed by the authors.

Panel A of fig 5.11 represents the response of CO_2 emissions due to one innovation shock in ff, GDP and trade volume in the USA. The first figure depicts that one innovation shock to ff has positive impact on emissions for 2 periods. The impact the becomes negative for six periods and eventually dies out. In the center figure, a shock in GDP shows positive response in emissions for 2 periods, which then changes to negative for 5 periods and becomes zero. Further the response shows negative association for 7 periods and eventually becomes positive. Similarly, a shock in trade reveals a positive contemporaneous response which then becomes negative for 4 periods and dies out. In panel B, a one standard deviation shock in CO_2 emissions and GDP depicts a positive contemporaneous response of ff which become negative till 8 periods and finally becomes positive for future periods. However, a shock in trade depicts a positive response for 1 period followed by negative response till 8 periods and eventually dies out. In panel C the response of GDP to a shock in emission propagates in three stages, starting from positive response for 3 periods, negative for 8 periods and finally depicts a positive response for future periods. The shock in ff yield different results, here the response due to a shock in ff shows a negative response for 6 periods which eventually turns positive and dies out. Similarly, a shock in trade reveals positive response for 2 periods, followed by negative and the response dies out. In panel D, the response of trade due to a shock in emissions depicts a fluctuating response, wherein, the response is positive for 3 periods, which then changes to negative for a brief period and again becomes positive for 7 periods. After this the response becomes negative and dies out. On the contrary, the response of trade due to one innovation shock in ff reveals no fluctuation. The graph depicts positive response for 6 periods followed by negative response in future periods. Lastly, a one innovation shock in GDP reveals no contemporaneous response. After 2 periods, the response becomes negative till 8 periods and changes to positive till future periods.

In the case of Australia (figure 5.12), Panel A represents the response of CO2 emissions due to one innovation shock in ff, GDP and trade volume. In the first figure, the response of emissions due to a shock in ff presents a negative trajectory for 2 periods followed by positive for 6 periods and dies out. In the center figure, the response to a shock in GDP is positive for 2 periods, which becomes negative but near to zero and eventually dies out. On the contrary, the response of emissions to a shock in trade reveals a negative contemporaneous impact which dies out after 3 periods.

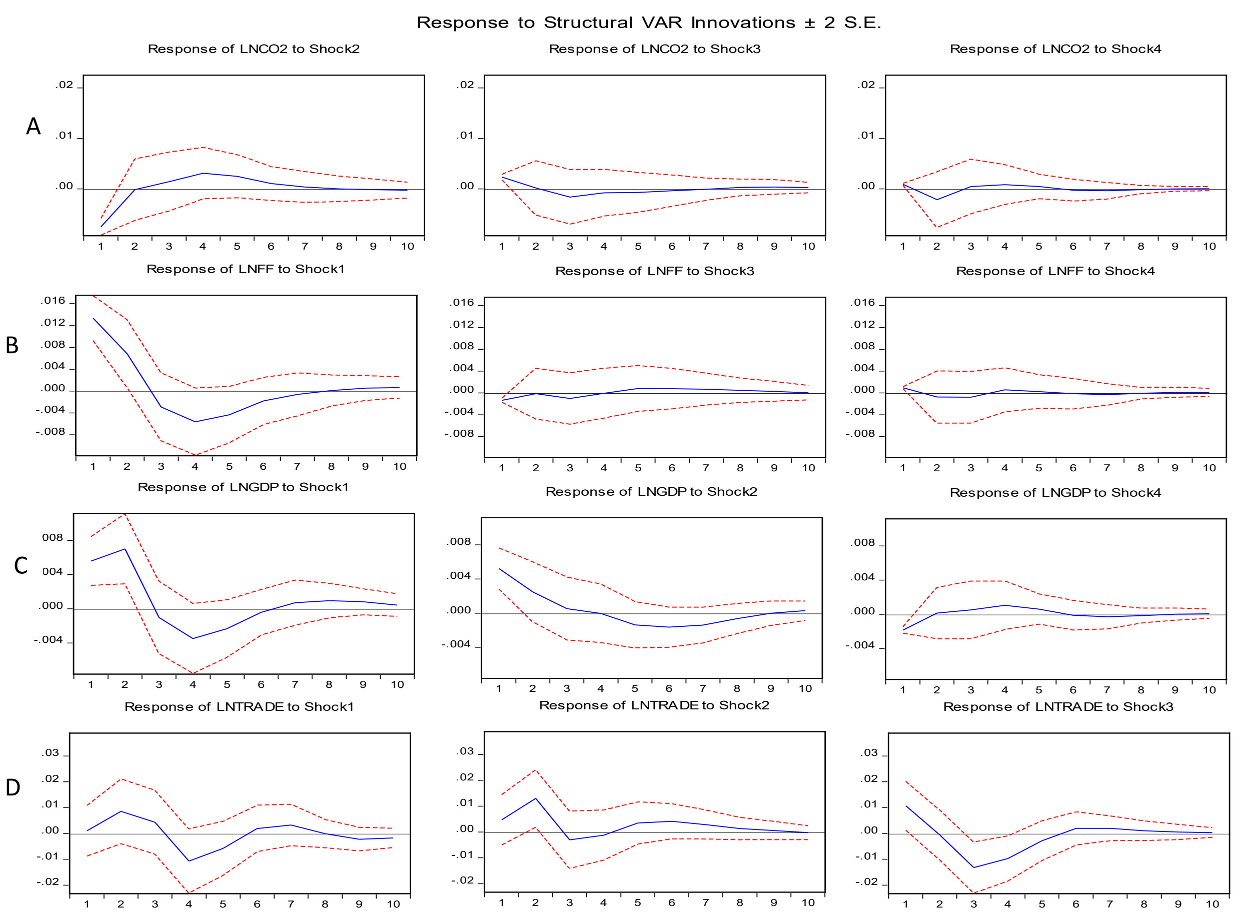


Figure 5.12 Structural Impulse Response Function with one innovation shock in CO_2emissions for Australia.
Source: Computed by the authors.

In panel B, a shock in emissions shows a positive impact on ff in 3 periods, which changes to negative for 6 periods and dies out. However, a shock in GDP and trade depicts negligible impact on ff in 10 periods. In panel C, the response of ff to a shock in emission propagates in three stages, starting from positive response for 3 periods, negative for 7 periods and finally dies out for future periods. A shock in ff depicts a positive response for the first three periods after which it becomes negative till 9 periods and finally dies out. The shock in trade does not follow the same trajectory, here one innovation shocks lead to a contemporaneous negative response which becomes positive till 6 period and dies out. In panel D, a shock in emissions, ff, and GDP leads to an initially positive response of trade for 3 periods, which subsequently turns negative till 5 and 6 periods respectively. The response eventually becomes positive and dies out for future periods.

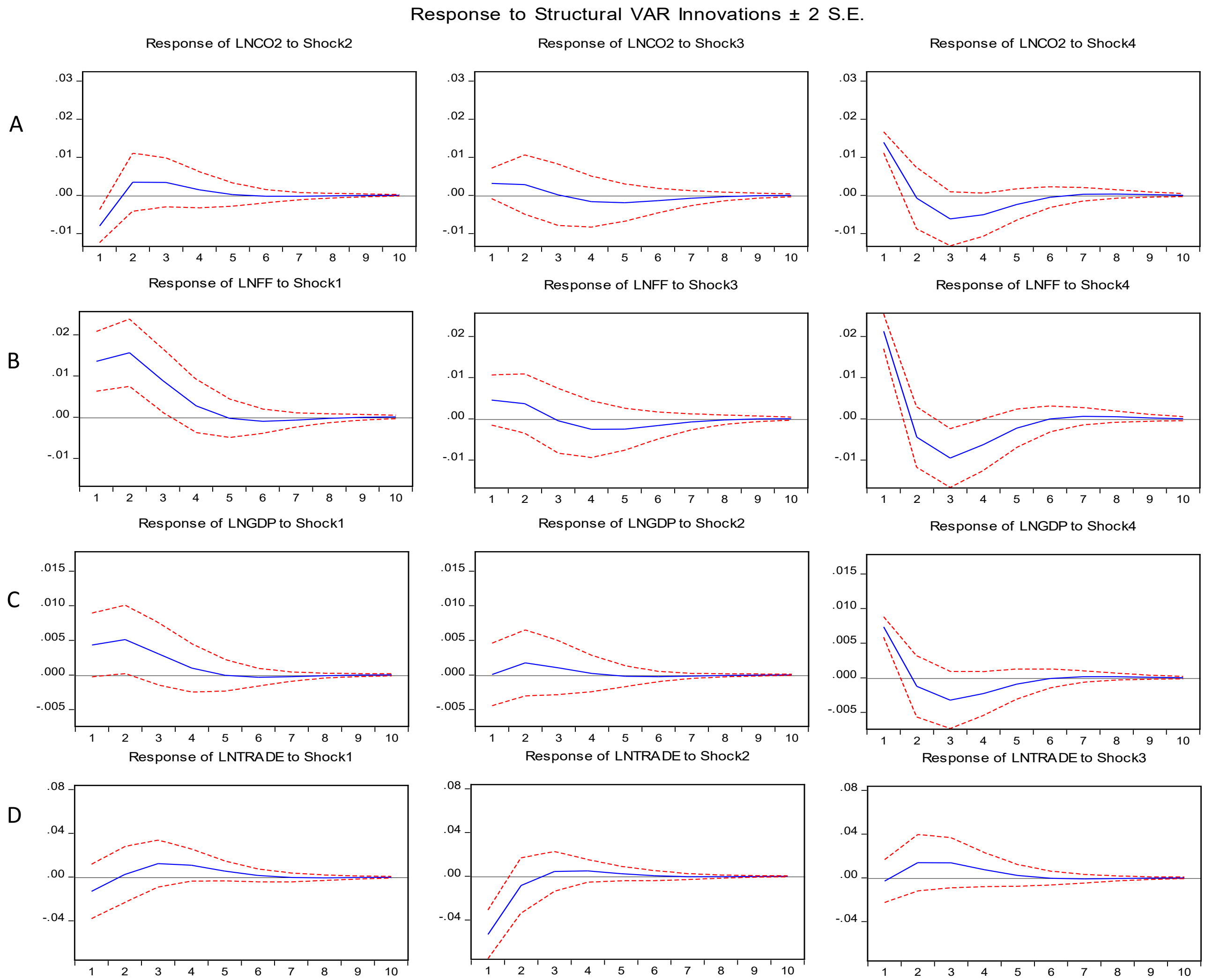


Figure 5.13 Structural Impulse Response Function with one innovation shock in CO_2emissions for Japan.
Source: Computed by the authors.

In the case of Japan (figure 5.13), Panel A represents the response of CO2 emissions due to one innovation shock in ff, GDP and trade volume. In the first figure, the response of emissions due to a shock in ff presents a negative trajectory for 2 periods followed by positive for 5 periods and dies out. In the center figure, the response to a shock in GDP is positive for 3 periods, which becomes negative but near to zero and eventually dies out. On the contrary, the response of emissions to a shock in trade reveals a positive contemporaneous impact which becomes negative for 6 periods and dies out. In panel B, a one standard deviation shock in CO2 emissions and GDP depicts a positive contemporaneous response of ff for 5 periods after which the response dies out. Similarly, one innovation shock in GDP reveals a positive response for 3 periods, followed by a negative response for 8 periods and dies out. Likewise, a shock in trade volume shows a positive impact in 2 periods, which changes to negative for 6 periods and dies out. In panel D, the response of trade to a shock in emissions, ff, and GDP is somewhat similar. A shock in emissions leads to a negative response for 2 period followed by positive impact for 6 periods and dies out. A shock in ff leads to a negative response for 3 periods followed by positive impact and dies out. Lastly, a shock in GDP leads to no contemporaneous response which changes to positive impact for 6 periods and dies out.

5.5.5 *Forecast Error Variance Decomposition (FEVD)*

The FEVD exhibits how important a shock is in explaining the variations of the variables in the model. It also highlights the fact that the importance of variables may change over time. For example, some shocks may not be responsible for variations in the short run but may cause longer-term fluctuations. Country specific figures (figure 5.14, 5.15, 5.16, and 5.17) below explain the importance of shock of different variables in the lag period 2^{nd}, 5^{th}, and 10^{th} only.

The results of figure 5.14 shows that in panel A, CO2 emissions itself explain 83.18% variation of emissions in the short-term (2^{nd} period), 78.80% in the mid-term (5^{th} period), and 65.69% in the long-term (10^{th} period). GDP explains 9.77% variation while trade volume explains 13.66% variation in short term. In the midterm, 12.76% variation is explained by GDP, 5.57% is explained by trade volume, and 2.95% is explained by ff. Similarly, in the long-term, 13.37% is explained by trade volume, 12.36% by GDP, and 8.56% by ff respectively. In panel B, 80.17% variations in ff are explained by emissions, 8.60% by trade volume and 5% by both

GDP and ff itself in the short run. In the midterm, 83.56% variation is explained by emissions, 6.48% variation is explained by GDP, 5.25% is explained by trade, and 4.52% variations in ff is explained by ff itself.

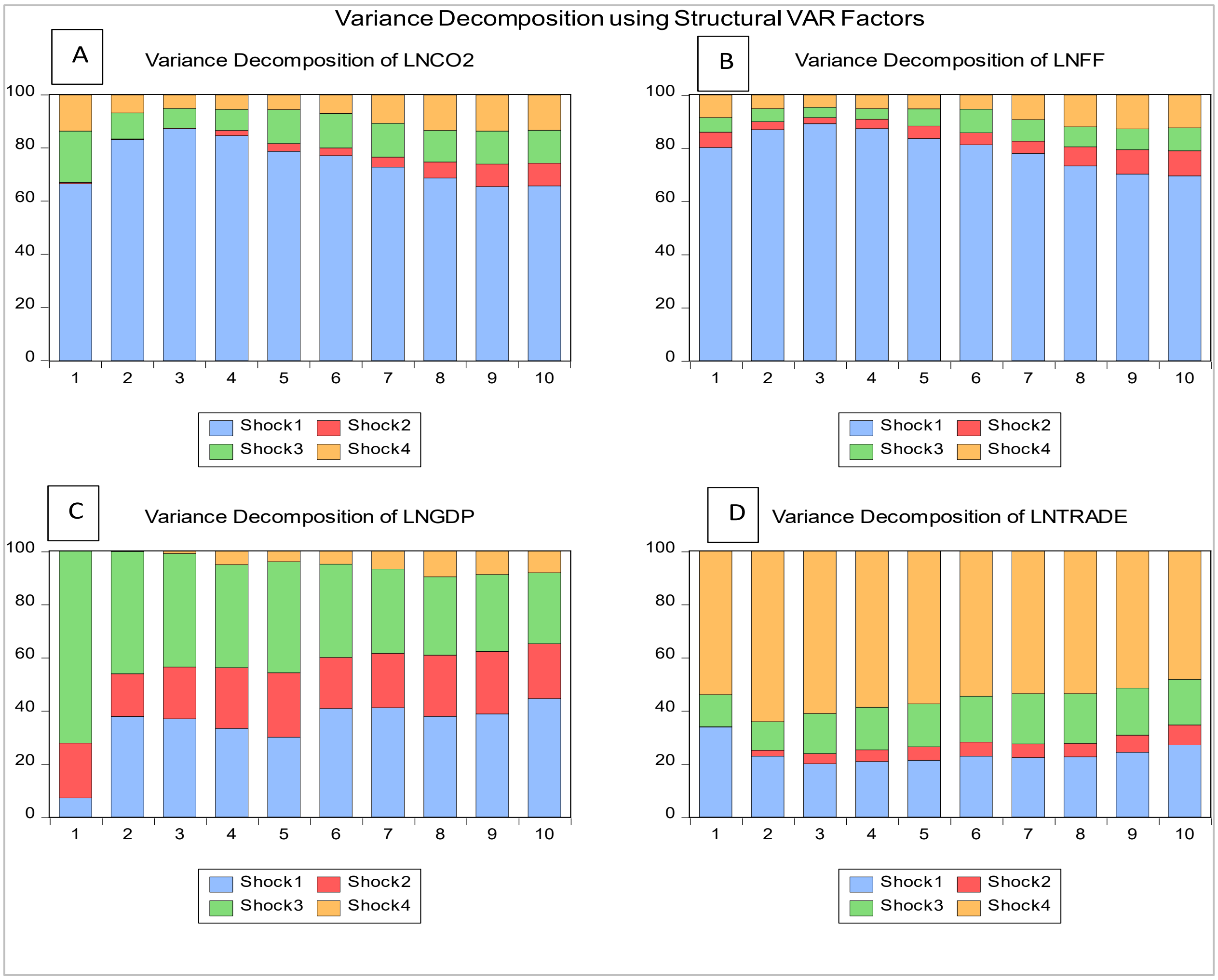


Figure 5.14 Forecast Error Variance Decomposition in India.
Source: Computed by the authors.

In panel C, 46.05% variations in GDP are explained by GDP itself, 37.79% by emissions, and 16.02% by ff in the short run. In the midterm, 41.78% variation is explained by GDP, 30% variation is explained by emissions, 24.20% is explained by ff, and 4% variations in GDP is explained by trade volume. In panel D, trade itself explains 64.16% variations, 22.82% variation is explained by emissions, 10.76% variations are explained by GDP, and 2.24%

variation is explained by ff in the short run. In the midterm, 57.48% variation is explained by trade itself, 21.29% variation is explained by emissions, 16.13% is explained by GDP, and 5% variations explained by ff.

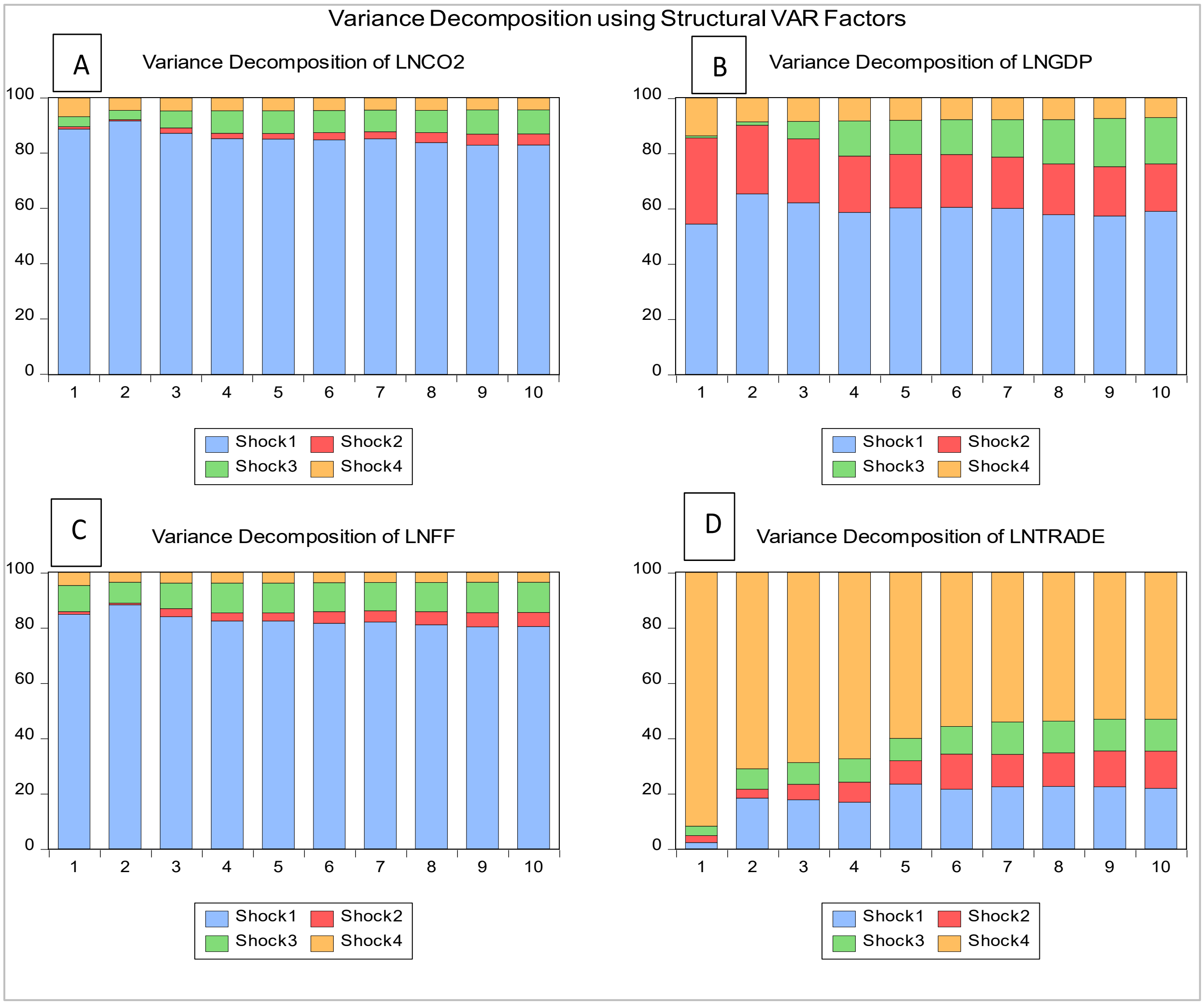


Figure 5.15 Forecast Error Variance Decomposition in the USA.
Source: Computed by the authors.

The results of figure 5.15 shows that in the second period, 91.61% of variations in FEVD of emissions can be attributed to emissions itself, 4.52% to trade, 2.43% to GDP, and 1.42% to ff. In the fifth and tenth periods, FEVD of emissions can be attributed to emission itself and GDP. These variables explain 82% and 8% of the FEVD of emissions, respectively. In the second period of panel B, 88.28%, 4.64%, 3.57%, and 3.49% variations in FEVD of ff can be attributed to emissions, GDP, trade, and ff. In the fifth and tenth periods, FEVD can mainly be attributed to emissions, trade, GDP, and ff as it explains 81%, 10%, 4%, and 3.6% of the variations in ff. In the case of variations in GDP in the short term, i.e., in the second period, 65% of variations in GDP can be explained by emissions; however, GDP, trade, and ff only explain 21%, 8.64%, and 4.13% variations in FEVD. In the mid-term, i.e., fifth period, and long-term, i.e., tenth period, FEVD in GDP can be attributed to CO_2emissions, GDP, ff, and trade by 60%, 21%, 12%, and 7%, respectively. In panel D, the FEVD of trade in the short term is mainly explained by trade itself at 71%, 18% by emissions, and 10% by ff. GDP does not explain FEVD. In the mid-term FEVD is attributed to trade, emissions, ff, and GDP by 60%, 23%, 13%, and 3.46%, respectively. While in the long term, FEVD is attributed to trade, emissions, ff, and GDP by 53.15%, 21.83%, 13.07%, and 11.93%, respectively.

The results of figure 5.16 shows that in the panel A, 85% variations in emissions are explained by emissions itself, 15% by ff, and 1.6% by trade in the second period, fifth period and 10th period. GDP does not explain any variation in emissions. In panel B, GDP and trade does not explain any variation in ff in the short, mid, and long term. While, emissions explain 50.54%, 46.35%, and 46.35% variations in the short, mid, and long term; and ff explains 48.39% and 52.51% variations in in the short, mid, and long term.

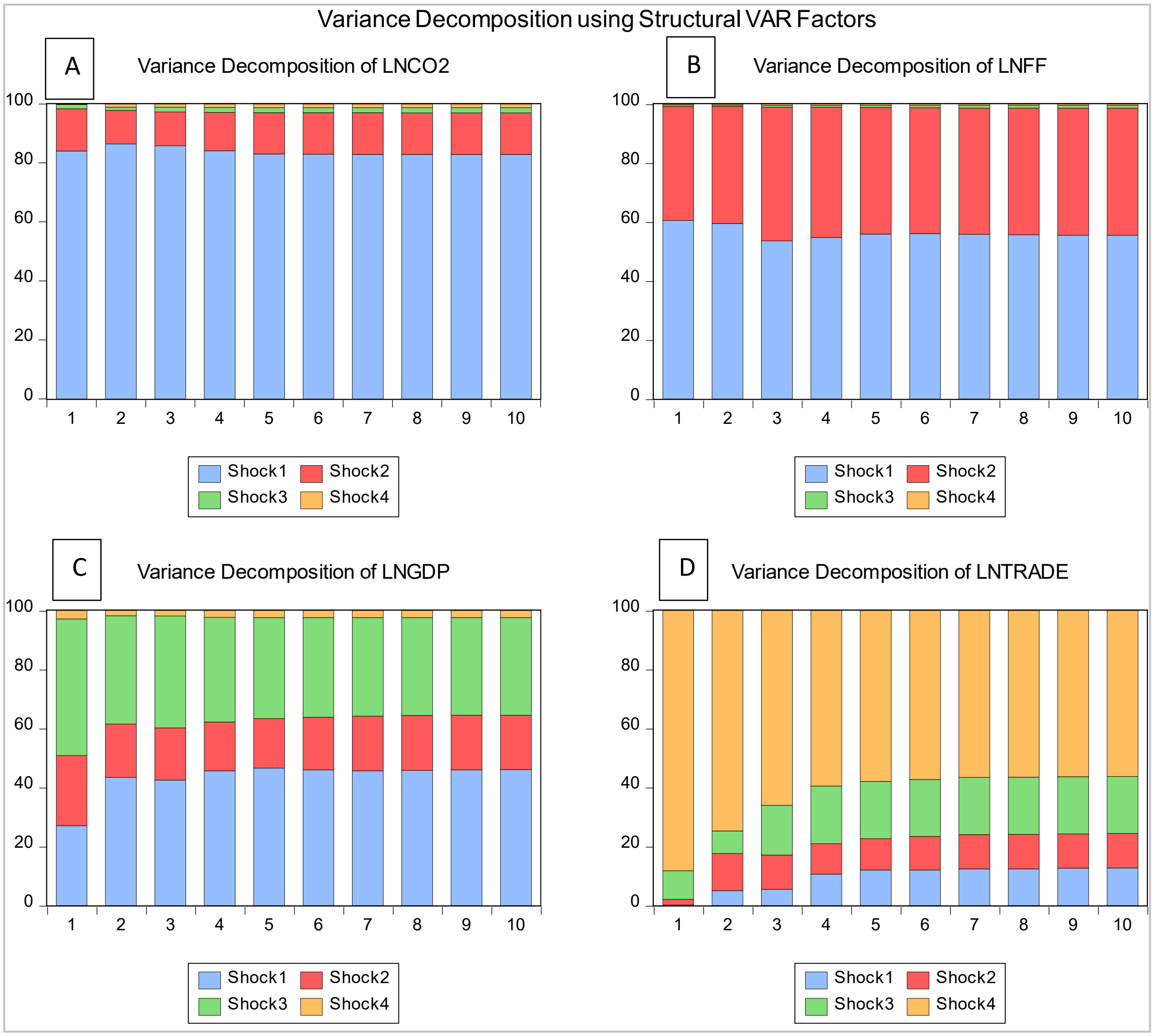


Figure 5.16 Forecast Error Variance Decomposition in Australia.
Source: Computed by the authors.

Similarly in panel C, GDP, emissions, and ff explain 57.71%, 28.71%, and 13.47% variations in GDP in the short, mid, and long term. Trade does not have any impact on the variations in the short, mid, and long term. In panel D, variations in trade volume are 81% explained by trade itself, 9% by ff, 6% by GDP, and 2% by emissions in the short, mid, and long term.

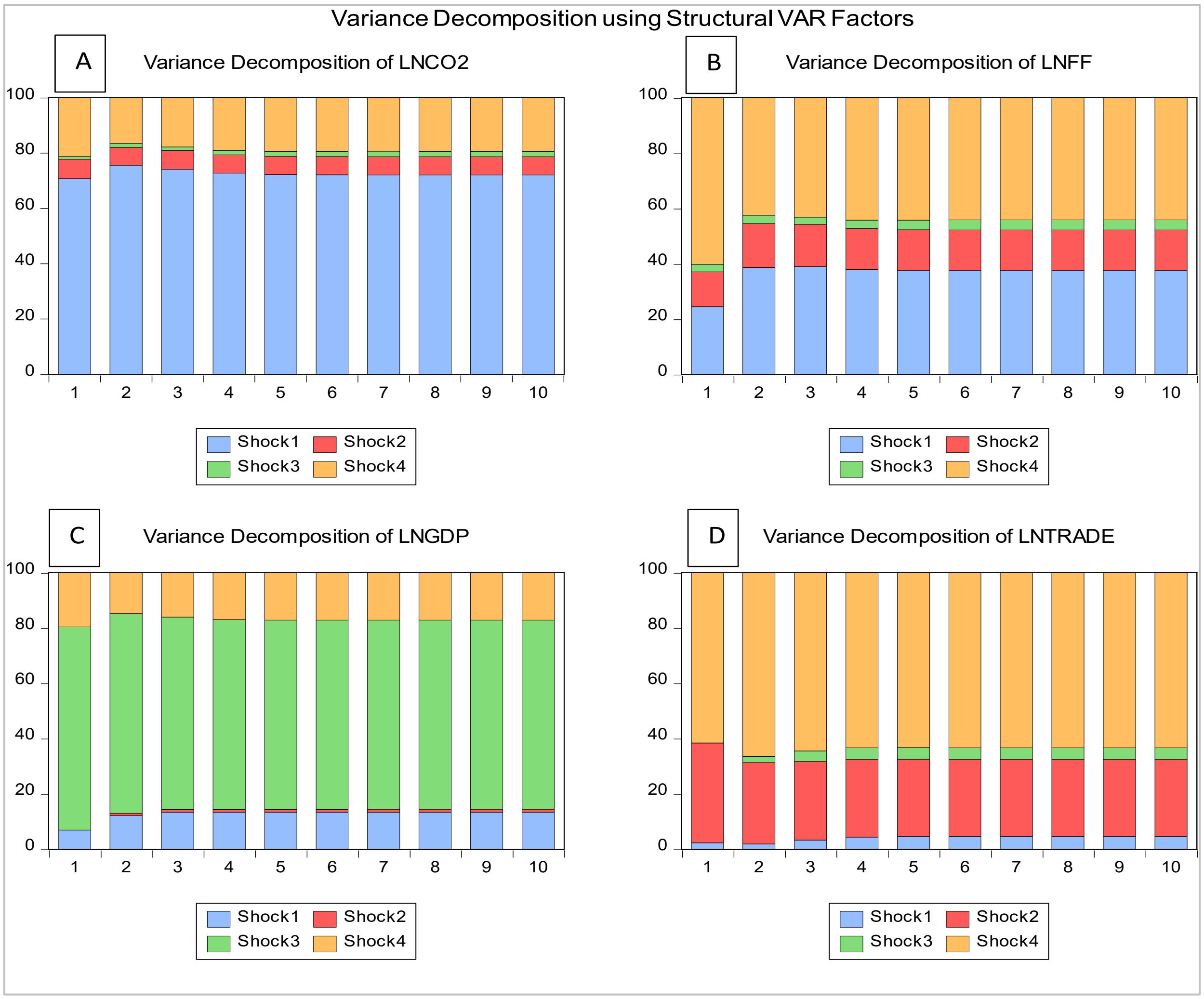


Figure 5.17 Forecast Error Variance Decomposition in Japan.
Source: Computed by the authors.

The results of figure 5.17 shows that in the second period, 84.46% of variations in FEVD of emissions can be attributed to emissions itself and 14.29% to trade. GDP and ff does not explain variation in the emissions. In the mid-term FEVD is attributed to emissions itself, trade, and ff by 71.24%, 25.56%, 1.6%, and 1.5%, respectively. While in the long term, FEVD is attributed to emissions, trade, ff, and GDP by 68.88%, 26.91%, 2.14%, and 2.04%, respectively. In the second period of panel B, 38.89%, 27.92%, 27.30%, and 5.87% variations in FEVD of ff can be attributed to emissions, trade, GDP, and ff. In the fifth and tenth periods, FEVD can mainly be attributed to trade, emissions, ff, and GDP, as it explains 34.8%, 32.2%, 23.7%, and 9% of the variations in ff. In the case of variations in GDP in the short term, i.e., in the second period, 73.85% of variations in GDP can be explained by GDP itself, 15.39% variation is explained by emissions, and 10.41% variations are explained by trade. In the mid-term, i.e., fifth period, and long-term, i.e., tenth period, FEVD in GDP can be attributed to GDP, CO_2emissions, and ff, by 66%, 15%, and 2% respectively. While trade explains 15% in the mid-term and 17% in the long-term. In panel D, the FEVD of trade in the short term is mainly explained by trade itself at 84%, 12.93% by ff, and 2.05% by GDP. CO2 emissions do not explain FEVD in trade volume. In the mid-term and long-term, FEVD is attributed to trade itself, ff, GDP, and emissions by 80%, 13.33%, 4.7%, and 1.3%, respectively.

5.6 Objective 2

For the second objective, the Environmental Kuznets Curve (EKC) hypothesis was tested for all the QUAD nations using a quadratic regression technique. The dataset employed to run the regression analysis spans from the year 1970 to 2022. The primary test to check the data-structure like the unit root test is already conducted, the result of which is reported in table 5.5, 5.6, 5.7, and 5.8 respectively for each individual nation. The test results depict that both GDP and CO2 emissions are stationary at different levels of integration. The table 5.11 demonstrates how the Environmental Kuznets Curve (EKC) hypothesis applies to different countries by showing the relationship between GDP (β1), its square (β2), and environmental quality. This approach allows for identification of inverted U-shaped trajectories, indicating that environmental degradation initially rises with income, reaches a turning point, and then declines beyond a threshold. The model specification follows a quadratic form, capturing potential nonlinearities in the environment-growth nexus, the equation (5.1) for model is given as:

$$CO_2 = \alpha + \beta_1 GDP + \beta_2 GDP^2 \quad (5.1)$$

Table 5.11 Results of quadratic regression for QUAD nations.

Country	β1	β2	Turning Point	Trend Formation
India	8.619*	-0.140*	30.72	Inverted U-Shape
USA	15.519*	-0.256*	30.21	Inverted U-Shape
AUSTRALIA	20.862*	-0.370*	28.16	Inverted U-Shape
JAPAN	-0.962 {0.308}*	0.022		Linear

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

Based on the five hypotheses of the EKC model, we confirmed the occurrence of an inverted U-shaped curve for India, the USA, and Australia. The turning point for India is calculated at 30.72, for the USA at 30.21, and for Australia at 28.16. Hence, corroborating with the earlier research findings in the literature (Adebayo et al., 2021; Aldy, 2005; Apergis et al., 2017; 295 Ben Youssef et al., 2016; Bilgili et al., 2016; Boutabba, 2014). It is important to highlight that a 1% increase in GDP leads to 0.14% decrease in the emissions of India, 0.25% decrease in emissions of the USA, and 0.37% decrease in the emissions of Australia. For India, the USA, and Australia, β1 is positive and significant while β2 is negative and significant, signifying an inverted U-shaped trend. It is important to note that the results of quadratic regression in case of Japan are insignificant at 1%, 5%, and 10% level of significance. This indicates that Japan's CO_2 emissions or environmental degradation do not follow the typical EKC trajectory, possibly due to unique factors like advanced early technology adoption, policies, and a mature economy with slower growth, which alter the expected pattern. However, in order to understand the type of relationship that exists between emissions and GDP in case of Japan, we estimated the linear and quadratic regression. The result of quadratic regression estimations was found to be insignificant; hence it was concluded that linear relationship exists between the variables. The result of linear regression is given in curly brackets in the table 5.15. Hence, we can conclude that a 1% increase in GDP leads to 0.30% increase in the emissions of Japan. This diversity highlights how structural, policy, and technological differences shape each nation's environmental path as they develop.

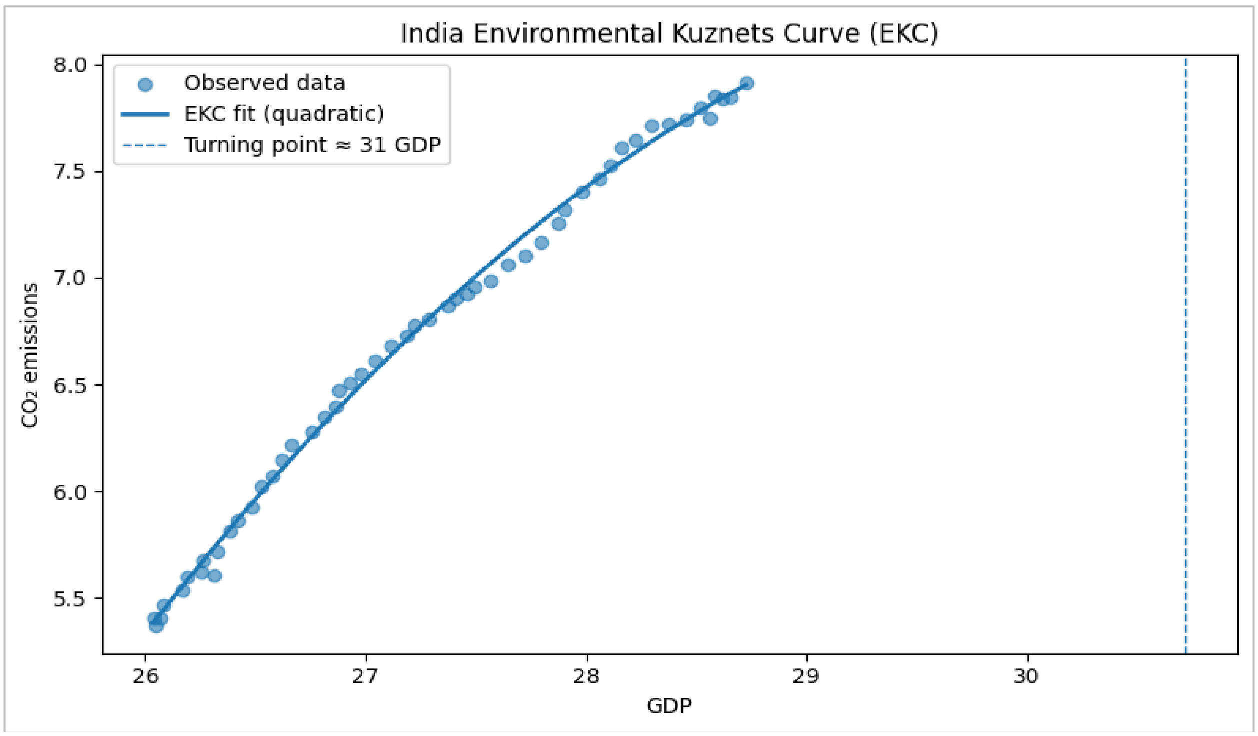


Figure 5.18 EKC for India.
Source: Computed by the authors.

The figure 5.18 presents the Environmental Kuznets Curve (EKC) for India, demonstrating the association between GDP and environmental quality indicated by CO_2 emissions. The scatter points represent the observed data, and the fitted quadratic curve illustrates the overall trend. The graph illustrates a positive relationship at lower income levels, where an increase in GDP corresponds with a rise in CO_2 emissions. This trend highlights the significant dependence on fossil fuels and industrial growth in the initial stages of development. Nonetheless, the curve demonstrates a turning point at around a GDP value of 28 (log-transformed), after which the relationship shifts direction. This indicates that with the continued growth of India's income, emissions are likely to stabilize and gradually decrease. This observation aligns with the theoretical Environmental Kuznets Curve hypothesis, which posits that environmental degradation tends to increase with economic growth initially, but eventually decreases as economies implement cleaner technologies, enhance energy efficiency, and enforce more robust environmental regulations. The positioning of the turning point indicates that India is moving away from a phase characterized by high emissions growth towards a more sustainable path. However, the speed and degree of this reduction will rely on factors such as policy decisions, innovation, and structural changes within the energy and industrial sectors.

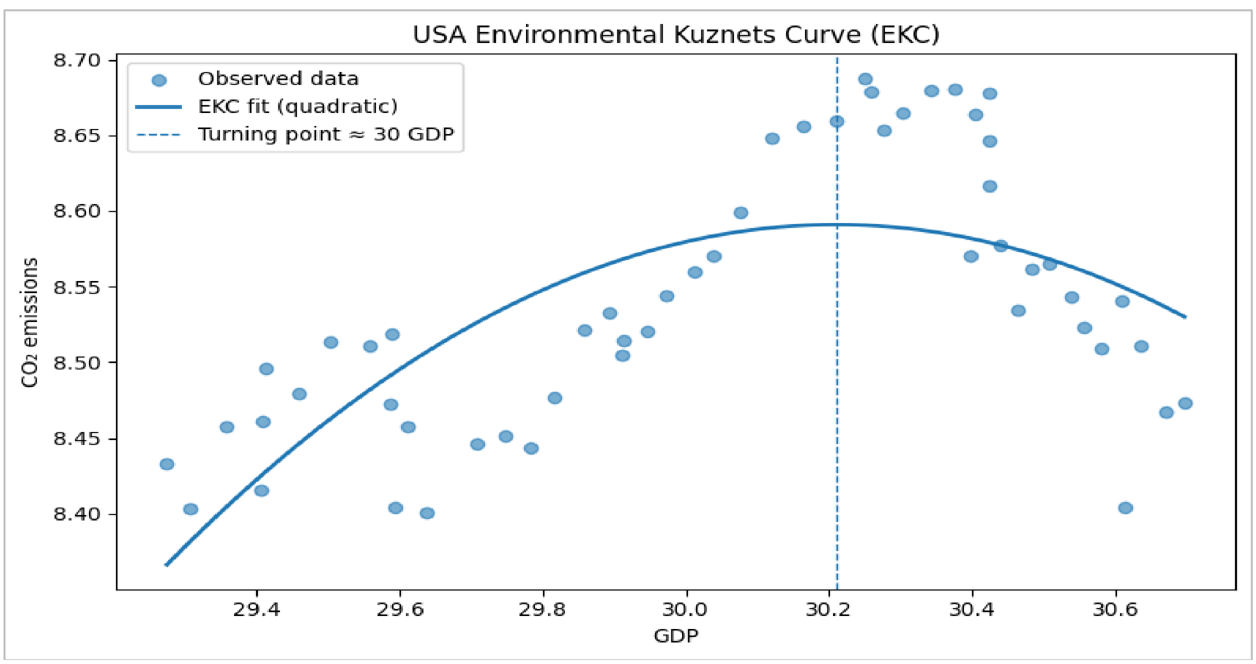


Figure 5.19 EKC for the USA.
Source: Computed by the authors.

The figure 5.19 depicts the Environmental Kuznets Curve (EKC) for the United States, illustrating the relationship between economic growth and CO_2 emissions. The scatter points illustrate the observed data, whilst the fitted quadratic curve represents the estimated trend. At lower income levels, emissions increase in along with increasing GDP, indicating the energy-intensive characteristics of industrial and economic growth. The curve attains its peak at around GDP value at 30, as denoted by the dashed vertical line, which signifies the turning point. Beyond this threshold, the curve declines, indicating that additional income increases lead to a decline in emissions. This pattern is consistent with the EKC hypothesis, which posits that advanced economies eventually decouple economic growth from environmental degradation through technological innovation, structural transformation, efficiency improvements, and stringent environmental policies. The distribution of data points around the fitted curve signifies short-term fluctuations probably influenced by variations in energy demand, industrial cycles, or regulatory interventions. Nonetheless, the overall trajectory indicates that the United States has reached a post-turning-point phase, wherein persistent expansion increasingly correlates with diminishing emissions.

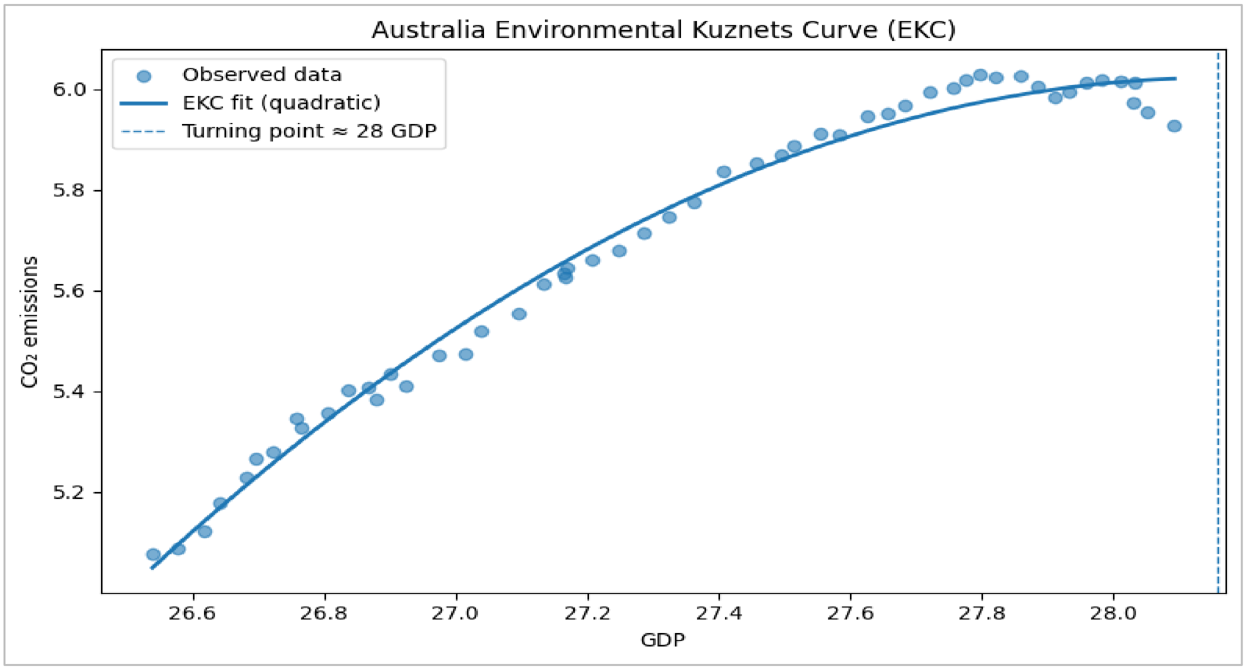


Figure 5.20 EKC for Australia.
Source: Computed by the authors.

The figure 5.20 illustrates the Environmental Kuznets Curve (EKC) for Australia, analyzing the relationship between economic growth and CO_2 emissions. The scatter plot denotes the observed data and the quadratic fit line captures the underlying trend. At lower GDP levels, the curve exhibits a positive trend, signifying that emissions increase with rising GDP, which is consistent with the initial growth phase characterized by rapid industrialization and energy demand expansion. The curve attains its inflection point at approximately 28 log-transformed GDP value, designated by the dotted vertical line. Beyond this level, the fitted curve starts to settle down and marginally decrease, indicating the potential for decoupling economic growth from emissions as the economy evolves. This pattern corresponds with the EKC hypothesis, the underlying reason for this pattern can be attributed to technical advancements, enhanced efficiency, and more comprehensive environmental regulations. The overall shape supports the theoretical framework, while the close clustering of data points around the fitted line signifies a relatively smooth transition, implying that structural and policy changes in Australia may have consistently impacted the emissions trajectory along with economic growth.

The figure 5.21 illustrates the significant linear graphical association between GDP and CO2 emissions. The scatter plot in the figure depicts a N-shaped relationship between variables, which however turned out to be insignificant when tested empirically using the cubic regression. Hence, it was concluded that in case of Japan the emissions keep rising with an increase in the economic growth, implying that degrowth strategies could have a positive influence on improving environmental quality of Japan.

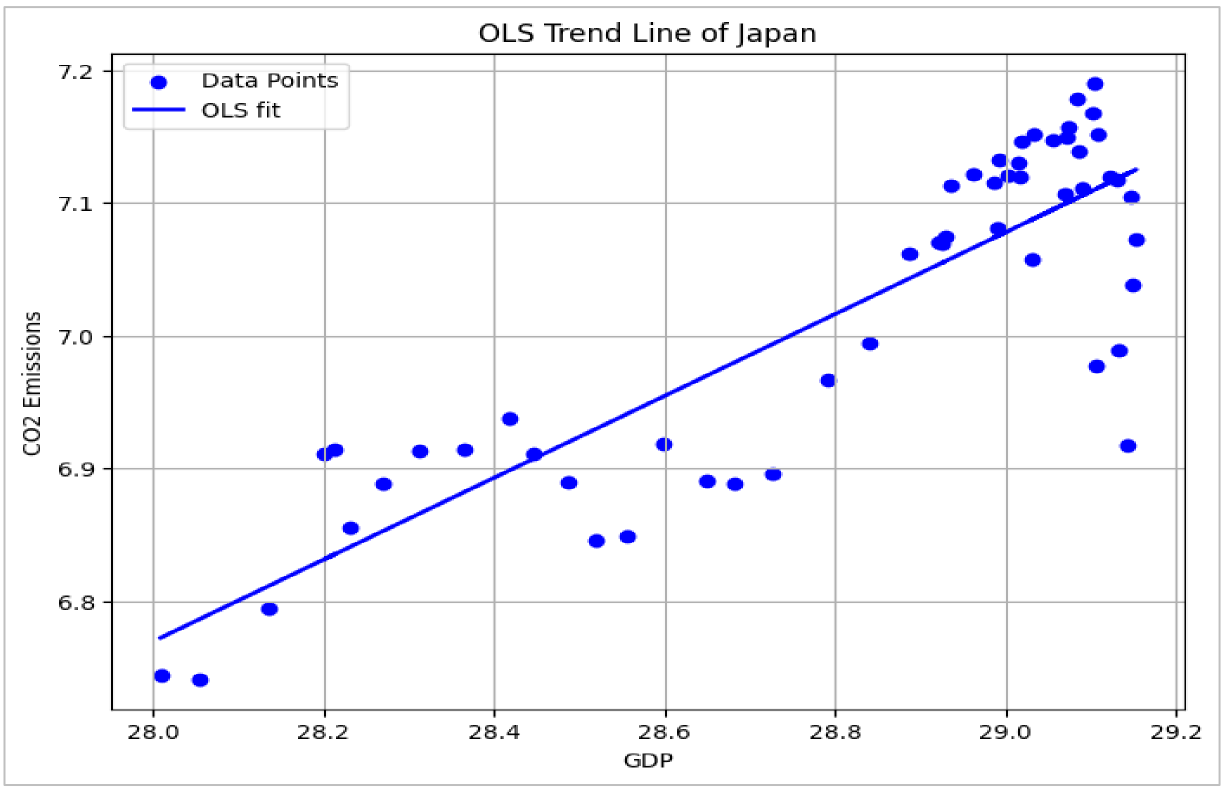


Figure 5.21 Trend of Japan.
Source: Computed by the authors.

5.7 Objective 3

The third objective investigates the difference between energy consumption, economic growth, and emissions level in rural and urban areas for QUAD countries. To achieve this objective, two-stage least square regression methodology was applied on the dataset from the year 1970 to 2022. Based on the results of the applied methodology, following hypothesis was tested:

HO31: There exists significant difference in energy consumption, economic growth, and emissions levels between rural and urban areas in the QUAD countries.

In the first stage of the estimation, the GDP of each country is regressed upon energy consumption, urban population, rural population, population density, and trade volume.

$$GDP = f(EC, Ur, Ru, Pd, Tv) \tag{5.2}$$

Under the assumption that explanatory variables and error terms have a strong correlation, we estimated this equation. In the second stage, CO2 emission is regressed upon energy consumption, urban population, rural population, population density, estimated GDP, and square of estimated GDP to get consistent and efficient estimates.

$$CO2 = f(EC, Ur, Ru, Pd, \widehat{GDP}, \widehat{GDP}^2) \tag{5.3}$$

The results of the first stage regression for individual countries are given below in table 5.12. Following which, a second stage regression was applied for all the QUAD nations.

Table 5.12 Results of first stage regression for QUAD nations.

	lnTV	lnUR	lnRU	lnPD	lnEC	df	R^2
Australia	0.336 (0.00)*	-19.322 (0.10)	-3.478 (0.10)	23.741 (0.09)***	-0.004 (0.93)	51	0.99
India	0.086 (0.00)*	-5.129 (0.00)*	-12.533 (0.00)*	19.748 (0.00)*	0.642 (0.00)*	50	0.99
Japan	0.373 (0.00)*	-3.712 (0.00)*	-0.485 (0.00)*	7.045 (0.00)*	0.077 (0.25)	51	0.99
USA	0.062 (0.24)	-1.276 (0.58)	-0.470 (0.39)	4.085 (0.19)	0.369 (0.01)*	51	0.99

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

5.7.1 *Two-stage Least Square Results*

The results of second stage least square estimates reveal interesting insights about the role of key macroeconomic and socio-economic factors in the rising emissions across QUAD nations. Results of 2SLS are given in table 5.13 for all the QUAD nations. Results of Australia indicate that a 1% increase in the GDP results in 8% rise in the CO2 emissions. Similarly, a 1% rise in urban and rural population leads to a rise in emissions by 27.11% and 4.58% respectively, indicating that demographic growth plays a role in increasing environmental pressures. Conversely, population density exhibits a significant negative impact, indicating that 1% increase in population density leads to a 32.80% decrease in emissions, highlighting the inefficiencies and environmental costs linked to dispersed populations. Energy use plays a significant positive role in degradation of environmental quality, whereas lagged CO_2 emissions underscore the persistence in environmental stress. The findings align with Australia's recent policy commitments to achieve a 62–70% reduction in emissions from 2005 levels by 2035 (Hunt, 2025), all while navigating its historical dependence on fossil fuels.

Likewise, the findings from India indicate a significant positive impact of GDP on the emissions, i.e., a 1% rise in the GDP leads to 12% increase in the emissions. Similarly, a 1% increase in urban and rural population leads to a decrease in emissions by 2.6% and 7.2%, which indicates that demographic shifts beyond urban areas limit sustainability outcomes. However, population density demonstrates a direct significant relationship with emissions, with 1% increase in population density leading to increase in emissions by 10.18%. Further, the analysis reveals that energy use has a significant positive influence on emissions, whereas lagged CO_2 emissions underscore the persistence in environmental stress. The findings reflect the current dynamics of growth and environment in India, highlight the transitional phase characterized by high growth and high emissions development.

Table 5.13 Results of second stage least square estimates for QUAD nations.

	GDP	**GDP^2**	**lnUR**	**lnRU**	**lnPD**	**lnEC**	**lnCO2(-1)**	**D-W Stat**	**df**	**R^2**
Aus	8.088 (0.00)*	-0.134 (0.02)**	27.118 (0.00)*	4.581 (0.01)*	-32.804 (0.00)*	0.311 (0.00)*	0.451 (0.00)*	1.61	50	0.99
India	12.032 (0.00)*	-0.216 (0.00)*	-2.626 (0.08)***	-7.218 (0.02)**	10.189 (0.06)***	1.102 (0.00)*	0.261 (0.02)**	1.88	43	0.99
Japan	13.945 (0.00)*	-0.250 (0.00)*	-3.537 (0.00)*	-0.807 (0.00)*	5.151 (0.00)*	1.054 (0.00)*	0.331 (0.00)*	1.514	42	0.98
USA	-14.001 (0.00)*	0.251 (0.00)*	14.781 (0.00)*	4.080 (0.00)*	-21.541 (0.00)*	0.591 (0.00)*		1.55	47	0.98

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

In the case of Japan, GDP demonstrates a significant positive impact on emissions. Urban and rural population leads to a decrease in emissions, wherein 1% increase in urban and rural population leads to a 3.5% and 0.80% decrease in emissions respectively. Indicating that Japan's sophisticated infrastructure and diminishing rural engagement play a role in reducing emissions. Nonetheless, population density continues to show a positive impact on emissions, a 1% increase in Population density results in 5.15% increase in emissions. On the other hand, energy consumption underscores the significant reliance of Japan on the energy sources and its significant positive impact on emissions. lagged CO_2 emissions underscore the persistence in environmental stress. The findings correspond with Japan's proactive climate strategy, which aims for a 46% reduction in emissions by 2030 and a 60% reduction by 2035, alongside the revival of nuclear energy and the expansion of renewable sources (The Government of Japan, 2024). Also, the results obtained for Japan are similar to those obtained for India, revealing that a similar pattern is being followed in Asia. The findings in case of the USA indicate that a 1% rise in the GDP leads to 14% decrease in the emissions. Similarly, a 1% increase in urban and rural population leads to an increase in emissions by 14.78% and 4.08% respectively; while, population density exhibits a significant negative impact on emissions, indicating that 1% increase in population density leads to a 21.54% decrease in CO2 emissions. Energy consumption plays a significant positive role in environmental degradation by increasing 0.59% emissions for every 1% increase in the consumption of energy. The results confirm that recent advancements in the USA, such as the enactment of the Inflation Reduction Act (2022), have facilitated cleaner growth (IEA, 2023). Nonetheless, recent policy changes have commenced the withdrawal of regulatory standards, which could hinder future emission reductions.

5.7.2 *Residual Diagnosis*

To test the residual diagnostics, three tests were performed namely, autocorrelation test, normality test, and Breusch-Pagan-Godfrey heteroscedasticity test. Autocorrelation was tested using the Q-statistics and correlogram. Thes test results are given in fig 5.14, wherein panel A, B, C, and D refer to Australia, India, Japan, and the USA. The autocorrelation diagnostics for all four nations demonstrate a well-behaved residual structure in each time series model. The computed autocorrelation coefficients for all the countries fluctuate between positive and negative values, and the corresponding Q-statistic remain significant at 5% level of significance, implying no evidence of serial correlation within the residuals. The results indicate that the time series models for each country are appropriately specified, displaying no significant persistence in the residuals. This outcome supports the reliability and robustness of further econometric analysis.

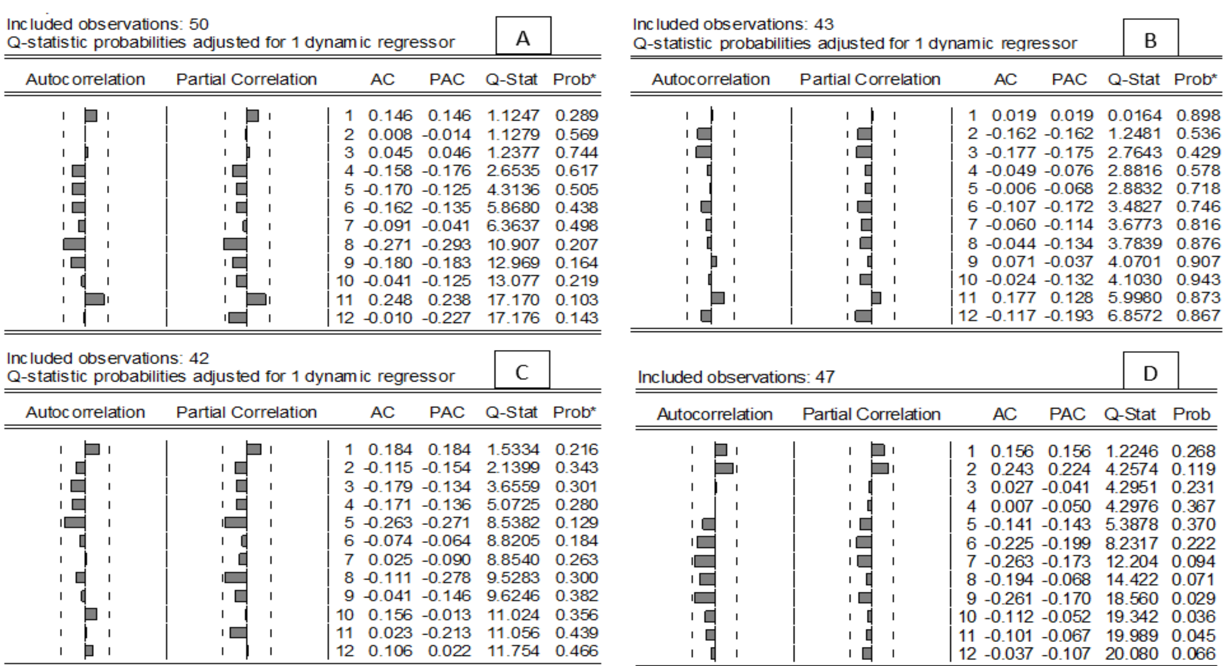


Figure 5.22 Autocorrelation test results for QUAD nations.
Source: Computed by the authors.

Further the residuals were checked for normality using the skewness, kurtosis, and Jarque-Bera test and heteroskedasticity was checked using the Breusch-Pagan-Godfrey test. The test results are given in table 5.14.

The test results indicate that in case of Australia, the skewness value is -0.23 and kurtosis value is 2.41, which depicts that residuals are negatively skewed. Further, Jarque Bera statistics was employed to test the normality in the residuals. The null of JB test states that the residual follows normal distribution, and based on the p-value we can confirm that acceptance of null hypothesis. Additionally, Breusch-Pagan-Godfrey test was utilized to check the presence of heteroscedasticity, the null hypothesis of Breusch-Pagan-Godfrey test states that no heteroskedasticity exists in the model. Based on the test statistics we accepted the null hypothesis as the p-value is not significant at 5% level of significance. Likewise, in the case of India, the test results indicate that the skewness value is 0.13 and kurtosis value is 2.52, which is a desirable statistic for normality. Further, Jarque Bera statistics was employed to test the normality in the residuals. The null of JB test states that the residual follows normal distribution, and based on the p-value accepted the null hypothesis. Additionally, Breusch-Pagan-Godfrey test was utilized to check the presence of heteroscedasticity, the null hypothesis of Breusch-Pagan-Godfrey test states that no heteroskedasticity exists in the model. Based on the test statistics we accepted the null hypothesis as the p-value is not significant at 5% level of significance. Similarly, in the case of Japan, the test results indicate that the skewness value is -0.07 and kurtosis value is 1.79, which indicates that residuals depict a platykurtic distribution. Further, Jarque Bera statistics was employed to test the normality in the residuals. The null of JB test states that the residuals follow a normal distribution, and based on the p-value we accepted the null hypothesis. Additionally, Breusch-Pagan-Godfrey test was utilized to check the presence of heteroscedasticity, the null hypothesis of Breusch-Pagan-Godfrey test states that no heteroskedasticity exists in the model. Based on the test statistics we accepted the null hypothesis as the p-value is not significant at 5% level of significance.

Table 5.14 Residual diagnostics for QUAD nations.

	Australia	India	Japan	USA
Mean	-0.000	-0.000	0.000	-0.000
Median	-0.000	-0.001	0.000	0.000
Maximum	0.025	0.029	0.027	0.027
Minimum	-0.029	-0.030	-0.025	-0.019
Std. Deviation	0.013	0.014	0.014	0.010
Skewness	-0.236	0.132	-0.071	0.033
Kurtosis	2.419	2.529	1.798	2.782
Jarque Bera	1.166 (0.55)	0.522 (0.77)	2.562 (0.27)	0.101 (0.95)
df	50	43	42	47
Breusch-Pagan-Godfrey	0.708 (0.66)	1.824 (0.11)	1.861 (0.10)***	1.656 (0.15)

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

In the case of the USA, the test results depict the skewness value of 0.03 and kurtosis value of 2.78, which is a desirable statistic for normal distribution. Further, Jarque Bera statistics was employed to test the normality in the residuals. The null of JB test states that the residual follows normal distribution, and based on the p-value accepted the null hypothesis. Additionally, Breusch-Pagan-Godfrey test was utilized to check the presence of heteroscedasticity, the null hypothesis of Breusch-Pagan-Godfrey test states that no heteroskedasticity exists in the model. Based on the test statistics we accepted the null hypothesis as the p-value is not significant at 5% level of significance. The visual representation of the normality for all the four nations is given below in fig 5.15.

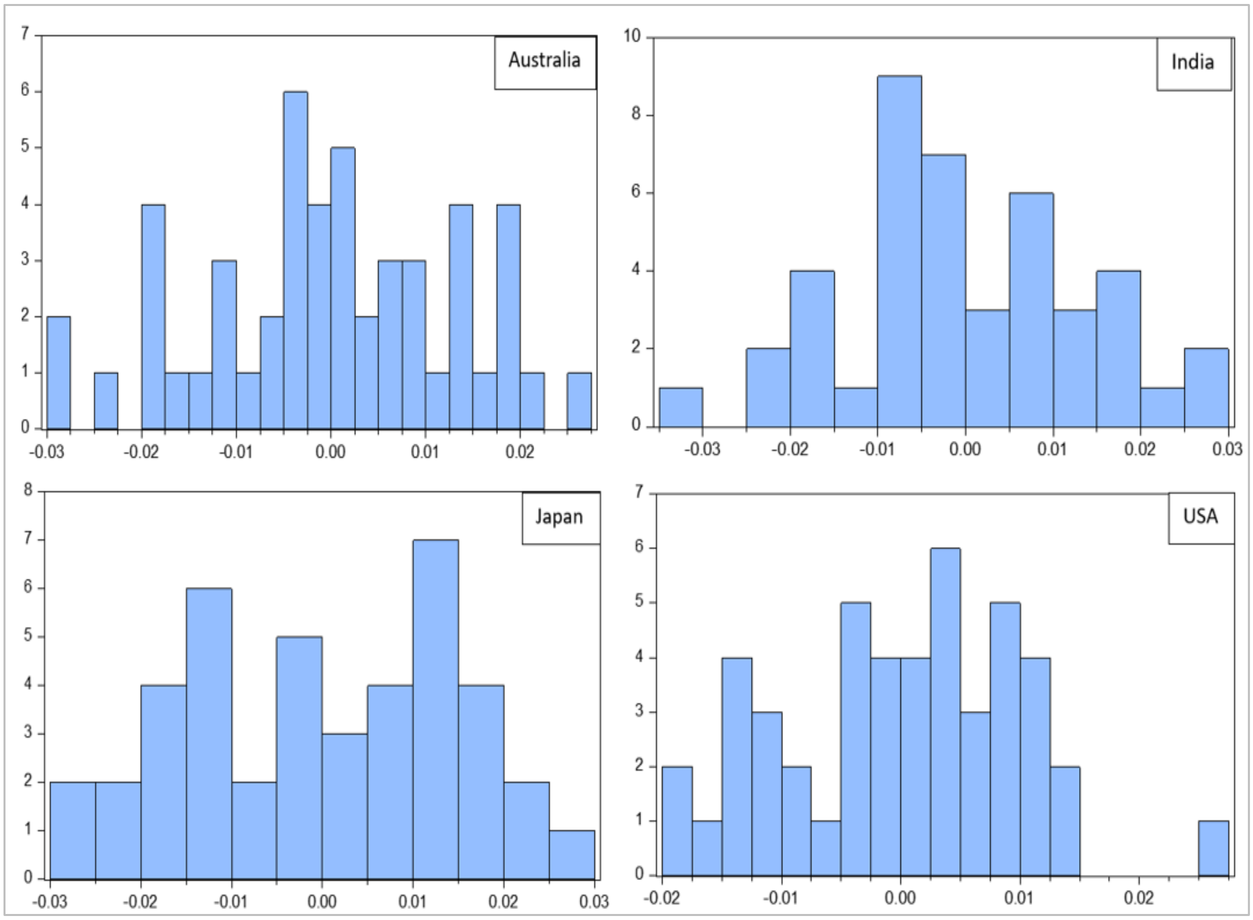


Figure 5.23 Normality test results for QUAD nations.
Source: Computed by the authors.

Hence, we can conclude that residuals of the model do not suffer with autocorrelation, follows normal distribution, and are homoscedastic in nature. Thereby confirming that the assumptions of the Ordinary Least Square models were satisfied.

5.8 Granger Causality

Further Granger causality was tested to check the direction of causation among the variables in the QUAD nations. The findings are given in table 5.15 considering maximum lag of 2 for different nations. The results reveal that in case of Australia, significant unidirectional relationship exists running from GDP to CO2 emissions. In India a significant unidirectional causality runs from CO2 emissions and energy consumption towards GDP. Similarly, in case of the USA a significant unidirectional causality runs from CO2 emissions and GDP towards energy consumption. However, in case of Japan there exists a unidirectional causality running from CO_2 emissions to GDP and bidirectional causality between CO_2 emissions and energy consumption.

Table 5.15 Result of Granger Causality for QUAD nations.

Country	Null Hypothesis	Lags	F-stat
Australia	GDP does not Granger cause CO2 emissions.	1	4.557 (0.03)**
	CO2 emission does not Granger cause GDP.		0.728 (0.39)
	GDP does not Granger cause energy consumption.	2	1.988 (0.14)
	Energy consumption does not Granger cause GDP.		0.370 (0.69)
	CO2 emission does not Granger cause energy consumption.	2	1.212 (0.30)
	Energy consumption does not Granger cause CO2 emissions.		1.32 (0.27)
India	GDP does not Granger cause CO2 emissions.	2	0.475 (0.62)
	CO2 emission does not Granger cause GDP.		4.476 (0.01)**
	GDP does not Granger cause energy consumption.	2	1.754 (0.18)
	Energy consumption does not Granger cause GDP.		4.288 (0.01)**
	CO2 emission does not Granger cause energy consumption.	2	0.748 (0.47)
	Energy consumption does not Granger cause CO2 emissions.		0.922 (0.40)
Japan	GDP does not Granger cause CO2 emissions.	1	0.037 (0.84)
	CO2 emission does not Granger cause GDP.		3.480 (0.06)***
	GDP does not Granger cause energy consumption.	1	0.618 (0.43)

	Energy consumption does not Granger cause GDP.		1.762 (0.19)
	CO2 emission does not Granger cause energy consumption.	1	4.848 (0.03)**
	Energy consumption does not Granger cause CO2 emissions.		4.978 (0.03)**
USA	GDP does not Granger cause CO2 emissions.	2	0.245 (0.78)
	CO2 emission does not Granger cause GDP.		0.876 (0.78)
	GDP does not Granger cause energy consumption.	1	5.309 (0.02)**
	Energy consumption does not Granger cause GDP.		2.037 (0.15)
	CO2 emission does not Granger cause energy consumption.	1	3.841 (0.05)**
	Energy consumption does not Granger cause CO2 emissions.		0.165 (0.68)

Note: Asterisk *, **, *** indicate significance at 1%, 5%, and 10% level of significance.
Source: Computed by the authors.

5.9 Summary of Chapter

Chapter 5 presents the empirical findings on the relationship between CO2 emissions and macroeconomic variables in the QUAD countries from 1970 to 2021. The analysis begins with the trend analysis followed by descriptive statistics and preliminary tests such as unit-root test, correlation heatmap, and VIF tests. The study employs the Structural Vector Autoregressive Model (SVAR) to capture the impact of each variable on the other, and quadratic regression was applied to establish the EKC hypothesis. Additionally, two-stage least square (2SLS) model was employed to estimate the relationships among the variables. The results highlight various key macroeconomic and socioeconomic factors and their impact on the emissions of QUAD nations.

Chapter 6

Conclusion

This chapter presents the concluding remarks of the study, summarizing the key findings, theoretical contributions, practical implications, and future research directions. The study has examined the relationship between Co2 emissions and various economic variables in the context of QUAD economies, incorporating various macroeconomic determinants and utilizing robust econometric techniques. The findings highlight the complex nature of emissions, influenced by factors such as GDP, energy consumption, urban and rural population, trade volume, and population density. Moreover, the cointegration tests establish a long-term relationship between CO2 emission and other macroeconomic variable, reinforcing the significance of managing emissions in fostering sustainable economic development. These insights contribute to a deeper understanding of the role of various macroeconomic factors in managing emissions and provide a basis for more targeted and effective policy interventions.

The chapter is structured as follows: Section 6.1 summarizes the major findings of the study, outlining key empirical results. Section 6.2 revisits the research objectives, assessing the extent to which the study has achieved its aims. Section 6.3 discusses the implications, examining how the findings align with existing economic theories and highlights the practical implications, offering recommendations for policymakers. Lastly, section 6.4 acknowledges the limitations of the study and suggests future research directions. The study consolidates its contributions through this chapter, offering valuable insights for academic research, policy formulation, and economic development strategies.

6.1 Major Findings

This study analyzed the relationship between CO2 emission and various macroeconomic and socioeconomic variables in QUAD nations. The empirical analysis led to several significant findings:

a. **Normality of Data:** The results from the Jarque Bera normality test indicated that the dataset follows a normal distribution for Australia and India. However, in case of the USA and Japan few variables do not fulfill the normality condition. This suggests the use of robust econometric techniques.

b. **Stationarity in the data:** The stationarity of the variables was examined using first generation unit root tests, specifically Augmented Dickey-Fuller (ADF) test and Phillips Perron (PP). The results indicated that variables are stationary at mixed level of integration.

c. **Cyclical movement of CO2 emissions and other variables:** The movement of cycles was captured by employing HP filter and Pearson correlation test. The results depicted that cross-correlation coefficient between the cyclical components of emissions and GDP, fossil fuel consumption, and trade volume was positive, suggesting that emissions are procyclical in nature for all the QUAD nations.

d. **Impact of GDP on emissions through EKC hypothesis:** The relationship between CO2 emissions and GDP was examined using Environmental Kuznets Curve hypothesis. The results depicted the presence of inverted U-shaped association between the parameters for India, Australia, and the USA. Suggesting decoupling of economic growth from environmental degradation through technological innovation, enhanced efficiency, and comprehensive environmental regulations in the nations.

e. **Impact of energy consumption on emissions:** The results from the Two-Stage Least Squares (2SLS) regression analysis reveal that energy consumption has a statistically significant and positive impact on the emission levels in the QUAD countries. This finding underscores the QUADs continuing dependence on energy sources that are emission intensive in nature.

f. **Impact of trade volume on emissions:** The results from the Structural Vector Autoregression (SVAR) model indicate that trade exerts a positive influence on emissions in India, Japan, and the USA. This suggests that trade is a significant driver contributing to increased emission levels in these countries.

g. **Impact of urban and rural population on emissions:** The results from the 2SLS regression analysis demonstrate that both urban and rural population exhibit a significant positive association with emission levels in Australia and the USA, whereas a significant negative association is observed for India and Japan. The results suggest that urban expansion leads to an increase in emissions in developed nations.

h. **Impact of population density on emissions:** The results from the 2SLS regression analysis demonstrate that population density has a positive impact on the emissions levels of Asian countries, suggesting that implementing tailored policies aimed at managing population density could be an effective strategy to mitigate emissions and promote sustainable development in these countries.

6.2 Revisiting the Objectives

This section revisits the core research objectives outlined at the beginning of the study and assesses the extent to which they have been achieved. The study aimed to analyze the relationship between CO2 emissions and various macroeconomic, socioeconomic variables in QUAD economies. The first objective of this research is:

Objective 1: To examine the relationship among energy consumption and economic growth and emissions level.

In objective 1, we tried to analyze the relationship among energy use, GDP, and emissions level in QUAD nations. In order to achieve this objective, we employed HP filter on the dataset of variables such as CO2 emissions (lnCO2), GDP (lnGDP), and Fossil Fuel consumption (lnff) for the time span from 1970 to 2020. The results of the HP filter's application on GDP, CO_2 emissions, and fossil fuel consumption, indicate the existence of a significant cyclical component in these variables. To further validate this, Pearson's correlation coefficients were computed between the cyclical components of GDP and other variables. The analysis confirmed a statistically significant positive correlation, indicating that GDP and CO_2 emissions are procyclical in nature for QUAD nations, which is consistent with the earlier findings of (Sarwar et al., 2021). In the case of the USA and India, a strong procyclical relationship exists among CO_2 emissions and conventional energy consumption. For Japan and Australia, while the cyclical components do not perfectly overlap, they closely track each other and also display a procyclical relationship. This suggests that fossil fuel consumption and CO_2 emissions move in tandem during different phases of the economic cycle in these countries.

The results of SVAR also indicates that GDP and fossil fuel consumption has a positive influence on the emissions level of QUAD nations.

Table 6.1 Hypothesis Testing for Objective 1

	Hypothesis	Finding
H_1	There exists a relationship between energy consumption and economic growth.	There exists a positive relationship between energy consumption and economic growth in QUAD nations except for the USA.
H_1	There exists a bidirectional relationship between energy consumption and economic growth.	In the QUAD nations, bidirectional relationship between energy consumption and economic growth was not found.
H_1	There exists a relationship between energy consumption and emissions.	There exists a positive relationship between energy consumption and emissions.
H_1	There exists a unidirectional relationship between energy consumption and emissions.	A unidirectional relationship was found between energy consumption and emission in case of the USA only.
H_1	There exists a bidirectional relationship between energy consumption and emissions.	A bidirectional relationship was found between energy consumption and emission in case of Japan only.

Objective 2: To test the EKC hypothesis for QUAD countries.

For the second objective, the Environmental Kuznets Curve (EKC) hypothesis was tested for all the QUAD nations using a quadratic regression technique. The dataset employed to run the regression analysis spans from the year 1970 to 2022. Based on the five hypotheses of the EKC model, the occurrence of an inverted U-shaped curve for India, the USA, and Australia was confirmed. The turning point for India is calculated at 30.72, for the USA at 30.21, and for Australia at 28.16. Hence, corroborating with the earlier research findings in the literature (Adebayo et al., 2021; Aldy, 2005; Apergis et al., 2017; 295 Ben Youssef et al., 2016; Bilgili et al., 2016; Boutabba, 2014). For India, the USA, and Australia, $\beta 1$ is positive and significant while $\beta 2$ is negative and significant, signifying an inverted U-shaped trend. It is important to note that the results of quadratic regression in case of Japan are insignificant at 1%, 5%, and 10% level of significance. This indicates that Japan's CO_2 emissions or environmental degradation do not follow the typical EKC trajectory. The result of quadratic regression estimations for Japan was found to be insignificant, hence linear regression was applied. The results of liner regression estimates depicted that linear relationship exists between the variables. This diversity highlights how structure, policy, and technological differences shape each nation's environmental path as they develop.

Table 6.2 Hypothesis Testing for Objective 2

	Hypothesis	Finding
H_1	There exists a relationship between economic growth and emissions.	Economic growth and emissions level follow an inverted U-shaped relationship in Australia, India, and the USA.
H_1	There exists a unidirectional relationship between economic growth and emissions.	Unidirectional relationship between economic growth and CO2 emissions was found for Australia, India, and Japan.

Objective 3: To investigate the difference between energy consumption, economic growth, and emissions level in rural and urban areas of QUAD countries.

The third objective investigates the difference between energy use, GDP, and emissions level in rural and urban areas for QUAD countries. To achieve this objective, two-stage least square regression methodology was applied on the dataset from the year 1970 to 2022. The results of second stage least square estimates reveal interesting insights about the role of key macroeconomic and socio-economic factors in the rising emissions across QUAD nations. Results of Australia indicate that a 1% increase in the GDP results in 8% rise in the emissions. Similarly, a 1% increase in urban and rural population leads to an increase in emissions by 27.11% and 4.58% respectively. The findings from India indicate a significant positive impact of GDP on the emissions, i.e., a 1% rise in the GDP leads to 12% increase in the emissions. Similarly, a 1% increase in urban and rural population leads to a decrease in emissions by 2.6% and 7.2%. Likewise, the findings of Japan indicate that GDP demonstrates a significant positive impact on emissions. Urban and rural population leads to a decrease in emissions, wherein 1% increase in urban and rural population leads to a 3.5% and 0.80% decrease in emissions respectively. The findings in case of the USA indicate that a 1% rise in the GDP leads to 14% decrease in the emissions. Similarly, a 1% increase in urban and rural population leads to an increase in emissions by 14.78% and 4.08% respectively. Further, to test the residual diagnostics, three tests were performed namely, autocorrelation test, normality test, and Breusch-Pagan-Godfrey heteroscedasticity test. The test results depicted that, that residuals of the model do not suffer with autocorrelation, follows normal distribution, and are homoscedastic in nature. Thereby satisfying the assumptions of the Ordinary Least Square model.

Table 6.3 Hypothesis Testing for Objective 3

	Hypothesis	Finding
H_1	There exists a significant difference in emission levels between rural and urban population of the USA.	There is a significant increase in CO2 emissions level when there is an increase in urban and rural population in the USA.
H_1	There exists a significant difference in emission levels between rural and urban population of India.	There is a significant decrease in CO2 emissions level when there is an increase in urban and rural population in India.
H_1	There exists a significant difference in emission levels between rural and urban population of Australia.	There is a significant increase in CO2 emissions level when there is an increase in urban and rural population in Australia.
H_1	There exists a significant difference in emission levels between rural and urban population of Japan.	There is a significant decrease in CO2 emissions level when there is an increase in urban and rural population in Japan.

6.3 Theoretical Implications of the study

The results derived from this study hold significant theoretical implications for understanding the complex relationship between economic growth, energy consumption, and environmental degradation in the QUAD nations. By examining the dynamics among these variables in the light of existing economic theories, the evidence provided by the study validates the well-established theories that provide new insights enriching the empirical literature.

One of the primary contributions of the study is the validation of Environmental Kuznets Curve (EKC) hypothesis. The study empirically validates the inverted U-shaped EKC for India, the USA, and Australia, confirming the classical notion that environmental degradation initially rises with economic growth and later declines once income surpasses a threshold. Thus, strengthening the theoretical validity of EKC hypothesis in both developed and developing economies, therefore the EKC hypothesis is verified empirically in case of India, Australia, and the USA. However, the EKC hypothesis is not empirically verified in case of Japan. This divergence suggests that advanced technological innovations, rigorous environmental regulation, and structural economic characteristics can produce alternative pathways beyond those traditionally captured by the EKC framework. The study further supports the growth hypothesis which suggests that energy use is a critical driver of economic expansion, given the strong correlation between GDP and energy consumption in the QUAD nations. Conversely, the findings of the study show diversion from the neutrality hypothesis given the observed significant linkages between energy consumption and GDP in India, Australia, and Japan. Moreover, the results reveal the coexistence of the Pollution Haven and Pollution Halo hypotheses. The strong positive relationship between growth and emissions in case of India and Australia is supported by the Pollution Haven Hypothesis. This implies that emissions-intensive activities accompany economic growth as established empirically by the study. On the other hand, the case of Japan shows linear emissions trajectory and also the evidence in case of the USA shows that there is inverse relationship between economic growth and emission which supports the Pollution Halo Hypothesis, that advocates FDI can help to improve the environmental quality of host nations. The existence of both types of phenomena within the QUAD suggests that the environmental impact of globalization depends on domestic institutional quality, policy design, and technology adoption. In this study we also analyzed the impact of rural-urban dynamics on the emissions of QUAD nations.

The results of rural–urban dynamics provides novel insights into the Urban Environment Transition Theory (UETT) which says that as cities develop, their focus on environment related challenges change from local and immediate problems to global issues like climate change. The urban population growth in Australia and the USA is linked with higher emissions, which is a result of rapid urban expansion leading to increased carbon intensity. However, India and Japan depict that urban and rural population growth lead to a decrease in the emissions level, suggesting that urbanization when combined with renewable energy use, efficient housing systems, and improved infrastructure can help mitigate environmental impacts. These findings allow for a theoretical extension of the urban environmental transition theory by demonstrating that the environmental effects of urbanization are shaped not only by population growth but also by the quality of energy transition mechanisms accompanying it. The existence of the EKC, neutrality hypothesis, economic growth hypotheses, UETT, and mixed evidence for pollution haven/halo effects confirms that energy-emission-growth nexus are context specific and cannot be explained by a single theory or hypothesis. The results point toward the need for an integrated theoretical approach that combines the insights of economic growth theories, environmental transition frameworks, and globalization-related hypotheses.

6.4 Practical Implications of the study

The findings of this study provide several practical implications for the QUAD nations that align with the broader perspectives of sustainable economic growth and low-carbon economy for policymakers in the QUAD nations. One of the significant findings of this study is the identification of procyclical association of GDP and fossil fuels consumption with CO2 emissions across the QUAD nations. The CO2 emissions cycle and GDP cycles track each other closely. It also highlights the fact of persisting carbon-intensive growth trajectories. Our study finds empirically the existence of CO2 cycle. These findings suggest that like economic business cycle management, there is a growing need to recognize and address CO2 emission cycle. Further, as the QUAD economies move in cycle and the GDP cycles are re-occurring phenomenon despite various policy initiatives; the CO2 emission cycles too seem to be re-occurring in nature and need to be monitored and controlled on regular basis.

There exists a strong positive correlation of CO2 emissions with GDP and Fossil Fuel consumption in the QUAD countries. This finding underscores the need to transform the energy portfolio within QUAD nations towards non-conventional energy sources such as renewables. In this endeavour, the QUAD should also focus on green initiatives. The study further establishes that GDP growth is having positive impact of CO2 emissions. This direct relation can be exploited by policy makers and formulate policies that should promote GREEN GDP. The presence of quadratic relationship between Co2 emissions and GDP in Australia, India, and the USA; and the absence of this relationship in Japan indicates differentiated national pathways, shaped by structural and technological variations. For India, where the EKC turning point has not yet been reached, strict climate regulations, increased adoption of renewable energy, and robust infrastructure investments in clean technology are essential to expedite the transition such as the integrated renewable energy project at Andhra Pradesh which is also the worlds largest renewable energy generation project. The USA and Australia, which are closer to or past their EKC turning points, should concentrate efforts on maintaining and accelerating their progress by integrating advanced green technologies, promoting circular economy practices, and investing in carbon-neutral infrastructure. Such measures will ensure that declining emissions are not reversed in subsequent growth phases. In the case of Japan, the absence of significant EKC results, implies that Japan must continue advancing structural decarbonization policies focusing on renewable integration and technological innovation such as the “Japan’s 7th Strategic Energy Plan, GX 2040 vision”, etc.

As per the findings of the study, the positive impact of GDP and fossil fuel consumption on emissions identified by the SVAR model also reaffirm the importance of integrating environmental externalities into economic decision making in the QUAD nations. Furthermore, the recent evidences of decline in economic activities and CO2 emission levels during COVID-19 and Ukraine-Russia war (Allam et al., 2022; Mohammed et al., 2023; Ronaghi & Scorsone, 2022) suggest that degrowth strategy could be a more feasible strategy to address the issue of climate change and global warming rather than decarbonization. Similarly, heterogenous influence of rural and urban populations on emissions demonstrates the need for country specific policies across the QUAD nations. The result of the current research work indicated that in Australia and the USA, where urbanization significantly drives higher emissions, priority lies in sustainable urban planning, investment in public transport systems, energy-efficient housing, and planned city development can help in mitigating urban CO2 emission levels. Further, the results of the study in the case of India and Japan indicate that the impact of urbanisation on co2 emission levels is negative. However, the population density which was used as a controlled variable in the study was found to be positively impacting the CO2 emissions level in case of both India and Japan. India, being a developing country where we can imagine rapid urbanisation in coming decades, the urbanisation process is not going to increase CO2 emissions level as per our study. Nonetheless, the government agencies must take care of population density in the urban areas as the study indicates positive relation of co2 emissions and population density. Thus, India and Japan present opportunities for promoting sustainable rural development and setting up advanced clean technologies in both urban and rural areas. Hence, the findings of the study demonstrate that while economic growth and development continue to exert substantial influence on the CO2 emissions across the QUAD nations, structural reforms in energy systems, proactive urban and rural planning, and co-ordinated regional initiatives are essential to achieve long-term sustainability.

6.5 Limitation and Future Research

Despite the significant contributions of this study, it is important to acknowledge several limitations that may have influenced the findings and their interpretation. Recognizing these constraints provides a balanced understanding of the research scope and highlights areas for potential improvement in future investigations. Firstly, omission of China is one of the major limitations of the study as it is among the largest contributors of global CO2 emissions. Inclusion of China in future studies can provide a more globally representative perspective on the growth-emission-energy nexus. Secondly, this study examines the aggregate CO2 emissions without distinguishing between different economic sectors. Since emissions vary considerably across industries such as energy, manufacturing, transport, agriculture, and residential services, a sectoral analysis will allow a comprehensive economic and environmental assessment of the nexus along with identification of key emission drivers. This approach will also help policymakers to design more targeted and specific strategies based on sector-specific challenges. Furthermore, the study is constrained by the absence of data reflecting the influence of the COVID-19 pandemic as our study uses the data from 1970 to 2021. The pandemic brought about a sharp, substantial, and unusual shifts in economic activities and energy use, which in turn affected CO2 emission levels drastically. Incorporating this dimension in future research works might provide important insights on the relationship investigated in the study.

By recognising these limitations, the study underscores the inherent complexity of examining the relationship among GDP, energy use, and environmental quality. Addressing these limitations in future research work will not only enhance our understanding but will also strengthen the empirical evidence for effective and targeted climate and energy usage policy in the QUAD.

6.6 Summary of Chapter

This chapter concludes the study by summarizing its key findings, theoretical and practical implications, and avenues for future research. The study focused on the QUAD nations and explored the relationship between CO2 emissions and other macro and socio-economic variables. The findings of the study highlighted the relationship between emissions, economic growth, energy consumption, urban and rural population, trade volume, and population density. The chapter revisited the research objectives and confirmed their fulfilment through empirical evidence. It further discussed the theoretical implications, stressing on how the findings enhance the existing literature and economic theories. Additionally, the study provided policy recommendations for mitigating emissions and supporting sustainable development. Lastly, the limitations of the study were acknowledged along with the proposed future research directions. Collectively, this chapter consolidated the study’s research outcomes and offered valuable insights for academics and policymakers.

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Appendix A (List of Publications):

S.No.	Type (Year)	Title	Journal	Indexation
1.	Research Article	Understanding the cyclical patterns of carbon dioxide emissions to mitigate climate change: evidence from the QUAD countries. **(2024)** DOI: https://doi.org/10.1016/j.jclepro.2023.140129	Journal of Cleaner Production	SCIE, ABDC-A, Q1 (IF: 10.7)
2.	Research Article	CO2 emissions response to GDP and crude oil price shocks: evidence from India and China using SVAR Model. **(2025)** DOI: https://doi.org/10.1016/j.sftr.2025.100479	Sustainable Futures	ABDC, Q1, ESCI (IF: 6.7)
3.	Research Article	Managing Emissions and Mitigating Global Warming through Collaborative Emission Control: Empirical Evidence from QUAD Countries. (**2026**) DOI: https://doi.org/10.1002/sd.70878	Sustainable Development	ABDC, Q1, SSCI (IF: 9.3)

Appendix B (Papers Presented in Conferences):

S.No.	Paper Title	Year	Conference Name and Venue
1.	Navigating Sustainability: How Innovation and Macro Trends Influence GHG Emissions.	2026	8th Pan-IIT International Conference on Financial Markets and Corporate Finance. **(IIT Madras, India).**
2.	Can India and China Learn from Japan? Revisiting the Energy-Economy-Emission Nexus.	2026	4th Asia-Pacific Conference on Economic Growth and Stability 2026. **(Asian Economic Letters)**
3.	Revisiting Status of Emissions-Macroeconomy Association in India: An ARDL Bounds Testing Approach with GST Inclusion.	2026	Two-day National Conference on "GST Reforms: Transforming India's Economic Landscape. **(IIT, Jammu, India)**
4.	Managing Emissions and Mitigating Global Warming through Collaborative Emission Control: Empirical Evidence from QUAD Countries.	2025	4th World PhD Students Symposium “Meeting the Challenges of Climate Change 2025”. **(Hamburg University of Applied Sciences, Hamburg, Germany)**
5.	The impact of urbanization and macroeconomic variables on managing GHG emissions in the QUAD countries: evidence from STIRPAT model.	2025	International Conference on Emerging issues in Commerce, Economics & Management. **(Hansraj College, University of Delhi, India)**
6.	Pathways to achieve Sustainable Emission Reduction in India.	2025	National Conference on Sustainable Practices for Environmental Remediation. **(Thapar institute of Engineering and Technology, India)**
7.	CO2 Emissions Response to GDP and Crude Oil Price Shocks: Evidence from Top ASIAN Emitters using SVAR Framework.	2024	International Conference on Renewable Energy and Sustainable Technologies. **(Jamia Milia Islamia, India)**

Matali Mahajan

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