A Study of the Interrelationship among Energy, Economy and Environment

Thesis

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in ECONOMICS

By

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Candidate's Declaration

I, hereby, certify that the thesis titled "A Study of the Interrelationship among

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The matter presented in this thesis has not been submitted elsewhere in part or fully

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Prof. Nand KumarDepartment of Humanities
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...It is impossible to start....

It gives me an immense pleasure to express my gratitude to all those who supported me and made their contributions in making this research a success. First and foremost, I must acknowledge and thank The Vishnuji and Hanumanji for their blessings, protection and guidance throughout this work. I could have never accomplished this work without the faith that I have in the Almighty.

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For any error or inadequacy that may remain in this work, the responsibility is, of course, solely mine.

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ABSTRACT

The intricate interplay among energy, economy, and environment constitutes a fundamental axis that significantly impacts sustainable development on a global scale. This research examines the coupling coordination of the 3Es through an extensive analysis of case studies from India, the United Kingdom, and Germany, covering various periods and contexts. The results underscore the intricate interplay between developmental trajectories, energy policies, and environmental strategies in shaping sustainability outcomes. In India, from 2006 to 2018, the coupling coordination index (CCI) exhibited notable variations, rising from 0.4, indicative of mild disorder, in 2006 to 0.6049, representing primary coordination, in 2015, before experiencing a decline to 0.579, which reflects a state of barely coordinated, by 2018. This trajectory was shaped by concerted initiatives aimed at broadening energy access, sustaining economic growth, and diminishing energy intensity. Nonetheless, the nation's dependence on coal for more than 60% of its electricity production has resulted in considerable greenhouse gas emissions, as demonstrated by the decrease in the Environmental Performance Index (EPI) to 0.306 in 2018. The contribution of renewable energy to the total energy demand stands at a modest 5%, with substantial obstacles in financing, characterised by elevated debt costs ranging from 12% to 14%, alongside challenges related to land availability that impede advancement.

Analysis of data from the United Kingdom spanning from 1965 to 2021 indicates a robust positive correlation between GDP, manufacturing, and energy consumption with CO2 emissions, observable in both short-term and long-term contexts. Notwithstanding the notable advancements achieved in diminishing emissions by 43% from 1990 to 2020, fossil fuels continued to represent a substantial 76% of the energy composition in 2021. The proportion of

renewable energy sources, while experiencing an increase from 4% in 1990 to 13% in 2021, continues to be inadequate in mitigating the environmental repercussions associated with emissions from industrial activities and transportation. Policy reforms have facilitated decarbonisation; however, to meet the Sixth Carbon Budget's objective of a 78% reduction in emissions by 2035, it is imperative to expedite the adoption of renewable energy sources, with a specific focus on offshore wind, aiming for a capacity of 40 GW by 2030. The examination of Germany's situation from 1970 to 2021 elucidates the complexities associated with industrial emissions and transportation in the endeavour to mitigate CO2 emissions, notwithstanding the considerable advancements in renewable energy implementation. The data indicated a positive correlation between CO2 emissions and both energy consumption and air freight transport, whereas the influence of renewable energy on emissions reduction was found to be statistically insignificant. Nuclear energy, which was originally advocated as a more environmentally friendly option, reached its zenith in 1985. However, following the Fukushima disaster and subsequent societal opposition, it experienced a downturn after 2012, culminating in its gradual discontinuation. As of 2021, renewable energy sources represented 42% of total electricity generation, while coal maintained a significant contribution of 28%. This highlights the urgent necessity for accelerated coal phase-out initiatives and the implementation of more stringent industrial emission regulations.

The analysis of these studies reveals significant systemic challenges in achieving a harmonious balance between economic growth and environmental preservation. The reliance on traditional energy sources, including coal and oil, persists in intensifying environmental degradation. Industrial emissions constitute 50% of greenhouse gas emissions in nations such as India, whereas transport and aviation play a substantial role in the emissions profile of developed

countries like Germany and the UK. The complexities presented by these challenges demand immediate and focused interventions, particularly the implementation of Carbon Capture, Utilisation, and Storage (CCUS) technologies. CCUS has surfaced as a credible approach for mitigating emissions from sectors that are challenging to decarbonise, including steel, cement, and thermal power. In the context of India, the incorporation of carbon capture, utilisation, and storage (CCUS) technologies within coal-fired power generation facilities has the capacity to diminish greenhouse gas emissions by an estimated 30% to 40%. On a global scale, the implementation of such technologies presents the opportunity for significant economic efficiencies, with potential cost savings ranging from \$60 to \$100 for each tonne of carbon dioxide captured. Concurrently, the expansion of renewable energy sources, particularly offshore wind and urban solar initiatives, has the potential to enhance energy diversification and mitigate reliance on fossil fuels. Denmark's achievement in wind energy, reaching a 72% share of renewable electricity in 2020, serves as a model that can be replicated. To attain sustainable development, nations must implement comprehensive strategies that incorporate renewable energy sources, enhance energy efficiency, and utilise carbon capture, utilisation, and storage technologies. The shift towards a sustainable energy future necessitates a careful equilibrium among economic development, energy security, and the preservation of the environment. This study highlights the critical necessity for synchronised international efforts, innovation in technology, and well-structured policy frameworks to realise the ambitious objectives of carbon neutrality and sustainable development.

CONTENTS

Certificate			i
Acknowledgen	nen	ts	iii
Abstract			V
Contents			viii
List of Figures			Х
List of Tables			xii
Nomenclature			xiv
CHAPTER I	:	INTRODUCTION	1-65
1.1		Background	1
1.2		Types of Energy Resources	4
1.3		Fossil Fuel	7
1.4		Renewable Energy sources	10
1.5		Nuclear Energy	15
1.6		Energy Production and Consumption Patterns	20
1.7		Energy Market Dynamics	26
1.8		Energy Prices and Economic Growth	32
1.9		Energy Policy Frameworks	38
1.10		National Energy Policies	42
1.11		International Energy Agreements	45
	ĺ		

1.12		Economic Incentives and Regulations	49
1.13		Subsidies and Tax Incentives	52
1.14		Carbon Pricing Mechanism	57
1.15		Technological Innovation and Investment	58
1.16		Motivation of the Study	63
1.17		Statement Problem	65
1.18		Signification of the Study	65
CHAPTER II	:	Literature Review	66-88
2.1		The assessment of different energy system	66
2.2		The relationship between Economic growth and energy sources	67
2.3		Energy system and sustainable development	67
2.4		The validity of EKC Hypothesis	68
2.5		Research gap	86
2.6		Research Question	87
2.7		Objectives	88
2.8		Publication	88
CHAPTER III	:	Methodology	89-92
3.1		Data Collection	89
3.2		Modelling the Interrelationship	90
3.3		Analysis Techniques	91
3.4		Data Interpretation and Discussion	92
3.5		Ethical Considerations	92

CHAPTER IV	:	The Nexus between Energy, Economy and Environment	93-114
4.1		Analysis of the relationship between three Es	93
4.2		Case Study for assessing the relationship of Energy, Economy, and Environment with a Special Reference to India	
4.3		Literature Review	98
4.4		Materials and Methods	102
4.5		Results and Discussions	107
4.6		Energy Transition Challenges	103
4.7		Conclusion	113
CHAPTER V	:	The impact of Conventional and Non- Conventional sources of Energy	115-13
		on Environment and Economy	
5.1		The impact of Energy on Environment and Economy	115
5.2		Case study of analysing the long run relationship between CO2 emissions and Energy use of United Kingdom	121
5.3		Literature Review	121
5.4		Methodology	125
5.5		Result and Discussions	126
5.6		Conclusion	130
CHAPTER VI	:	The Combination of Technology and Policy mix that ensure Reliable, Affordable and Clean Energy	131-164
6.1		Technological solutions for Reliable, Affordable and Clean Energy	131
6.2		Case Study on CCUS technology can enhance the COP-28 Carbon Neutrality Target of India: Evidence from Fuzzy Analytical Hierarchy Process	136

6.3	Literature Review	137
6.4	Materials and Methods	144
6.5	Results and Discussions	150
6.6	Conclusion	163
CHAPTER VII	: Policies and Strategies for Energy, Economy and Environment	165-184
7.1	Economic Policies	165
7.2	Case study for analysis of renewable energy and economic growth of Germany	168
7.3	Literature Review	169
7.4	Methodology	174
7.5	Results and Discussions	175
7.6	Conclusion	182
CHAPTER VIII	Conclusion, Recommendation and Future Scope	185-202
REFERENCES		203
Appendices		229

List of Figures

Figure	Description	Page
No.		No.
4.1	The trend of the comprehensive index of 3Es in India	109
4.2	Trends of Coupling of Energy-Economy(XY)	110
4.3	Trends of Coupling of Energy-Environment	110
4.4	Trends of Coupling of Economy-Environment (YZ)	111
4.5	Trends of Coupling of Energy-Economy-Environment(XYZ)	111
4.6	Combine trends of Coupling of Energy-Economy(XY), Energy-Environment(XZ), Economy- Environment(YZ), and Energy-Economy-Environment(XYZ)	111
4.7	The Trends of development of India from 2006 - 2018	112
5.1	CO2 emission	122
5.2	Energy Usage	123
5.3	CUSUM test	129
6.1	Model construction	145
6.2	Graph of Fuzzy Triangle Set	153

6.3	Comparison of different parameters	155
6.4	BAU estimates of CO2	157
6.5	Total energy mix of India	157
6.6	BAU estimates of renewable energy generation and electricity demanded	157
6.7	BAU estimates of total energy demand	159
7.1	CUSUM Test	181
7.2	Business usual estimates	182

List of Tables

Table No.	Description	Page No.
2.1	Summary of the literature review	69
4.1	Energy Data	102
4.2	Economy Data	104
4.3	Comprehensive Index of Energy, Economy, and Environment	107
4.4	Comprehensive Index of Energy, Economy, and Environment	108
4.5	Coupling and Coordination Development degree of energy, economy and environment of India	110
5.1	ADF unit root test	126
5.2	ARDL bound test	127
5.3	ARDL short run	127
5.4	ARDL long run	128
5.5	Diagnostic tests	128
5.6	Granger causality test	129
6.1	Summary of various studies for AHP and other methods used in CCUS analysis by researchers	142

6.2	AHP pairwise comparison scale	147
6.3	Fuzzy comparison scale	148
6.4	Random Consistency Ratio	149
6.5	CCUS facilities in India	150
6.6	Correlation matrix	151
6.7	Descriptive stats	151
6.8	Pair wise comparison	153
6.9	Value wise comparison of the parameter	154
7.1	List of Variables	175
7.2	ADF Unit Root Test	176
7.3	Auto Regressive Distributed Lag bond test for co-integration	177
7.4	Auto Regressive Distributed Lag Short-Run Estimates	177
7.5	Auto Regressive Distributed Lag Long-Run Estimates	178
7.6	Diagnostic tests	179
7.7	Granger Causality Test	180

Nomenclature

Nomenclature:

 α Deterministic term n Time index

 β Estimated parameter R Real part of complex variables

γ Slope Coefficient S Smoothing operator

 ϑ Coefficient S_t Partial sum of OLS residuals

 ϵ Error terms s Scale

 ε_t Stationary disturbance with variance t Time

 ω Estimator u_t Stationary error term with variance

C Cointegration W Wavelet

k Single frequency selected for the y Casualty

approximation

liquefied petroleum gas

Acronyms

LPG

GDP CIS Gross development product Commonwealth of Independent States **ARDL** Autoregressive Distributed Lag **FMOLS** Fully modified ordinary least squares **FBTY** Fourier Bootstrap Toda-Yamamoto **ECM** Error correction model EKC Environmental Kuznets Curve QLF Quadratic functional form

VECM

Vector error correction model

BRICS	Brazil, Russia, India, China, and South Africa	DOLS	Dynamic ordinary least square
OECD	Organization for Economic Co-operation and Development	OLS	Ordinary least squares
GCC	Gulf Cooperation Council	LM	Lagrange Multiplier
NE	Nuclear Energy	TYGC	TodaYamamoto Granger Causality
KPSS	Kwiatkowski-Phillips-Schmidt-Shin	AMG	Classical algebraic multigrid
VAR	Vector auto regression	ECM	Error correction model
SO_2	Sulphur dioxide	NOx	Nitrous Oxide
CO2	Carbon dioxide	ADF	Augmented Dickey-Fuller test
GLS	Generalized least squares		

CHAPTER 1

INTRODUCTION

1.1 Background

Energy, Economy and Environment are the three wheels to reach the goal of development of any country. We all need energy that support social and economic development, especially in developing countries, to ensure a better quality of life. However, during the generation of more energy, we need to ensure that the environment remains protected for this there is a need to know the existing relationship between the energy, economy and environment.

Therefore, 3Es have been a research hotspot in the past years, and have gained importance due to the era of sustainable development. It is important to know the relationship of the three Es to reach the desired equilibrium. The SDG7 affordable and clean energy, SDG12 responsible consumption and production, and SDG13 Climate action can only be reached when all the three Es balances. There exist a complex relation between the energy, economy, and environment in which they interact, promote and limit each other but through proper policy and coordination between them sustainable development can be achieved.

■ Importance of the Interrelationship

The complex interaction between energy, economy, and the environment is critical in the context of sustainable development. This triadic nexus is the foundation of modern societal progress, as the energy industry promotes economic expansion while also influencing environmental sustainability. Understanding the intricacies of this interaction is crucial for governments,

corporations, and academics who want to balance economic progress and environmental stewardship.

Energy is the cornerstone of economic activity, powering companies, transportation, and homes. The availability and price of energy supplies have a direct impact on economic productivity, competitiveness, and growth. However, the extraction, production, and consumption of energy, particularly fossil fuels, have serious environmental consequences. Greenhouse gas emissions, air and water pollution, and natural resource depletion are all contributing factors to global climate change and biodiversity loss. As a result, the pursuit of economic growth through energy exploitation frequently causes severe environmental deterioration, creating a difficult trade-off between economic and environmental aims.

4 Challenges with the Interdependence of three Es

The interconnection of energy, economics, and environment, also known as the "three Es," poses a complex set of difficulties that are essential to modern global policy discussion. One of the most significant difficulties resulting from the interconnection of energy, economy, and environment is the incompatibility of economic expansion with environmental sustainability. Historically, economic growth has been directly linked to rising energy use, notably from fossil fuels, resulting in considerable environmental deterioration. The economic imperative to grow frequently prioritises short-term advantages over long-term environmental health, resulting in a continual conflict between economic goals and environmental conservation efforts. This difficulty is exacerbated by the fact that many economies, particularly those in developing nations, rely significantly on carbon-intensive industries, making the shift to sustainable energy sources both expensive and complicated.

Resource scarcity and energy security are also key issues in the framework of the three Es. As global energy consumption rises due to population expansion and economic development, the pressure on finite natural resources increases. This not only worsens environmental degradation, but also jeopardises economic stability due to variable energy costs and the possibility of resource wars. Ensuring energy security while moving to cleaner energy sources necessitates significant investment in infrastructure, technology, and innovation, often against the backdrop of uncertain economic returns and geopolitical dangers. Furthermore, the uneven distribution of energy resources around the world makes it more difficult to develop a balanced and equitable approach to energy, economics, and the environment.

Managing externalities is another significant issue at the intersection of the three Es. Energy production and consumption have considerable negative externalities, including air and water pollution, greenhouse gas emissions, and habitat destruction. These environmental costs are frequently underestimated in market prices, resulting in market failures that disguise the true cost of economic activity. This gap not only jeopardises environmental sustainability but also distorts economic decision-making, encouraging ongoing reliance on unsustainable energy sources. Addressing this issue needs the deployment of policies that internalise environmental costs, such as carbon pricing, taxes, or cap-and-trade systems, which can match economic incentives with environmental objectives.

A further major difficulty in the three Es principle is technological and infrastructure lock-in. Many economies rely on existing energy systems and infrastructures based on fossil fuels. This lock-in effect makes it difficult to move to more sustainable energy sources since it necessitates significant financial commitment, legislative support, and social adaption. The inertia of current technologies and infrastructures can stymie the adoption of renewable energy and energy-efficient practices,

continuing environmental degradation and impeding economic growth. To support the proliferation of clean technology, this challenge requires strategic planning, public-private sector collaboration, and long-term investment in R&D.

1.2. Types of Energy Resources

Energy resources are categorized according to their accessibility, ecological effects, and potential for renewal. Broadly, they fall into two categories: non-renewable and renewable resources. Each category encompasses various subtypes, characterized by their origin, utilization processes, and sustainability considerations. Here, I provide a comprehensive overview of these classifications. Energy resources are classified based on their availability, environmental impact, and renewability. Broadly, they fall into two categories: non-renewable and renewable resources. Each category encompasses various subtypes, characterized by their origin, utilization processes, and sustainability considerations. Here, is a comprehensive overview of these classifications.

a. Non Renewable Energy Resources

Finite in nature, non-renewable energy resources are formed over millions of years through intricate geological processes. This category of resources is finite within a human timeframe, as the rates of extraction and consumption significantly surpass their natural replenishment rates. The burning of these resources typically results in considerable carbon emissions, which play a role in climate change and environmental degradation.

Fossil Fuels: Fossil fuels, encompassing coal, oil, and natural gas, are the primary non-renewable energy sources on a global scale. The formation of these resources occurs through the anaerobic decomposition of ancient organic matter, particularly from plant and marine organisms, subjected to high pressure and temperature over extensive geological periods. Fossil fuels possess a high energy density, rendering them suitable for applications with

significant energy demands. However, their combustion results in the emission of greenhouse gases and pollutants, which present considerable risks to both the environment and public health.

Nuclear energy: Nuclear energy originates from the process of nuclear fission, where heavy atomic nuclei, such as uranium-235 or plutonium-239, are divided to release a significant amount of energy. Nuclear power stands out due to its significant energy production while producing minimal direct carbon emissions. Nonetheless, it produces radioactive waste that has extended decay periods, necessitating intricate and enduring waste management strategies. Moreover, the issues surrounding nuclear accidents and the spread of weapons pose significant regulatory and safety challenges.

b. Renewable Energy Sources

Renewable energy resources possess an intrinsic sustainability, originating from natural processes that are consistently replenished over relatively brief timescales. These resources typically have a reduced impact on the environment, generating minimal to no greenhouse gases or other pollutants while in use. Nonetheless, certain renewable technologies rely on geographic, climatic or temporal factors, which may influence their reliability and implementation.

- Solar energy is harnessed from the sun's radiation through the use of photovoltaic (PV) cells or solar thermal systems. This energy source is remarkably abundant and widely accessible across the globe. Although solar energy production holds significant promise, it can be inconsistent due to daily and seasonal fluctuations, which requires the implementation of storage solutions or hybrid systems to ensure a reliable supply.
- **Wind energy** is captured using wind turbines, which transform the kinetic energy of the wind into either mechanical or electrical energy. This approach demonstrates significant efficacy in

areas characterized by stable wind patterns, including coastal regions and open plains. Wind energy can exhibit spatial variability and is sometimes subject to criticism regarding its visual impact and potential effects on local wildlife, particularly concerning bird and bat populations.

- **Hydropower energy** harnesses the kinetic energy generated by flowing or falling water, usually through the use of dams or run-of-river systems. This is a well-established and extensively utilized renewable energy source capable of delivering a dependable base load supply in areas with adequate water resources. Nonetheless, large-scale dams associated with hydropower initiatives can significantly impact ecosystems, modify water quality, and displace communities, raising various social and environmental issues.
- ♣ Biomass energy is derived from organic materials such as wood, agricultural residues, and specific energy crops. Biomass can be directly burned for heat or transformed into biofuels via biochemical methods, including fermentation or anaerobic digestion. While biomass is a renewable resource, it requires careful management to prevent negative effects on land use, food security, and carbon emissions.
- Geothermal energy harnesses the Earth's internal heat, which can be accessed through natural features like hot springs and geysers, or through engineered geothermal systems. Geothermal plants offer reliable, base-load power generation while occupying a minimal geographic area; however, their implementation is restricted to regions with tectonic activity. Possible environmental consequences encompass the emission of trace greenhouse gases and the potential for induced seismic activity in specific contexts.

♣ Marine energy encompasses both tidal and wave energy, which are generated from the movement of ocean waters influenced by gravitational forces and wind. Tidal energy demonstrates a high level of reliability, attributed to its predictable tidal cycles, whereas wave energy exhibits greater variability. Technological advancement in marine energy is progressing, as issues concerning marine environment durability, ecological effects, and installation expenses are actively being tackled.

1.3. Fossil Fuel

Fossil fuels, which include coal, oil, and natural gas, have played a crucial role in the development of modern industrialized economies throughout history. Their elevated energy density, convenience of transport, and comparatively low production costs (relative to renewables until recently) facilitated swift economic growth, increased productivity, and enhanced energy security. Nonetheless, the environmental impacts of fossil fuel use are significant, especially regarding greenhouse gas emissions and other pollutants, loss of biodiversity, and depletion of resources. The simultaneous effects on economic and ecological systems are under growing examination, particularly as worldwide priorities evolve towards sustainability and climate resilience. This analysis delves into the intricate connections among fossil fuels, economic reliance, and the deterioration of the environment.

a. Economic Impact of Fossil Fuels

Economic Growth and Industrialization

The presence of fossil fuels played a pivotal role in driving the Industrial Revolution and the ensuing phases of swift economic expansion, allowing nations to enhance their manufacturing capabilities, transportation systems, and infrastructure development. The energy intensity of fossil

fuels has equipped industries with the necessary power for large-scale production, leading to cost reductions and enhanced productivity. The role of oil has been pivotal in shaping the global transportation sector, whereas natural gas has gained significant importance in electricity generation and as a fundamental resource for chemical industries.

Job Creation and Income Generation

The fossil fuel sector continues to be a major source of employment worldwide, especially in nations abundant in resources. It generates significant government income via taxes, royalties, and exports. In countries such as Saudi Arabia, Russia, and Venezuela, oil exports play a crucial role in shaping national economies, providing essential funding for public services, infrastructure, and social welfare initiatives. Furthermore, fossil fuels enable downstream industries, including petrochemicals and heavy manufacturing, thereby indirectly sustaining millions of jobs across the globe.

♣ The Dynamics of Energy Security and Geopolitical Power

Fossil fuel resources provide significant geopolitical influence, impacting alliances and occasionally leading to conflicts. Countries abundant in resources wield significant power in global markets, as demonstrated by the Organization of Petroleum Exporting Countries (OPEC), which manages oil production to affect pricing. Nonetheless, reliance on fossil fuel imports can expose nations to price fluctuations, as evidenced by past oil crises and recent interruptions in petrol supply. The fluctuations present considerable challenges for economies reliant on fossil fuels, affecting inflation rates, trade balances, and the stability of currencies.

Economic Fragility and Transition Expenses

With the growing emphasis on decarbonisation in global policy, economies reliant on fossil fuels encounter significant challenges. Moving away from fossil fuels involves significant structural

changes and possible economic challenges, particularly regarding job losses, diminished asset value for stranded resources, and shifts in investment patterns. The risks are especially pronounced in areas where fossil fuels serve as both an economic cornerstone and a significant component of the labour market, highlighting the need for just transition policies to assist impacted workers and communities.

b. Effects of Fossil Fuels on the Environment

Emissions of Greenhouse Gases and Climate Change

The combustion of fossil fuels stands as the primary contributor to human-induced greenhouse gas emissions, accounting for around 75% of global CO₂ emissions. The emissions play a significant role in global warming, leading to more frequent and intense extreme weather events, rising sea levels, and disruptions in ecosystems. The total environmental costs, frequently overlooked, are considerable, with projected economic losses from climate-related disasters increasing each year. The reliance on fossil fuels, which are high in carbon emissions, poses significant obstacles to achieving global climate objectives, including the goals set forth in the Paris Agreement aimed at restricting temperature increases to 1.5°C above pre-industrial levels.

♣ The Impact of Air Pollution on Public Health

The combustion of fossil fuels emits a range of pollutants, such as sulphur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM_{2.5}), and volatile organic compounds (VOCs), which present significant health hazards. Air pollution exposure is associated with respiratory and cardiovascular diseases, cancer, and premature mortality, with health costs frequently impacting vulnerable populations. According to estimates from the World Health Organization, outdoor air pollution is responsible for approximately 4.2 million premature deaths each year, primarily due to the

combustion of fossil fuels. The health impacts have considerable economic consequences, leading to higher healthcare costs and diminished workforce productivity.

Contamination of Water and Soil

The extraction and processing of fossil fuels, especially through coal mining and hydraulic fracturing for natural gas, often result in contamination of soil and water resources. Contaminants like heavy metals, fracking chemicals, and oil spills compromise ecosystems and have the potential to infiltrate food and water sources. Oil spills can lead to catastrophic consequences for marine ecosystems, as demonstrated by incidents such as the Deepwater Horizon spill. Additionally, polluted land frequently renders itself unfit for farming or human settlement, exacerbating financial setbacks for the impacted areas.

Deterioration of Ecosystems and Decline in Biodiversity

The extraction and combustion of fossil fuels have resulted in extensive deforestation, habitat destruction, and fragmentation of ecosystems. The practices of coal mining, especially mountaintop removal, along with oil extraction in vulnerable regions like rainforests and the Arctic, pose significant risks to biodiversity and jeopardise various species. The degradation interferes with essential ecosystem services that are crucial for human well-being, including water filtration, soil fertility, and carbon sequestration. The decline in biodiversity presents both a conservation challenge and an economic concern, impacting industries such as agriculture, fisheries, and tourism.

1.4. Renewable Energy Sources

Renewable energy stands as a fundamental element of sustainable development, providing a viable alternative to fossil fuels that can address climate change, decrease pollution, and enhance energy security. Various sources, including solar, wind, hydropower, biomass, and geothermal energy,

offer a range of low-carbon alternatives that have the potential to significantly impact economies and enhance environmental health. The implementation of renewable energy sources involves a complex interaction of economic benefits, obstacles, and ecological advantages. This study investigates the influence of renewable energy on economic development, employment sectors, energy stability, and ecological health, highlighting the crucial contribution of renewables in promoting a sustainable future.

a. The Economic Impact of Renewable Energy

Economic Expansion and Investment Prospects

The rise of renewable energy has catalyzed substantial global investment, positioning it as one of the most rapidly expanding sectors within the energy market. Recent data from the International Renewable Energy Agency (IRENA) indicates that global investments in renewable energy have surpassed \$300 billion, with significant growth observed in technologies like solar photovoltaics (PV) and wind power. This influx of capital not only invigorates economic activity but also promotes innovation across various sectors, including manufacturing, materials science, data analytics, and artificial intelligence in grid management. Renewables are driving the emergence of innovative business models, including energy-as-a-service, distributed generation, and microgrid systems, which in turn are expanding economic participation.

Employment Generation and Workforce Evolution

The renewable energy sector has significantly contributed to job creation. Recent estimates indicate that over 12 million individuals globally are engaged in the renewable energy sector, with the solar and wind industries at the forefront of job creation. Jobs in the renewable sector are varied, encompassing areas such as installation, manufacturing, operations, and the advancement of new technologies. These positions typically demand specialised skills and provide consistent,

long-term job opportunities in contrast to the fluctuating nature seen in fossil fuel sectors. The shift towards renewable energy necessitates the implementation of reskilling initiatives to prepare workers from conventional energy industries with the competencies required for renewable technologies, highlighting the importance of forward-thinking labour policies to guarantee an equitable transition.

■ Distribution of Authority and Accessibility to Energy

Renewable energy promotes decentralized power generation, lessening dependence on large, centralized power facilities and supporting electrification in rural and off-grid areas. Solar micro grids and standalone systems have demonstrated significant impact in energy-deficient areas, boosting productivity, elevating quality of life, and aiding small enterprises. In sub-Saharan Africa, decentralized solar solutions are empowering millions of households and schools with electricity, diminishing dependence on expensive diesel generators and enhancing access to education and healthcare services. Decentralization fosters local ownership and economic empowerment, enabling communities to take on the roles of both producers and consumers of energy.

Stability in Energy Supply and Diminished Market Fluctuations

The adoption of renewable energy significantly improves energy security by decreasing reliance on imported fossil fuels, which are often vulnerable to price fluctuations and geopolitical uncertainties. Wind, solar, and hydropower are accessible in many areas, offering nations a reliable energy source that is more resilient to changes in the global market. This stability can protect economies from price shocks, like those experienced during oil crises, enabling governments to redirect resources to other essential sectors. Furthermore, the decentralized characteristics of renewable energy contribute to grid resilience, minimizing the likelihood of extensive blackouts and bolstering national security.

Lead of the Capital Intensity and Grid Integration

Although renewable energy sources provide a variety of economic advantages, they encounter certain obstacles as well. The initial capital costs associated with renewable installations, including solar farms and offshore wind turbines, tend to be significant, necessitating a considerable upfront investment. While these costs are mitigated by reduced operational expenses in the long run, financing continues to pose a challenge, especially in developing economies. Furthermore, incorporating variable renewables such as wind and solar into current power grids requires investment in energy storage, modernization of the grid, and demand response technologies to address intermittency and maintain a stable power supply. Confronting these challenges necessitates the implementation of supportive policy frameworks, the establishment of incentives, and the pursuit of technological advancements.

b. Environmental Effects of Renewable Energy

Reduction of Greenhouse Gases and Mitigation of Climate Change

Renewable energy plays a crucial role in mitigating greenhouse gas (GHG) emissions, directly tackling the fundamental cause of climate change. In contrast to fossil fuels, renewable energy sources produce little to no greenhouse gases during their operation, thereby playing a significant role in the decarburization of the energy sector, which is responsible for more than 70% of global emissions. With an increasing number of nations committing to carbon neutrality by the middle of the century, the growth of renewable energy sources is crucial for meeting these objectives. For instance, solar and wind energy could contribute to almost 50% of the necessary carbon reductions to achieve the 1.5°C goal set by the Paris Agreement.

Enhancement of Air Quality and Its Impact on Public Health

The utilisation of renewable energy plays a crucial role in enhancing air quality by decreasing the emissions of harmful pollutants, including sulphur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM_{2.5}). The combustion of fossil fuels serves as a major source of these pollutants, which are linked to respiratory and cardiovascular diseases. Transitioning to renewables allows urban areas to mitigate pollution-related health problems, lower healthcare expenses, and enhance the overall quality of life. The advantages of renewable energy for public health are especially significant in areas with high population density and industrial activity, where inadequate air quality leads to serious economic and social consequences.

♣ Preservation of Water Resources and Ecosystem Integrity

A variety of renewable energy technologies, including wind and solar, utilise minimal to no water during their operation, unlike fossil fuel and nuclear plants that depend significantly on water for cooling purposes. This trait renders renewable sources especially significant in areas with limited water availability, where the struggle for water resources among agriculture, industry, and human needs is fierce. Hydropower presents distinct challenges; large dams can modify river ecosystems, displace communities, and affect biodiversity. Consequently, there is a growing interest in small-scale hydropower and run-of-river systems as more sustainable alternatives.

4 Concerns Regarding Biodiversity and Land Use

Although renewable energy sources are typically less harmful to the environment compared to fossil fuels, they still possess certain environmental impacts. Wind turbines can present risks to avian and bat populations, while solar farms necessitate considerable land use, potentially conflicting with agricultural or conservation priorities. Appropriate siting, the design of technology that is considerate of wildlife, and meticulous planning are crucial to reduce these effects. Innovations like floating solar farms and agrovoltaics, which integrate agriculture with solar PV,

demonstrate effective strategies for mitigating land-use conflicts and fostering sustainable deployment.

Decrease in Environmental Harm and Resource Exhaustion

The extraction and processing of fossil fuels result in deforestation, soil erosion, and pollution, which in turn cause habitat loss and a decline in biodiversity. In contrast, renewables do not necessitate the same magnitude of resource extraction. Biomass must be managed in a sustainable manner to avoid deforestation and soil depletion. By minimizing reliance on energy sources that require significant resources, renewable options ease the strain on ecosystems, facilitating the advancement of natural regeneration and conservation initiatives.

1.5. Nuclear Energy

Nuclear energy holds a distinctive role in global energy frameworks, offering a concentrated, low-carbon source of baseload power that is gaining acknowledgement as crucial for lowering greenhouse gas emissions while ensuring energy security. Even with these benefits, nuclear energy continues to be a topic of debate because of significant initial investments, intricate waste disposal challenges, and the possible dangers linked to accidents and the spread of nuclear weapons. This examination explores the economic and environmental effects of nuclear energy, emphasising its significance in a low-carbon economy, its contribution to energy security, and the obstacles it presents for sustainable development.

a. The Economic Impact of Nuclear Energy

Significant Capital Expenditures and Economic Feasibility

Nuclear energy represents a highly capital-intensive energy source, necessitating substantial initial investment for the construction of plants, adherence to regulatory standards, and implementation of safety protocols. Although the operational expenses are generally modest once a facility is

running, the significant initial investments frequently render nuclear initiatives financially difficult. The financial implications are intensified by prolonged construction schedules and intricate permitting procedures, which elevate the financial risk for investors and postpone the completion of projects. In certain instances, nuclear initiatives encounter budget overruns, as evidenced by recent developments in the United States and Europe, rendering nuclear less appealing in comparison to the growing affordability of renewable energy sources.

Advantages of Minimal Operating Expenses and Consistent Power Supply

Even with elevated construction expenses, nuclear energy presents significant long-term economic advantages owing to its minimal operational and fuel costs. Once operational, nuclear plants generate a consistent and reliable supply of electricity at a relatively low marginal cost, contributing to grid stability and mitigating the variability associated with renewable energy sources such as solar and wind. Nuclear power plants deliver baseload power, ensuring a continuous output that satisfies a region's minimum energy requirements. This characteristic makes nuclear energy particularly advantageous for energy-intensive sectors that depend on stable, round-the-clock electricity supply.

Employment Opportunities and Skilled Workforce Development

The nuclear sector encompasses a variety of highly skilled, specialised roles, including engineering, plant operations, regulatory oversight, and investigative work. Nuclear power facilities necessitate a dedicated workforce for ongoing maintenance, oversight, and security, thereby fostering stable, long-term job prospects. The nuclear sector also promotes advancements and the cultivation of expertise in areas such as materials science, physics, and safety engineering. Nonetheless, the creation of jobs in the nuclear sector is frequently confined to nations that have

established nuclear energy initiatives, whereas decommissioning efforts can result in job loss if appropriate retraining programs are not implemented.

Energy Security and Geopolitical Factors

Nuclear energy plays a crucial role in enhancing energy security through the diversification of the energy mix and the reduction of reliance on fossil fuel imports. Nuclear energy offers a consistent and robust source of power, in contrast to renewables that frequently rely on weather conditions. Countries that possess restricted renewable resources, such as Japan, or have limited fossil fuel reserves, like France, depend on nuclear energy to sustain their energy autonomy. Additionally, nuclear fuel is dense and comparatively economical, with uranium resources sourced from geopolitically stable areas. Nonetheless, the dissemination of nuclear technology brings forth apprehensions regarding proliferation, as the knowledge and materials associated with nuclear capabilities might be redirected towards weapons initiatives, thereby complicating geopolitical relations.

Financial Considerations: Decommissioning, Waste Management, and Accountability

The economic lifecycle of a nuclear plant spans significantly beyond its operational years, encompassing essential decommissioning and waste management obligations. The process of decommissioning a nuclear plant is intricate, expensive, and requires significant time, as it entails the secure removal and disposal of radioactive materials. The management of nuclear waste presents significant long-term economic challenges, as high-level radioactive waste necessitates secure, deep geological storage for tens of thousands of years. In the case of an accident, such as the Chernobyl or Fukushima disasters, the implications of liability can result in substantial economic losses and enduring social costs, frequently placing the burden on governments and taxpayers.

b. The Environmental Impact of Nuclear Energy

Minimal Greenhouse Gas Emissions and Potential for Climate Mitigation

Nuclear energy stands out as one of the limited large-scale, low-carbon power sources, producing minimal carbon dioxide emissions during its operation. This feature renders nuclear power essential for meeting deep decarbonisation goals, especially in nations with significant baseload electricity needs or constrained renewable resources. Throughout a plant's lifecycle, the carbon footprint of nuclear energy is similar to that of renewable sources, positioning it as a compelling choice for nations aiming to move away from fossil fuels. The Intergovernmental Panel on Climate Change (IPCC) indicates that nuclear power may be essential in keeping global warming under 2°C, in conjunction with renewable energy sources and carbon capture technologies.

Management of Radioactive Waste and Associated Environmental Risks

An important environmental issue associated with nuclear energy is the production of radioactive waste, which encompasses spent nuclear fuel and various radioactive byproducts. High-level radioactive waste poses a significant hazard for thousands of years, highlighting the urgent need for secure and long-term disposal solutions, including deep geological repositories. In the absence of widely accessible permanent storage solutions, the majority of countries opt to store nuclear waste on-site, which presents potential risks to local ecosystems and communities. The environmental hazards linked to waste storage, transportation, and possible leakage represent significant issues for policymakers and the general public alike.

The Environmental Consequences of Uranium Extraction and Resource Exhaustion

The process of the nuclear fuel cycle initiates with the extraction of uranium, a practice that may result in habitat degradation, water pollution, and potential radiation exposure for surrounding populations. The process of uranium mining generates tailings, or waste rock, which frequently harbours radioactive materials and heavy metals capable of leaching into adjacent soil and water systems. Furthermore, although uranium is quite plentiful, the most readily available reserves are limited. With the increasing demand for nuclear energy, the industry might have to investigate more energy- and water-intensive extraction techniques, potentially leading to further environmental and social consequences.

♣ Potential Hazards of Nuclear Incidents and Prolonged Ecological Pollution

While nuclear power facilities are designed with comprehensive safety measures, the potential for accidents continues to be a significant environmental issue. Significant incidents, like those at Chernobyl (1986) and Fukushima (2011), have illustrated the risk of severe environmental pollution and enduring ecological harm. Incidents involving radiation release can lead to widespread contamination of air, soil, and water, making land uninhabitable and causing disruptions to ecosystems that can last for decades. The enduring consequences of nuclear accidents encompass heightened cancer incidences, genetic alterations in plants and animals, along with considerable socioeconomic burdens stemming from displacement and the erosion of livelihoods.

■ Water Utilisation and Thermal Contamination

Nuclear power facilities necessitate significant water usage for cooling purposes, potentially putting pressure on local water supplies, particularly in areas where water is already limited. Nuclear plants not only consume significant amounts of water but also discharge heated water into nearby waterways, a situation referred to as thermal pollution. The release of heated water can significantly impact aquatic ecosystems by lowering oxygen levels and influencing fish and other species that are sensitive to temperature fluctuations. While closed-loop cooling systems address

certain impacts, the use of water continues to be a significant environmental concern for nuclear energy, especially as climate change exacerbates water scarcity in various areas.

1.6. Energy Production and Consumption Patterns

The patterns of energy production and consumption are essential for comprehending the intricacies of economic development, environmental sustainability, and geopolitical strategy. Patterns exhibit considerable variation across different countries and regions, influenced by disparities in resources, technological capabilities, socioeconomic priorities, and policy frameworks. This overview examines the primary trends in energy production and consumption, emphasising the factors driving the global transition to sustainable energy systems and the difficulties in reconciling energy demand with environmental objectives.

a. Patterns in global energy production

Prevalence of Fossil Fuels

In recent decades, fossil fuels, including coal, oil, and natural gas, have played a significant role in global energy production, representing around 80% of the world's primary energy supply. Fossil fuels possess high energy density, reliability, and widespread availability, rendering them a practical energy source for industrial, transportation, and residential uses. Nonetheless, dependence on fossil fuels has resulted in significant greenhouse gas (GHG) emissions, which play a role in global warming and climate change. The environmental impacts linked to fossil fuels have spurred global initiatives aimed at decreasing reliance on these energy sources.

Emergence of Sustainable Energy Sources

Renewable energy sources such as solar, wind, hydro, biomass, and geothermal have seen significant growth, propelled by decreasing costs, advancements in technology, and favourable

policy environments. The growth of solar and wind energy has been remarkable, driven by their modular characteristics and decreasing capital expenses. In certain areas, renewable energy sources have achieved grid parity, indicating that they can compete with fossil fuels on cost without the need for subsidies. A multitude of nations have established ambitious renewable energy goals in alignment with their obligations under the Paris Agreement, thereby propelling the shift towards cleaner energy sources.

♣ Significance of Nuclear Energy

Nuclear energy serves as a reliable, low-carbon source of baseload power, contributing around 10% to the total global electricity production. Despite a deceleration in the expansion of nuclear energy in recent years attributed to safety concerns, substantial capital expenditures, and the enduring challenge of managing radioactive waste, it continues to play a crucial role in the energy landscape of nations such as France, the United States, and China. The advancement of sophisticated nuclear technologies, including small modular reactors (SMRs), presents opportunities for safer and more adaptable nuclear solutions that may enhance renewable energy sources within a decarbonised energy framework.

Variations in Energy Production across Regions

Energy production patterns exhibit considerable variation across different regions. The Middle East continues to be a leading producer of oil and gas, whereas coal extraction is mainly concentrated in nations such as China, the United States, and India. The production of renewable energy tends to be highest in areas that possess advantageous natural conditions, exemplified by solar energy in the Middle East and North Africa (MENA) and wind energy in Europe and North America. Hydropower plays a crucial role in nations that boast extensive river systems, including Brazil and Norway. Geographical factors, resource accessibility,

infrastructure development, and the focus of governmental policies significantly shape the variations in production across different regions. Following are the patterns of global energy consumption

b. Patterns of global energy consumption

Increasing Worldwide Energy Needs

The demand for energy worldwide has consistently risen, largely fuelled by population growth, industrial development, and urban expansion in developing nations. Asia, spearheaded by China and India, has emerged as the foremost contributor to this growth, with swift economic expansion propelling the demand for electricity, transportation, and industrial energy. Even with advancements in energy efficiency, it is anticipated that global energy demand will keep rising, exerting strain on energy resources and infrastructure.

♣ Sectoral Consumption

Electricity, Transportation, and Industry: The electricity sector is undergoing a notable transformation, increasingly integrating cleaner energy sources, as renewable energy continues to expand its contribution to electricity generation. The anticipated increase in electricity demand is linked to the ongoing electrification of transport and heating systems, aimed at mitigating emissions from fossil fuel usage.

Transportation

The transportation sector continues to depend significantly on oil, representing almost 25% of global energy consumption. Initiatives aimed at decreasing transportation emissions have led to increased investment in electric vehicles (EVs) and alternative fuels, including biofuels and hydrogen. Nonetheless, the shift towards electric mobility is currently in its nascent phase, and

oil is expected to continue being the primary fuel source for transportation in the foreseeable future.

Technology

The industrial sector, especially heavy industries such as steel, cement, and chemicals, represents a significant portion of energy consumption and is a primary contributor to CO₂ emissions. Decarbonising industry presents significant challenges, particularly because numerous industrial processes demand high-temperature heat that current renewable technologies struggle to provide. Exploration of strategies like carbon capture, utilisation, and storage (CCUS) and hydrogen fuel is underway to mitigate industrial emissions.

♣ The Relationship between Urbanisation and Energy Demand Trends

The process of urbanisation is transforming the patterns of energy consumption, with cities increasingly representing a significant portion of energy demand and emissions. Urban areas serve as hubs for residential, commercial, and industrial activities, necessitating significant energy for heating, cooling, lighting, and transportation. The swift pace of urban growth, particularly in developing nations, presents a significant challenge for sustainable energy planning. The expansion of infrastructure must address the demands of increasing urban populations while avoiding further pollution and congestion.

Energy Use and Accessibility in Households

Household energy consumption exhibits significant variation influenced by factors such as climate, income levels, and the availability of modern energy sources. In advanced economies, households utilise significant amounts of energy for heating, cooling, and various appliances, whereas numerous developing areas still face restrictions in accessing modern energy sources.

About 770 million individuals worldwide do not have access to electricity, particularly in rural and remote regions where the challenges are most pronounced. Enhancing access to affordable and dependable energy is crucial for elevating living standards and fostering economic growth in marginalised areas. Following are the transition patterns and their consequences for the future

c. Transition patterns and their consequences for the future

Reducing Carbon Emissions and Environmental Regulations

The pressing nature of climate change has positioned decarbonisation as a pivotal focus in global energy policy discussions. A significant number of nations have committed to reaching net-zero emissions by the middle of the century, necessitating a transition from fossil fuels to renewable energy sources, nuclear energy, and low-carbon technologies. Policies like carbon pricing, renewable energy subsidies, and emissions regulations are being enacted to decrease dependence on carbon-heavy fuels and encourage cleaner alternatives.

The Integration of Electrification and Digital Technologies

The transition to electrification in areas such as transport and heating represents a crucial approach for emission reduction, given that electricity can be sourced from renewable energy. The increasing adoption of electric vehicles, heat pumps, and electric industrial equipment is leading to a significant shift in demand from fossil fuels to electricity, thereby altering energy consumption patterns. Simultaneously, advancements in digital technologies, including smart grids, demand response systems, and the Internet of Things (IoT), are enhancing energy efficiency and optimising energy distribution, facilitating more responsive and adaptable energy systems.

Distributed Energy and Decentralisation

Decentralised energy production is being driven by distributed energy resources (DERs) like rooftop solar, battery storage, and small-scale wind. This trend empowers individuals to produce and store their own energy, decreasing dependence on centralised power facilities and enhancing the resilience of the grid. Decentralised energy systems offer significant advantages for remote or rural regions with limited grid connectivity, delivering dependable power without requiring extensive infrastructure.

Learner Storage and Grid Integration

Energy storage is increasingly crucial for managing supply and demand in systems that rely heavily on renewable sources, as it helps to address the variability associated with wind and solar energy. Innovations in battery technology, pumped hydro storage, and thermal storage are enhancing the reliability of renewable energy sources and facilitating increased flexibility within the grid. The integration of renewable energy sources and storage solutions is essential for maintaining a stable energy supply and optimising the efficiency of energy systems.

Enhancing energy efficiency in various sectors is essential for the development of sustainable energy systems. Technologies that prioritise energy efficiency effectively diminish demand, cut emissions, and lower expenses for consumers. Demand-side management techniques, including peak shaving and load shifting, enable utilities to enhance energy efficiency and alleviate pressure on the grid, particularly during peak demand periods. Standards for energy efficiency, regulations for buildings, and guidelines for appliances are essential in reducing demand and fostering sustainable consumption habits.

1.7. Energy Market Dynamics

The dynamics of the energy market encompass the intricate relationships among supply, demand, policy, and technological innovations that influence the global availability, pricing, and distribution of energy resources. The dynamics at play are shaped by various factors, such as the availability of resources, geopolitical considerations, economic development, and initiatives aimed at addressing climate change. Grasping these dynamics is essential for decision-makers, financiers, and industry participants as they manoeuvre through the shift towards a sustainable energy framework.

a. Essential Elements Shaping Energy Market Trends

The determination of energy prices primarily hinges on the fundamental economic principle of supply and demand. As economies expand, energy demand escalates, exerting upward pressure on prices when supply fails to keep pace with the growing demand. In contrast, during times of economic downturn or decreased activity, the demand for energy might decrease, resulting in lower prices. In recent years, variations in energy supply and demand have become increasingly evident due to factors such as:

- **♣ Economic Growth and Industrialisation**: The swift industrialisation occurring in emerging markets such as China and India has been a major factor in the substantial increase in global energy demand.
- **↓ Urban growth and increasing wealth**: In urban areas, elevated living standards are associated with a rise in energy consumption, particularly in the realms of electricity and transportation.
- ♣ Energy efficiency: energy efficiency has seen significant improvements due to advancements in technology and policy incentives across various sectors, especially in developed economies. This progress has somewhat moderated demand growth, despite the rise in economic activity.

b. Availability of Resources and Geopolitical Factors

The distribution of energy resources is not uniform globally, resulting in specific regions being essential for the overall energy supply worldwide. For instance:

- ♣ The Middle East: The Middle East possesses a significant portion of the global oil reserves, establishing its crucial role in the oil markets. Political instability or conflict in this region has the potential to disrupt supply chains and result in price fluctuations.
- Essential Minerals for Renewable Energy: The transition to renewable energy depends on essential minerals (such as lithium, cobalt, and rare earth elements) that are primarily found in areas like China, Chile, and the Democratic Republic of Congo. The interplay of geopolitical risks and trade tensions related to these materials can significantly influence their prices and availability, thereby presenting challenges for renewable energy markets.
- **♣ Disasters**: Natural disasters, extreme weather, and climate-related events have the potential to disrupt energy production and infrastructure, which in turn affects supply and leads to price volatility.

c. Progress in Technology and Creative Developments

Technological advancements significantly influence the dynamics of the energy market by lowering costs, enhancing efficiency, and facilitating innovative methods of energy production and storage. Significant technological influences encompass:

♣ Decrease in Renewable Energy Expenses: Progress in solar, wind, and battery technologies has significantly lowered costs, enhancing the competitiveness of renewables against fossil fuels. This has resulted in heightened investment in renewable energy and has transformed the structure of the energy market.

- ♣ Enhancements in Energy Storage: Technologies such as battery storage, pumped hydro, and other storage solutions play a vital role in addressing the variability associated with renewable energy sources. Energy storage plays a crucial role in facilitating the integration of increased renewable energy into the grid, highlighting its significance as a burgeoning investment sector.
- ♣ **Digitalisation and Smart Grids**: The incorporation of digital technologies in energy management facilitates demand response, improves grid stability, and boosts efficiency. Smart grids enable a more adaptable and decentralised approach to energy systems, transforming the dynamics of power generation and distribution.

d. Climate Policies and Regulatory Frameworks

Policies implemented by the government to lower carbon emissions, encourage clean energy, and improve energy security have had a substantial impact on energy markets in recent years. Significant regulatory effects encompass:

- ← Carbon Pricing: Mechanisms such as carbon taxes and cap-and-trade systems aim to incorporate the environmental costs associated with carbon emissions, promoting a transition from fossil fuels. The increase in costs associated with carbon-intensive energy has expedited the shift towards renewable sources.
- Financial Support and Motivations for Renewable Energy: Government financial support and tax motivations have played a crucial role in lowering the expenses associated with renewable energy technologies, especially during the initial phases of market growth. Policies such as feed-in tariffs and renewable portfolio standards have driven considerable expansion in renewable energy capacity.
- ♣ Phasing Out of Coal: Numerous nations have implemented strategies to gradually eliminate coal-fired power plants in alignment with their climate obligations. The transition from coal to

lower-carbon energy sources, including natural gas and renewables, has significantly influenced energy markets.

♣ Electric Vehicle (EV) Policies: Initiatives that encourage the adoption of electric vehicles, such as subsidies, tax credits, and prohibitions on internal combustion engines, have impacted oil markets by decreasing the demand for petroleum in the transportation sector. The adoption of electric vehicles generates increased demand for electricity, thereby changing energy consumption patterns.

e. Market Structures and Competitive Dynamics

The structures of energy markets, differing by region and resource, are crucial in shaping price levels, investment incentives, and the overall dynamics of the market. Two main market structures exist:

- Monopolistic or Regulated Markets: In certain areas, energy markets are controlled by stateowned or monopolistic entities, with government oversight on pricing and investments being stringent. This framework is frequently observed in developing economies or within industries such as electricity transmission and distribution.
- Liberalised or Competitive Markets: In these energy markets, a variety of private companies engage in competition to provide energy, with prices determined by the forces of supply and demand. Opening up markets fosters creativity, enhances productivity, and frequently leads to better pricing options for consumers. Nonetheless, it may also result in fluctuations, as prices mirror immediate changes in supply and demand.

f. Trends in Investment and Financing

Investment in energy infrastructure is crucial for addressing demand, facilitating the shift to cleaner sources, and strengthening energy security. Current trends encompass:

- **Transition to Renewable Energy**: There has been a notable increase in global investment directed towards renewable energy, driven by decreasing costs, favourable policies, and the pressing need to meet climate objectives. The International Energy Agency (IEA) reports that a considerable share of new energy investments globally is now directed towards renewables.
- ♣ Divestment from Fossil Fuels: Numerous institutional investors, especially in Europe and North America, have diminished or halted their investments in fossil fuels, driven by apprehensions regarding climate risk and regulatory pressures. This trend has significantly influenced fossil fuel companies and has played a role in the shift of capital towards low-carbon energy sources.
- ♣ Energy Storage and Grid Modernisation: There is an increasing investment in energy storage and grid infrastructure as nations work to incorporate a greater share of renewable energy into their power systems. Battery storage initiatives and advancements in grid infrastructure are essential for maintaining reliability and stability as an increasing number of intermittent energy sources are integrated into the system.

g. Emerging Trends in Energy Market Dynamics.

Decentralisation and Distributed Energy Resources (DERs)

The emergence of distributed energy resources (DERs), including rooftop solar panels, home batteries, and community energy initiatives, is reshaping conventional, centralised energy systems. Distributed energy resources enable individuals to produce and store their own energy, thereby decreasing reliance on the centralised grid and enhancing resilience in the face of outages. In certain areas, distributed energy resources have resulted in the emergence of "prosumers"—individuals who generate and utilise energy—capable of selling surplus energy back to the grid, thereby transforming the landscape of energy consumption and distribution.

■ The Shift in Energy Paradigms and Hydrogen's Contribution

Hydrogen, especially green hydrogen generated from renewable energy sources, is gaining recognition as a viable option for reducing carbon emissions in challenging sectors such as heavy industry and long-distance transportation. The advancement of hydrogen infrastructure, encompassing electrolysers and fuel cells, remains in its nascent phase yet has attracted considerable investment and attention from both governmental bodies and the industry. The adaptability of hydrogen as an energy carrier suggests it could play a vital role in the transition to low-carbon energy, particularly as advancements in storage and transport technologies continue to develop.

Heightened Fluctuations and Ambiguity

The volatility in energy markets has escalated as a result of supply constraints, geopolitical tensions, and the fluctuating characteristics of renewable energy sources. The 2021–2022 European energy crisis serves as a clear illustration of the fluctuations within natural gas markets and the difficulties encountered in maintaining supply amidst a swiftly evolving energy landscape. With the growing integration of renewable energy into the energy mix, there is a potential for increased price volatility, highlighting the importance of effective grid management and adaptable backup sources.

Changes in Global Politics and Self-Sufficiency in Energy

The shift from fossil fuels carries important geopolitical consequences, as nations aim to lessen their reliance on imported oil and gas. This trend is especially significant in Europe, where initiatives aimed at attaining energy independence have intensified in response to geopolitical disruptions. The increasing dependence on essential minerals for renewable technologies has redirected geopolitical attention to nations that possess substantial reserves of lithium, cobalt, and

rare earth elements. As nations strive to ensure their access to these minerals, the dynamics of energy geopolitics are expected to change.

1.8. Energy Prices and Economic Growth

The relationship between energy prices and economic growth is intricate and multifaceted, carrying important consequences for production costs, household spending, trade balances, and inflation. The connection is clear in both advanced and emerging economies, where energy prices—particularly oil, natural gas, and electricity—are crucial in influencing macroeconomic conditions and guiding policy choices. To grasp this dynamic, it is essential to analyse the effects of energy price fluctuations on economic activities across different sectors, including industry, government, and households.

a. Costs of Industrial Production and Economic Competitiveness

Energy serves as a fundamental input across nearly all sectors of the economy, encompassing everything from heavy manufacturing to service industries. Consequently, fluctuations in energy prices can have a direct effect on production expenses. Rising energy prices lead to increased operational costs for businesses, potentially resulting in reduced profit margins, diminished competitiveness, and impacts on employment rates. On the other hand, decreased energy prices can enhance the cost-competitiveness of industries and foster economic growth by lowering production expenses. The U.S. shale oil boom between 2009 and 2015 resulted in a significant increase in domestic oil production, which in turn led to a decrease in energy prices for industries across the nation. This benefit allowed energy-intensive sectors, including chemicals and steel, to enhance their global competitiveness by lowering energy expenses. According to data from the U.S. Energy Information Administration (EIA), between 2011 and 2014, industrial electricity

prices in the U.S. were 30–50% lower than those in Europe, where energy costs remained elevated, providing competitive advantages for American manufacturers.

b. Household Expenditure and Available Income

Households experience significant impacts from fluctuations in energy prices, particularly regarding heating, electricity, and transportation expenses. As energy prices rise, households tend to direct a larger portion of their income towards energy costs. This shift can lead to a decrease in disposable income available for other goods and services, potentially hindering economic growth. On the other hand, reduced energy prices boost disposable income and promote consumer spending, thereby enhancing economic activity. Between 2014 and 2016, there was a notable decrease in global oil prices, dropping from more than \$100 per barrel in mid-2014 to under \$30 per barrel by early 2016. The observed decline resulted in reduced petrol prices, particularly in the United States, where the average price of petrol decreased by almost 50% between 2014 and 2016. The rise in disposable income resulted in an estimated additional \$100 billion in consumer spending in the U.S. during this timeframe, as households had greater income for discretionary purchases, thereby enhancing sectors like retail and services.

c. Funding in the Energy Sector and Associated Technologies

The fluctuations in energy prices play a significant role in shaping investment choices across both traditional and renewable energy industries. Elevated energy prices frequently result in heightened investment in energy production, exploration, and technological advancements. Investments in energy infrastructure can yield significant long-term economic advantages, fostering job creation and enhancing GDP growth. Reduced energy prices can diminish the motivation for investment, particularly in regions with high extraction costs or in advancements related to energy efficiency. In the early 2000s, high oil prices prompted a significant increase in Canadian oil sands production,

with companies channelling billions into extraction and refining processes. As of 2013, the oil sands sector in Canada was responsible for more than 100,000 jobs and made an annual contribution of around \$91 billion to the Canadian economy. Nonetheless, the significant decline in oil prices in 2014 rendered numerous oil sands projects financially unviable, resulting in job losses and a decrease in economic output.

d. Inflationary Pressures and Responses from Monetary Policy

The influence of energy prices on inflation is considerable, affecting the overall cost of goods and services throughout the economy. Central banks meticulously observe energy prices, given that inflation driven by energy can necessitate changes in monetary policy. Elevated energy prices could compel central banks to increase interest rates in an effort to control inflation, potentially hindering economic growth by raising the cost of credit and suppressing investment. In the European Union, the escalation of natural gas prices during 2021–2022 played a significant role in driving inflation upward, culminating in a Eurozone inflation rate of 8.6% by mid-2022, influenced in part by soaring energy expenses. The European Central Bank (ECB) increased interest rates from 0% in early 2022 to 2% by the end of the year as a measure to address inflation. The recent rate hikes have led to an increase in borrowing costs throughout the Eurozone, which in turn has contributed to a slowdown in growth and heightened concerns regarding a possible recession.

e. Fluctuations in Energy Prices and Economic Instability

Implications on Global Politics and Interruptions in Supply Chains

Energy prices exhibit a notable sensitivity to geopolitical events, particularly in areas rich in fossil fuel reserves. Disruptions in supply caused by political instability, trade embargoes, or conflicts can result in abrupt price surges, affecting economies on a global scale. Countries that rely

significantly on energy imports face heightened risks from such disruptions, leading to potential energy insecurity and economic instability. The 2022 Russia-Ukraine conflict led to significant disturbances in European energy markets, given Russia's role as a primary supplier of natural gas and oil to the region. With the dramatic rise in natural gas prices, various industries throughout Europe encountered significant energy shortages and escalating expenses. The European Union's statistics agency, Eurostat, reports that GDP growth in the European Union decreased from 5.5% in 2021 to approximately 3.5% in 2022, attributing this slowdown primarily to the energy crisis. A number of European nations enacted emergency energy subsidies to protect businesses and households from the short-term economic effects.

Learn Street Economic Uncertainty and Investment Risks

The fluctuations in energy prices can lead to economic unpredictability, complicating the ability of businesses to strategize for long-term investments. In periods of energy price volatility, firms operating in energy-intensive sectors might postpone their capital-heavy initiatives, which could lead to a decline in productivity and growth. Japan's economy, which depends significantly on imported fossil fuels, experienced notable fluctuations in energy prices after the 2011 Fukushima nuclear disaster. This event led to the shutdown of nuclear reactors and a heightened dependence on imported oil and natural gas. From 2011 to 2014, Japan experienced a near doubling of its energy import costs, leading to significant uncertainty for energy-intensive sectors such as manufacturing. Investment decisions by companies have been delayed as a result of elevated energy costs and ambiguity surrounding Japan's energy policy, resulting in a deceleration of industrial growth.

f. Transformational Changes and Economic Robustness

- Transition to Sustainable Energy Sources and Self-Sufficiency in Energy: To address the challenges posed by fluctuations in energy prices, numerous economies are transitioning to renewable energy sources, which offer greater price stability and improve energy security. By diversifying their energy mix, nations can lessen reliance on fossil fuels, which frequently face geopolitical risks and price volatility. Germany's Energiewende policy focusses on enhancing the share of renewable energy in its power mix to diminish dependence on imported fossil fuels. As of 2022, Germany sourced more than 40% of its electricity from renewable energy. This transition, though initially expensive, is anticipated to protect Germany's economy from future price volatility in fossil fuels, given that renewable energy sources like wind and solar are less susceptible to global market changes. Data from Germany's Federal Ministry for Economic Affairs and Climate Action indicates a significant decrease in Germany's dependence on Russian gas imports, with a reduction of over 50% from 2021 to 2023, thereby lessening economic vulnerability.
- Commitment to Enhancing Energy Efficiency and Advancing Technology: Times of elevated energy costs frequently drive advancements and the uptake of energy-saving technologies. Organisations and individuals aiming to cut energy expenses are adopting technologies that boost energy efficiency, potentially leading to sustained economic advantages through reduced operational costs and enhanced productivity. In the aftermath of the oil crises during the 1970s, Japan achieved notable advancements in energy efficiency, especially within the sectors of manufacturing and transportation. As of 2010, Japan had achieved a reduction in energy intensity—defined as the energy consumed per unit of GDP—by over 40% relative to 1980 levels, thereby enhancing the resilience of its economy against

fluctuations in energy prices. Japan's Ministry of Economy, Trade, and Industry reports that these efficiency improvements have led to increased productivity and strengthened the resilience of the country's industrial sector.

g. Role of International agencies

A number of studies present empirical evidence regarding the relationship between energy prices and economic growth. For instance:

- ♣ World Bank Analysis: The World Bank indicates that a 10% rise in global oil prices may lead to a decrease in GDP growth in oil-importing nations by approximately 0.1 to 0.5 percentage points, with developing countries frequently experiencing greater impacts due to their increased reliance on oil for energy and transportation.
- ♣ The International Monetary Fund (IMF) has projected that a 10% rise in energy prices may lead to a reduction in global economic growth by around 0.2 percentage points. Energy price spikes were identified as a significant factor contributing to the reduced global growth projections in 2022, stemming from the Russia-Ukraine conflict and the resulting disruptions in energy markets.
- U.S. Energy Information Administration (EIA): In the United States, data from the EIA reveals a significant correlation between oil price shocks and recessions. Since World War II, almost every recession in the U.S. has been foreshadowed by a surge in oil prices, highlighting the vulnerability of the U.S. economy to fluctuations in energy costs.

1.9. Energy Policy Frameworks

Energy policy frameworks are organised strategies that governments, organisations, and international entities create to oversee and control energy production, distribution, and consumption in a manner that corresponds with wider societal objectives. These frameworks act as guides for tackling the complex issues surrounding energy security, affordability, and sustainability, while also taking into account the geopolitical, environmental, and economic factors that shape energy systems. They formulate foundational principles, define quantifiable objectives, and delineate policy tools to promote a stable, efficient, and low-carbon energy sector. Through the integration of regulatory, economic, and technological tools, energy policy frameworks enable a transition to sustainable energy systems that reconcile present energy needs with overarching global sustainability goals.

a. Fundamentals of Energy Policy Structures

Energy policy frameworks fundamentally seek to balance the frequently conflicting priorities of energy access, environmental preservation, and economic development. Their structure is established on three essential pillars:

- **♣ Energy Security:** Guaranteeing a dependable and continuous energy supply to satisfy present and future needs. This encompasses broadening energy sources, minimising reliance on imports, and enhancing infrastructure to alleviate risks stemming from geopolitical conflicts or natural calamities.
- **♣ Environmental Sustainability:** Minimising greenhouse gas (GHG) emissions, improving energy efficiency, and preserving ecosystems are essential components. Frameworks integrate

approaches such as renewable energy mandates, carbon pricing, and energy efficiency standards to reduce environmental impact.

Economic Competitiveness: Policies seek to harmonise energy expenses with economic advancement by fostering innovation, generating employment in new sectors, and guaranteeing energy affordability for both households and industries.

b. Essential Elements of Energy Policy Frameworks

Energy policy frameworks consist of multiple interrelated elements aimed at tackling particular facets of energy systems.

Regulatory Instruments

Regulatory mechanisms establish the guidelines and criteria for energy production and consumption. These encompass emissions limits, efficiency standards, and requirements for the adoption of renewable energy. Renewable Portfolio Standards (RPS) mandate that utilities obtain a designated percentage of their electricity from renewable sources, thereby promoting the expansion of clean energy markets. The Renewable Energy Directive (RED) in the European Union (EU) requires member states to reach a 32% share of renewable energy by 2030, which is stimulating investments in wind, solar, and bioenergy.

Mechanisms Based on Market Principles

Market-based instruments utilise economic incentives to promote sustainable practices. Carbon pricing, via mechanisms such as carbon taxes or emissions trading systems (ETS), incorporates the environmental costs associated with fossil fuel consumption. The EU's ETS, initiated in 2005, sets a limit on overall emissions and facilitates the trading of allowances, thereby generating financial motivations for reducing emissions. In a similar vein, tax incentives and subsidies facilitate the adoption of renewable energy technologies, including

solar photovoltaics and wind turbines, by lowering initial costs for both investors and consumers.

Economic Instruments

Energy transitions necessitate significant financial commitments, and frameworks typically incorporate strategies to attract funding for clean energy initiatives. Green bonds, public-private partnerships, and international climate funds are essential components. The Green Climate Fund (GCF) has allocated billions to bolster renewable energy and resilience initiatives in developing countries. In India, public-private partnerships have significantly propelled the establishment of extensive solar parks, drawing interest from both local and international investors.

Advancements in Technology and Research Development

The advancement of cutting-edge energy technologies is fundamentally supported by policies related to research and development (R&D). Funding is provided by governments, alongside the establishment of innovation hubs, to promote advancements in fields such as battery storage, hydrogen energy, and smart grid systems. Germany's Energiewende initiative invests significantly in research and development to bolster its ambitious renewable energy objectives.

Access to Energy and Fairness

Energy policy frameworks need to tackle the inequalities in energy access to promote inclusivity. Decentralised renewable energy systems, including mini-grids and off-grid solar solutions, play a crucial role in providing electricity to remote areas. For example, the rural electrification initiatives in Kenya, bolstered by solar home systems, have greatly enhanced energy access in communities that have been historically underserved.

c. Analysis of Energy Policy Framework Implementation

The Green Deal of the European Union

The EU's Green Deal exemplifies a thorough energy policy framework aimed at attaining carbon neutrality by 2050. This approach combines various regulatory, economic, and financial instruments to promote decarbonisation alongside economic development. Essential measures comprise:

- Expansion of Renewable Energy: Aiming to elevate the proportion of renewables in the EU's energy mix to 40% by 2030.
- Emissions Trading System (ETS): Broadening the scope of the ETS to encompass additional sectors like transport and buildings.
- Green Infrastructure Investments: Dedicating €1 trillion over ten years to bolster renewable energy, enhance energy efficiency, and promote clean transport initiatives.
 As of 2022, the EU successfully lowered GHG emissions by more than 30% compared to 1990 levels and reached a renewable energy share surpassing 40% in electricity generation. Nonetheless, obstacles like the affordability of energy and the need for policy alignment among member states continue to exist.

♣ Japan's Fundamental Energy Strategy

The Basic Energy Plan of Japan, updated following the 2011 Fukushima disaster, highlights the importance of energy security, safety, and sustainability. The strategy emphasises the importance of diversifying energy sources to lessen reliance on oil from the Middle East, alongside the implementation of more rigorous safety measures for nuclear energy. Essential steps consist of: Increasing liquefied natural gas (LNG) imports to ensure a stable supply. Reinitiating the operation of nuclear reactors with improved safety protocols in place.

Advancing the adoption of renewable energy sources, especially solar and wind, via feed-in tariffs. The implementation of these measures has successfully decreased Japan's dependence on oil from 90% in 2011 to 77% by 2022, concurrently boosting the share of renewables to 22% in electricity generation.

♣ The United States: Inflation Reduction Act (IRA)

The IRA, established in 2022, represents a significant advancement in the energy policy landscape of the United States. A total of \$369 billion is allocated to clean energy and climate initiatives, providing tax incentives for renewable energy, electric vehicles, and energy-efficient technologies. The legislation further promotes the domestic production of clean energy components, enhancing economic competitiveness.

1.10. National Energy Policies

The national energy policies of India are designed to tackle the increasing energy demand, guarantee energy security, promote economic growth, and fulfil international climate obligations. India, with a population surpassing 1.4 billion, is among the fastest-growing economies, confronting the dual challenge of fulfilling its developmental goals while maintaining environmental sustainability. The energy policies include various initiatives aimed at integrating renewable energy, enhancing energy efficiency, managing fossil fuels, and ensuring access to affordable energy. The policies are in accordance with India's wider economic and environmental goals, which encompass commitments made under the Paris Agreement to lower greenhouse gas (GHG) emissions intensity and enhance the proportion of non-fossil fuel-based energy within its overall capacity.

a. Fundamentals of India's Energy Strategies

The framework of India's energy policy is shaped by essential objectives:

- ♣ Energy Security: Minimising reliance on imported energy through the diversification of domestic energy sources and the improvement of energy self-sufficiency.
- Affordability and Accessibility: Guaranteeing that energy is both affordable and equitably accessible, especially for rural and marginalised communities.
- Sustainability: Advancing renewable energy initiatives and decreasing carbon emissions to alleviate the effects of climate change.
- ♣ Economic growth: Economic growth relies on the development of robust energy infrastructure to support industrialisation and urbanisation, while also promoting advancements in clean energy technologies.

India's energy policies reflect a commitment to global initiatives, notably the United Nations' Sustainable Development Goals (SDGs), with a specific focus on SDG 7, which seeks to guarantee access to affordable, reliable, and sustainable energy for everyone.

b. Essential Elements of India's National Energy Policies

Advancement in Renewable Energy

India has established itself as a prominent player in the realm of renewable energy, setting ambitious goals for the advancement of solar, wind, hydro, and biomass energy. The National Solar Mission, initiated in 2010 as part of the National Action Plan on Climate Change (NAPCC), aimed to reach a solar power capacity of 100 GW by 2022, which was subsequently increased to 280 GW by 2030. In a similar vein, the National Wind-Solar Hybrid Policy encourages the development of hybrid power systems to enhance the efficiency of current infrastructure. By 2022, India had surpassed 125 GW in renewable energy capacity, representing around 40% of its overall installed electricity capacity. The International Solar

Alliance (ISA), launched by India in collaboration with France, exemplifies a commitment to enhancing worldwide collaboration for the advancement of solar energy utilization.

♣ Initiatives for Enhancing Energy Efficiency

India has introduced various initiatives aimed at improving energy efficiency throughout different sectors. The Perform, Achieve, and Trade (PAT) Scheme, initiated by the Bureau of Energy Efficiency (BEE), encourages industries to lower their specific energy consumption by utilising tradable energy-saving certificates. This initiative focusses on sectors that consume significant amounts of energy, including steel, cement, and power generation. The Ujala Scheme, which facilitates the distribution of energy-efficient LED bulbs, has led to considerable energy savings and a decrease in carbon emissions. As of 2022, more than 360 million LED bulbs had been distributed, leading to a reduction in energy consumption by 48 TWh each year and a decrease in GHG emissions by around 40 million tonnes.

Availability of Energy

India's initiatives to achieve universal energy access are illustrated by the Saubhagya Scheme (Pradhan Mantri Sahaj Bijli Har Ghar Yojana), which sought to electrify all households by 2019. By the conclusion of the initiative, India successfully electrified more than 99% of rural households, a significant milestone in tackling energy poverty. The Ujjwala Yojana facilitates access to subsidised liquefied petroleum gas (LPG) connections for low-income households, enhancing indoor air quality and decreasing dependence on biomass for cooking. By 2022, more than 90 million households had reaped the advantages of the scheme.

Management of Fossil Fuels

India continues to depend significantly on coal, which constitutes approximately 50% of its electricity generation. The government has acknowledged the environmental consequences of

coal and has thus prioritised the development of cleaner coal technologies, including supercritical and ultra-supercritical thermal plants, to improve efficiency and minimise emissions. In an effort to lessen reliance on oil imports, India has prioritised the enhancement of domestic oil and gas production, implementing strategies such as the Hydrocarbon Exploration and Licensing Policy (HELP). HELP implements a revenue-sharing model, provides operators with marketing and pricing autonomy, and promotes investment in oil and gas exploration.

♣ Green Hydrogen Initiative

In 2023, India initiated its National Green Hydrogen Mission aimed at establishing itself as a leading centre for the production and export of green hydrogen. The objective is to generate 5 million tonnes of green hydrogen each year by 2030, bolstered by investments in the production of electrolysers and renewable energy sources. This initiative is in accordance with India's objective of reaching net-zero emissions by 2070.

Energy Infrastructure and Intelligent Grids

The development of energy infrastructure in India emphasizes the modernization of power grids, the integration of renewable energy sources, and the minimization of transmission losses. The National Smart Grid Mission (NSGM) advocates for the implementation of smart grids to bolster grid stability, increase energy efficiency, and facilitate the incorporation of distributed energy resources. The One Nation, One Grid initiative seeks to establish a cohesive national grid to enable smooth electricity transmission between different regions. As of 2022, India successfully developed a transmission network that can manage more than 1,000 GW of renewable energy.

1.11. International Energy Agreements

International energy agreements are structured arrangements and treaties between countries aimed at coordinating, regulating, or facilitating activities associated with energy production, consumption, trade, and environmental protection. The significance of these agreements is paramount in tackling global energy challenges, including energy security, resource allocation, environmental sustainability, and climate change. In an interconnected world, energy flows cross national boundaries, highlighting the need for collaborative frameworks to secure a stable, sustainable, and fair energy future. The formation of these agreements is influenced by a variety of factors, including geopolitical interests, economic needs, and environmental concerns. They take on various forms, from bilateral agreements to multilateral treaties facilitated by global institutions.

a. Essential Global Energy Treaties

♣ The Paris Agreement (2015)

The Paris Agreement, established under the United Nations Framework Convention on Climate Change (UNFCCC), represents the most extensive international framework tackling energy and climate change issues. Ratified by 196 nations, this agreement seeks to restrict global temperature rise to under 2°C compared to pre-industrial levels, while also striving for a more ambitious target of 1.5°C. This highlights:

- Nationally Determined Contributions (NDCs): Nations articulate their strategies for addressing climate change, emphasising the decarbonisation of the energy sector.
- Finance and Technology Transfer: Advanced economies committed to providing \$100 billion each year by 2020 to assist emerging nations in the adoption of clean energy technologies.
- Adaptation and Resilience: Initiatives aimed at developing infrastructure and systems that can endure the effects of climate change. The Paris Agreement has prompted substantial national

policies, such as renewable energy targets, carbon pricing strategies, and the gradual elimination of coal-fired power plants.

♣ The Energy Charter Treaty (ECT)

The ECT, established in 1994, offers a legal structure for facilitating cross-border energy collaboration among its 54 member states. This document focusses on critical elements including the safeguarding of investments, the streamlining of trade processes, and the mechanisms for resolving disputes within the energy industry. Initially centred on post-Soviet energy markets, its significance has broadened alongside the globalisation of energy trade. Concerns regarding the ECT focus on its investor-state dispute settlement (ISDS) mechanism, with some arguing that it favours corporate interests at the expense of environmental and social goals.

♣ The Kyoto Protocol (1997)

The Kyoto Protocol served as a foundational step prior to the Paris Agreement, being the inaugural international treaty to require reductions in greenhouse gas emissions, establishing binding targets specifically for industrialised nations. Although it effectively created market-based mechanisms such as the Clean Development Mechanism (CDM) and Joint Implementation (JI), its influence was constrained by the lack of participation from major emitters like the United States and the increasing emissions from developing nations that were not subject to reduction targets.

Agreements of the International Energy Agency (IEA)

The IEA is an independent entity created under the OECD framework, dedicated to promoting energy security and sustainability. The agreements encompass:

- Emergency Response Measures: Organizing strategic oil stock releases to ensure market stability amid supply disruptions.
- Energy Technology Collaboration Programmes: Promoting global research and development in renewable energy, carbon capture, and energy efficiency.
- ♣ The Organization of the Petroleum Exporting Countries (OPEC)

The organization is pivotal in maintaining stability within the global oil markets through the coordination of production levels among its member nations. Collaborative agreements among OPEC members, frequently involving non-member nations (OPEC+), play a significant role in shaping global oil prices and supply dynamics. These agreements play a crucial role for nations and sectors reliant on oil as a fundamental resource.

- Collaborative Efforts in Energy across Regions
 Regional agreements concentrate on tackling energy challenges that are distinctive to particular geographic regions.
- Illustrations encompass: The Energy Union of the European Union seeks to unify energy markets among member states, thereby improving security and promoting sustainability.
- African Renewable Energy Initiative (AREI): Advocates for extensive renewable energy initiatives throughout Africa to tackle energy accessibility and climate objectives.
 North American Energy Cooperation promotes the exchange of resources and the advancement of infrastructure among the United States, Canada, and Mexico, with a focus on oil, gas, and electricity.

b. Effects of Global Energy Treaties

Financial Advantages

Agreements like those under OPEC+ play a crucial role in stabilising energy markets, thereby minimising price volatility that has the potential to disrupt economies. Treaties such as the ECT holds a significant role in attracting foreign direct investment in energy infrastructure, especially in developing regions. Efforts associated with the Paris Agreement, including the implementation of renewable energy, lead to the creation of jobs in developing industries.

Environmental Results

The Paris Agreement and Kyoto Protocol have catalysed substantial national policies aimed at reducing emissions, although the level of progress differs among countries. Agreements related to transboundary water and hydropower, like those established by the Mekong River Commission, play a crucial role in harmonising energy requirements with the imperative of environmental conservation.

♣ Progress in Technology

Rapid advancements in technology: Joint research and development efforts within the IEA have resulted in significant progress in solar, wind, and energy storage solutions. Capacity building through knowledge sharing under agreements such as the UNFCCC has enhanced technical expertise in developing countries.

♣ Societal Effects

Initiatives such as the AREI have broadened electricity availability in underserved areas, enhancing living conditions. Certain agreements, like the ECT, encounter scrutiny for prioritising corporate interests at the expense of public welfare, underscoring the necessity for inclusive frameworks.

1.12. Economic Incentives and Regulations

Economic incentives and regulations are fundamental components of energy policy frameworks, acting as complementary instruments to steer markets, industries, and consumers towards sustainable and efficient energy practices. Regulations set forth essential standards and guidelines, whereas economic incentives utilise market dynamics to promote voluntary adherence and foster innovation. These approaches collectively strive to harmonise the goals of energy security, cost-effectiveness, and environmental sustainability.

a. The Role of Economic Incentives

Economic incentives serve as financial tools aimed at influencing the actions of market participants to achieve preferred energy results. These encompass subsidies, tax advantages, feed-in tariffs, and tradable permits. Incentives play a crucial role in tackling market failures, like the insufficient investment in renewable energy or energy efficiency, by alleviating the perceived risks and costs associated with the adoption of cleaner technologies.

Types of Economic Incentives Financial Assistance and Funding Opportunities Authorities offer direct monetary assistance to stimulate investment in renewable energy initiatives, energy-efficient devices, or infrastructure enhancement. For instance: The U.S. Production Tax Credit (PTC) has played a crucial role in advancing the deployment of wind energy.

The subsidies provided by India under the National Solar Mission have played a crucial role in lowering the expenses associated with solar photovoltaic (PV) installations. Feed-in Tariffs (FiTs) ensure that renewable energy producers receive consistent payments for supplying electricity to the grid. This mechanism mitigates market uncertainty and encourages long-term investments. The Renewable Energy Act (EEG) in Germany stands out as a significant case, playing a crucial role in the country's advancement in solar and wind energy implementation. Carbon Pricing Mechanisms Carbon pricing incorporates the external costs associated with

greenhouse gas emissions, establishing economic disincentives for the utilisation of fossil fuels.

b. Various mechanisms encompass:

- ♣ Carbon Taxes: Implementing a tax on carbon emissions, similar to Sweden's approach, which imposes a charge of \$130 per tonne of CO₂, promoting a transition to cleaner energy sources.
- Cap-and-Trade Frameworks: Establishing an emissions cap and implementing tradable permits, as demonstrated by the European Union Emissions Trading System (EU ETS). Tax Incentives Tax credits, deductions, and exemptions alleviate the financial pressures faced by entities that implement renewable energy technologies or enhance energy efficiency measures. The U.S. Solar Investment Tax Credit (ITC) has facilitated the swift growth of solar installations. Green bonds serve to attract private investment for sustainable energy initiatives by providing appealing financial returns. The global green bond market surpassed \$500 billion in issuance in 2021, driven significantly by contributions from both governments and corporations.

c. The Significance of Regulations

Regulations create binding standards and frameworks to guarantee adherence to energy and environmental objectives. In contrast to incentives, regulations impose obligatory actions, like energy efficiency targets or emissions limits, and frequently entail penalties for failing to comply. Regulations play a crucial role in tackling issues related to public goods, including air quality and climate mitigation, especially when market-based solutions fall short.

a. Categories of Regulations

Regulations on Renewable Energy A number of nations implement Renewable Portfolio Standards (RPS), mandating that utilities obtain a specific proportion of their electricity from

renewable energy sources. As an illustration: India has set a requirement for 40% of its energy capacity to come from non-fossil fuel sources by the year 2030. California aims to achieve 100% clean electricity by the year 2045 through its Renewable Portfolio Standards.

Standards for Energy Efficiency Energy efficiency regulations, including appliance performance standards, building codes, and industrial efficiency benchmarks, play a crucial role in minimising energy consumption across various sectors. Illustrations consist of: The Energy Efficiency Directive of the European Union requires a 32.5% enhancement in energy efficiency by the year 2030. Japan's Top Runner Program establishes performance standards for appliances and vehicles, encouraging manufacturers to pursue innovation.

Emission Regulations Emissions standards impose limitations on the discharge of pollutants originating from power plants, industrial facilities, and vehicles. As an example: The Clean Power Plan in the United States sought to achieve a 32% reduction in CO₂ emissions from power plants compared to 2005 levels by the year 2030.

The emissions standards established in India in 2017 for coal-fired power plants impose restrictions on particulate matter, sulphur dioxide, and nitrogen oxides. Regulations regarding grid access and integration policies guarantee that renewable energy generators receive equitable access to electricity grids, promoting their seamless integration. The Third Energy Package of the EU advocates for unbundling and enhanced market access, thereby encouraging competition and innovation. Environmental Impact Assessments Environmental Impact Assessments serve as essential regulatory instruments that mandate projects to evaluate and address their potential environmental effects prior to receiving approval. They play a vital role in harmonising development alongside environmental preservation.

1.13. Subsidies and Tax Incentives

Subsidies and tax incentives serve as essential policy instruments aimed at promoting investment and consumption in targeted sectors, especially in renewable energy, energy efficiency, and clean technology. The purpose of these mechanisms is to tackle market inefficiencies, mitigate financial risks, and decrease the expenses linked to the shift towards sustainable energy systems. Direct financial support and the reduction of tax liabilities through subsidies and tax incentives play a crucial role in fostering innovation, decreasing greenhouse gas (GHG) emissions, and promoting economic growth.

Subsidies represent financial assistance from governments aimed at lowering the expenses associated with the production or consumption of various goods and services. In the energy sector, financial support is mainly directed towards advancing clean energy technologies, alleviating high upfront expenses, and maintaining energy affordability for consumers.

a. Types of Energy Subsidies

- → Direct Monetary Assistance: Authorities allocate one-time financial assistance to facilitate the development of renewable energy systems or enhance energy-efficient technologies. India's Ministry of New and Renewable Energy (MNRE) provides financial incentives for rooftop solar photovoltaic (PV) installations, which can cover as much as 40% of the initial investment for residential users.
- Feed-in Tariffs (FiTs): FiTs ensure consistent payments to renewable energy producers for supplying electricity to the grid over a designated timeframe. This promotes consistent investment returns and fosters a focus on long-term strategies. The Renewable Energy Act (EEG) in Germany implemented Feed-in Tariffs (FiTs) for solar and wind energy, resulting in significant expansion of renewable energy capacity.

- Support for Production: These payments are determined by the amount of energy generated from renewable sources, encouraging increased production. Example: The U.S. Production Tax Credit (PTC) offers a per-kilowatt-hour (kWh) incentive for wind energy producers, playing a significant role in the U.S. achieving the status of the world's largest producer of wind energy. Subsidies for Consumption Authorities reduce energy costs for consumers, enhancing the affordability of clean energy options. In Sweden, financial incentives for electric vehicle (EV) purchasers greatly lower the initial expenses associated with EVs in comparison to traditional petrol vehicles.
- Subsidies for Research and Development (R&D): Funding for research and development propels advancements in clean technologies, including sophisticated batteries and carbon capture solutions. The European Union's Horizon 2020 program designated substantial funding for energy research and development initiatives.

b. Tax Incentives: Definition and Functionality

Tax incentives lower the tax obligations for individuals or organisations that invest in clean energy technologies or implement energy-efficient practices. The purpose of these incentives is to reduce expenses, improve competitiveness, and encourage investment from the private sector.

- Categories of Tax Incentives: Tax credits serve to directly decrease the tax liability, on a dollar-for-dollar basis, for those who invest in or implement clean energy systems.

 For instance, the U.S. Investment Tax Credit (ITC) enables developers of solar energy projects
 - to subtract as much as 30% of the installation costs from their federal tax obligations.
- ♣ Accelerated Depreciation: This incentive enables companies to accelerate the depreciation of renewable energy assets, thereby lowering taxable income during the early years of operation.

- India's Accelerated Depreciation Scheme for wind turbines allowed companies to recoup as much as 80% of their investment in the initial year, facilitating swift adoption of wind energy.
- Tax Exemptions and Deductions: These incentives provide exemptions for particular products or activities from certain taxes or permit deductions for expenses related to renewable energy. Norway provides tax exemptions for the acquisition of electric vehicles (EVs), which encompass VAT and registration fees, thereby enhancing the affordability of EVs for consumers.
- Lowered Corporate Tax Rates: Organisations involved in the production of renewable energy or the advancement of clean technologies frequently enjoy reduced corporate tax rates. South Korea offers lower corporate tax rates for firms engaged in green energy research and development, as well as production.
- Tax Exemptions for Green Bonds: The interest income generated from green bonds that are issued to finance renewable energy projects frequently enjoys tax-exempt status, thereby appealing to investors. For instance, tax exemptions are available in the United States for specific municipal green bonds.

c. Illustrations of Effective Implementations

The Role of Solar Energy in Germany: The Feed-in Tariffs established by Germany's Renewable Energy Act have motivated countless homeowners and businesses to adopt solar photovoltaic systems. From 2000 to 2020, Germany's solar capacity expanded significantly, increasing from 1 GW to more than 54 GW, positioning the country as a frontrunner in solar energy production. The FiTs provided consistent returns for investors and contributed to reducing solar costs by leveraging economies of scale.

- Wind Energy in the U.S: The U.S. Production Tax Credit (PTC) for wind energy offered a per-kWh subsidy for the generation of wind power. From 2010 to 2020, the PTC facilitated the installation of more than 100 GW of wind capacity, establishing wind energy as the predominant source of renewable power in the nation.
- Electric Vehicles in Norway: Norway has implemented a thorough tax incentive program for electric vehicles, which encompasses exemptions from VAT, registration fees, and road tolls, as well as privileges such as access to bus lanes and complimentary parking. Consequently, electric vehicles represented more than 80% of new car sales in Norway by 2022, establishing a standard for worldwide electric vehicle adoption.
- Solar Energy Utilisation on Rooftops in India: The subsidy scheme implemented by the government under the National Solar Mission has successfully lowered the cost of rooftop solar PV systems by 40% for residential consumers, resulting in the installation of more than 7 GW of rooftop solar capacity by 2023.

d. Effects of Subsidies and Tax Benefits

- Economic Expansion: Subsidies and tax incentives foster investments in renewable energy, generating employment opportunities and propelling economic development. The International Renewable Energy Agency (IRENA) reported that the global renewable energy sector provided employment for more than 12 million individuals in 2020, with notable contributions from solar and wind energy sources.
- Expense Minimisation: The provision of financial support has significantly expedited the reduction of costs associated with renewable energy technologies. For instance, the expense associated with solar PV has decreased by more than 80% over the last ten years, propelled

by subsidies and tax incentives that enabled large-scale production and technological progress.

- Advantages for the Environment: Subsidies and incentives have played a crucial role in lowering GHG emissions through the encouragement of clean energy adoption. For example, wind energy, bolstered by the PTC in the U.S., has been estimated to prevent around 200 million metric tonnes of CO₂ emissions each year.
- Social Equity: Subsidies for consumption facilitate access to clean energy technologies for low-income households, effectively tackling energy poverty. For instance, solar home systems in rural Africa, bolstered by subsidies, have delivered electricity to millions.

1.14. Carbon Pricing Mechanisms

Carbon pricing mechanisms serve as crucial instruments for tackling climate change by incorporating the environmental costs of greenhouse gas (GHG) emissions into economic frameworks. Assigning a monetary value to carbon emissions creates incentives for businesses, governments, and individuals to embrace cleaner technologies and practices. Two main strategies exist for carbon pricing: carbon taxes and cap-and-trade systems. A carbon tax establishes a specific cost for each tonne of carbon dioxide equivalent (CO₂e) emissions, ensuring clarity in pricing and ease of understanding. For instance, Sweden implemented a carbon tax in 1991, which now surpasses \$130 per tonne, leading to a notable decrease in emissions alongside economic growth. On the other hand, cap-and-trade systems, like the European Union Emissions Trading System (EU ETS), establish a cap on permissible emissions and facilitate a market for trading emission allowances. This approach guarantees environmental results through emission limits while encouraging economically efficient

reductions. Hybrid systems that integrate tax and cap features significantly improve flexibility and efficiency.

The effects of carbon pricing are diverse. It stimulates investments in renewable energy, energy efficiency, and low-carbon technologies, while also generating revenues that governments can reinvest in environmentally friendly initiatives or social programs. For example, the carbon tax implemented in British Columbia has resulted in notable decreases in emissions while simultaneously fostering economic growth through the strategic allocation of revenues to households and businesses. From an environmental perspective, these mechanisms promote substantial reductions in emissions; for instance, the EU ETS has played a role in achieving a 35% decrease in emissions from the sectors it covers since its launch in 2005. In light of these advantages, obstacles like carbon leakage, equity issues, price fluctuations, and political opposition continue to exist. To tackle these challenges, it is essential to implement carefully considered policy frameworks. This includes strategies such as revenue recycling to alleviate regressive effects, border carbon adjustments to prevent leakage, and fostering global collaboration to align pricing standards. Carbon pricing serves as a fundamental element of international climate initiatives, facilitating the shift of economies towards sustainable practices while promoting innovation and strengthening economic resilience.

1.15. Technological Innovation and Investment

Technological innovation and investment play a crucial role in reshaping global energy systems, tackling climate change, and promoting sustainable economic growth. The incorporation of cutting-edge technologies alongside the careful distribution of financial resources facilitates the shift from carbon-heavy energy systems to cleaner, more efficient, and

resilient options. This transformation is essential for addressing increasing energy demands, fulfilling global climate objectives, and enhancing economic competitiveness.

Advancements in technology and capital allocation in energy frameworks: Fostering sustainable progress

Technological innovation and investment play a crucial role in reshaping global energy systems, tackling climate change, and promoting sustainable economic growth. The incorporation of cutting-edge technologies alongside the thoughtful distribution of financial resources facilitates the shift from carbon-heavy energy systems to cleaner, more efficient, and robust alternatives. This transformation is essential for addressing increasing energy needs, fulfilling global climate objectives, and enhancing economic competitiveness. The advancement of technology within the energy sector involves the creation and implementation of new technologies or the substantial improvement of those that already exist. It includes progress in the areas of energy generation, storage, distribution, and consumption.

- Sustainable Energy Innovations: Advancements in renewable energy have transformed the energy sector, enhancing the efficiency and affordability of clean energy sources such as solar, wind, and hydropower. In the past ten years, the price of solar photovoltaic (PV) modules has decreased by more than 80%, influenced by progress in materials science, improvements in manufacturing techniques, and increased economies of scale.
- ♣ Energy Storage: Energy storage technologies, including lithium-ion batteries and innovative options like solid-state batteries and flow batteries, play a vital role in tackling the intermittency associated with renewable energy sources. For instance, the extensive battery installations by Tesla, like the Hornsdale Power Reserve in Australia, illustrate the capability of battery storage to enhance grid stability and deliver peak power.

- Intelligent Energy Networks: Smart grids incorporate advanced digital technologies, including sensors, data analytics, and artificial intelligence (AI), to improve energy distribution, minimise losses, and boost reliability. China's implementation of AI-powered grid systems has notably decreased electricity waste and enhanced the integration of renewable energy sources.
- Hydrogen Economy: Green hydrogen, generated via water electrolysis with renewable energy sources, is becoming a crucial solution for reducing carbon emissions in challenging sectors such as heavy industry and transportation. The Hydrogen Strategy of the European Union seeks to deploy 40 GW of electrolysers by 2030 for the production of green hydrogen, which will support sectors such as steel manufacturing, shipping, and aviation.
- ♣ Carbon Capture, Utilisation, and Storage: CCUS technologies are designed to capture CO₂ emissions produced by industrial processes and power generation, subsequently storing them underground or repurposing them for various industrial applications. Norway's Northern Lights project effectively captures and stores CO₂ emissions from industrial facilities, setting a precedent for large-scale carbon sequestration efforts.
- Innovations in Energy Efficiency: Innovative building materials, intelligent thermostats, and streamlined industrial processes contribute to lower energy usage without compromising or even boosting productivity. Japan's Top Runner Program encourages industries to create energy-efficient appliances, resulting in considerable energy savings.

a. Technological Investment

Technological investment involves the strategic allocation of financial resources aimed at the research, development, deployment, and scaling of innovative technologies across diverse sectors, such as energy. In the realm of energy systems, investments in technology play a crucial role in driving innovation, expediting the shift to clean energy, improving energy

- efficiency, and bolstering economic growth. These investments allow societies to fulfil increasing energy needs while tackling essential issues like climate change, energy security, and resource sustainability. The primary areas for Technological Investment in Energy are:
- Technologies for Renewable Energy: Investments in solar, wind, hydropower, and biomass technologies have led to notable reductions in costs and enhancements in efficiency. Between 2010 and 2020, the cost of solar photovoltaic (PV) systems saw a remarkable decline of over 80%, driven by advancements in manufacturing processes, improvements in materials, and extensive large-scale deployment.
- Systems for Energy Storage: Energy storage technologies, including lithium-ion batteries, flow batteries, and hydrogen storage, play a vital role in tackling the intermittency associated with renewable energy sources. Tesla's Gigafactories signify a significant commitment from the private sector towards battery production, which reduces costs and facilitates the widespread adoption of electric vehicles and grid storage solutions.
- ♣ Carbon Capture, Utilisation, and Storage (CCUS): CCUS technologies are designed to capture CO₂ emissions generated from industrial processes and power plants, with options for either underground storage or repurposing for industrial applications. ExxonMobil's substantial investment in CCUS technologies is designed to mitigate emissions from its operations and challenging sectors.
- Hydrogen Technologies: Investment in hydrogen production, storage, and distribution is facilitating the development of a hydrogen economy, especially in the decarbonisation of heavy industries and transportation. For instance, the European Union has allocated €9 billion towards its Hydrogen Strategy, with the objective of achieving 40 GW of electrolyser capacity by the year 2030.

- Intelligent Grid Framework: Smart grids incorporate advanced digital technologies, data analytics, and automation to enhance energy distribution and boost reliability. The U.S. Department of Energy's Smart Grid Investment Grant (SGIG) program allocated \$4.5 billion towards grid modernisation initiatives, enhancing the efficiency and resilience of the grid.
- Lutting-Edge Nuclear Energy: Investments in advanced nuclear technologies, including small modular reactors (SMRs) and fusion energy, are focused on delivering dependable, low-carbon energy solutions. Bill Gates' TerraPower is working on advanced nuclear reactors, with backing from both private and public funding.
- Electric Vehicles and Charging Infrastructure: The advancement of electric vehicle technology and the development of corresponding charging networks are essential for the shift towards sustainable transportation. In 2021, investments in electric vehicles worldwide surpassed \$300 billion, with major players such as Tesla, BYD, and Volkswagen at the forefront of the industry.
- Technologies for Enhancing Energy Efficiency: Investments in building insulation, smart appliances, and industrial efficiency technologies effectively lower energy consumption without compromising productivity. Japan's top runner program promotes energy-efficient appliances, resulting in notable decreases in national electricity consumption.

b. Types of Technological Investment

Investment in the Public Sector: Governments allocate resources to energy research and development (R&D) via grants, subsidies, and specialised programs. Public investments frequently focus on nascent technologies and high-risk initiatives that do not demonstrate immediate commercial potential. The U.S. Department of Energy's Advanced Research

- Projects Agency-Energy (ARPA-E) supports ground breaking projects that have the potential to bring about significant change.
- Investment from the Private Sector: Private companies and venture capitalists play a crucial role in driving technological innovation, especially in the commercialisation and scaling of technologies. In 2021, investment in climate technology by venture capitalists amounted to \$53 billion, with a concentration on energy storage, renewable energy sources, and carbon removal innovations.
- ♣ Public-Private Partnerships (PPPs): These partnerships merge public funding with private expertise to expedite technological deployment and mitigate risks. India's International Solar Alliance (ISA) utilises collaborations to fund solar initiatives in developing countries.
- Multilateral and International Financing: Entities such as the World Bank, Green Climate Fund, and regional development banks offer financial assistance for clean energy initiatives in developing nations. The Desert to Power initiative by the African Development Bank aims to establish 10 GW of solar capacity throughout the Sahel region.
- ♣ Corporate Sustainability Efforts: Companies allocate resources to clean energy technologies to meet sustainability objectives and lower operational emissions. Google has pledged to function solely on carbon-free energy by 2030, making significant investments in renewable energy and enhancing energy efficiency.

1.16. Motivation of the study

The motivation for researching the complex relationship of energy, economy, and environment stems from the compelling necessity to confront the various issues that this triadic interaction presents in the context of sustainable development. As the globe grapples with the repercussions of climate change, resource depletion, and economic inequality, understanding the complicated

links between these three realms becomes increasingly important for informing policy, guiding economic strategy, and encouraging environmental stewardship.

One key motive is the rising understanding that conventional economic development patterns, which have historically relied on the abundant use of fossil fuels, are no longer viable in the face of environmental deterioration and climate change. This study is motivated by the urgent need to decouple economic growth from environmental degradation, with the goal of determining how economies might continue to grow and prosper without increasing environmental crises. This necessitates a thorough examination of how energy usage, economic policies, and environmental consequences are linked and how they may be realigned to support the transition to a low-carbon, sustainable economy.

A further significant motivator is the worldwide need to achieve energy security while also addressing environmental issues. The study is motivated by the need to understand how to reconcile the demand for reliable and inexpensive energy with the need to reduce greenhouse gas emissions and protect natural ecosystems. This is especially important in light of the current transition to renewable energy sources, where the economic ramifications must be properly managed in order to minimise disruptions in energy supply and economic stability.

The study is also motivated by an awareness of the social and economic disparities that result from the current energy-environment-economy dynamics. Developing countries, in particular, confront the dual task of stimulating economic growth to pull people out of poverty while also managing the environmental consequences of such expansion. By exploring the interdependence of the three Es, the study hopes to contribute to more fair and just policy frameworks that can support global sustainable development, ensuring that the advantages of economic growth and energy access are equitably distributed while minimising environmental harm.

1.17. Statement Problem

- ❖ It is necessary to study the level of optimal energy mix for environment sustainability.
- Clarity is required to decide the evaluation standard for energy, economy and environment sustainability is not uniform.
- ❖ To determine the unique unified energy investment goals is necessary mainly for the developing country.
- ❖ CO₂ emission can't be a proxy to environment pollution as it is not the only cause of environment pollution. Research should been done by including other polluting indicators.

1.18. Significance of the study

- ❖ The significance of this study lies in recognising and addressing the challenges associated with the interrelationship among energy, economy and environment by highlighting the problems faced by the nations. This will give the blue print and help solve the problems of the developing nations
- As time series data was analysed of various nations hence the exclusivity of results helps to pinpoint the reason, why some nations have successfully reached the sustainability through a proper linkage of energy, economy and environment.
- The study is also of much significance to the policy makers as it reflects the how a nation can develop sustainably.

CHAPTER 2

LITERATURE REVIEW

2.1 The assessment of different energy system

The research on the sustainability mainly focuses on the assessment of sustainability in energy system, economy, society, environment and technology. Guzmán et al. (2019) established a renewable energy sustainability assessment system based on environmental, economic and social dimensions, and verified that the combination of life cycle analysis and multi-criteria decision making is correct for the assessment of renewable energy system sustainability. (Harjanne and Korhonen, 2020) presented key issues in the concept of renewable energy in terms of sustainability, inconsistency, policy impact, decoy and conversion strategies, and general misleading; and proposed models for classifying energy production based on carbon content and combustion.

Guen et al. (2018) used energy maps to qualitatively analyse the promising energy technologies in Swiss villages and improve energy sustainability in Swiss villages through building renovation and renewable energy integration. Wang and Chen (2010) analysed the role of the Clean Development Mechanism in promoting the sustainable development of renewable energy in China by reviewing CDM activities. Chuang et al. (2019) assessed the sustainability of Taiwan's renewable energy sources and determined whether Taiwan's future electricity supply was stable. Böhringer et al.(2017) found that the amount of Internet subsidies had little direct impact on the sustainability of renewable energy technologies, but could lead to higher electricity prices and

encourage technological innovation in renewable energy. Maes et al. (2015) used the bio-refinery as a case to evaluate the EU Renewable Energy Directive Sustainability Guidelines, the results show that combining RED-based sustainability assessment with other more comprehensive assessments can more accurately understand the sustainability of the project. Tareen et al. (2018) provided an insight into the potential of these resources in Pakistan to generate electricity for the national grid on a large scale, the results show that biomass is the most sustainable, available, implementable and environmentally friendly resource that can be used to reduce Pakistan's energy demand and supply gap.

2.2 The relationship between Economic growth and energy sources

Inglesi-Lotz (2016) used panel data to study the impact of renewable energy consumption on economic growth; the results show that the impact of renewable energy consumption on economic growth is positive, and promoting the development of renewable energy can promote the sustainability of economic growth. Pierie et al. (2016) discussed an integrated system approach for determining the sustainability of biogas or green gas production pathways and demonstrates that this approach can be used as a sustainable solution for generating and identifying energy production pathways. Maulidia et al. (2019) discussed Indonesia's current renewable energy policy and how to achieve sustainable development of renewable energy and its goals. Sinha et al. (2018) analysed the causal relationship between economic growth, carbon emissions, fossil fuels and renewable energy consumption during the period 1990–2016; the results demonstrate that renewable energy is implemented to ensure sustainable economic growth by reducing carbon emissions and increasing energy supply.

2.3 Energy system and Sustainable Development

Zhao and Guo (2015) established an evaluation index system for the sustainability of external benefits of renewable energy based on economic, social and environmental factors. Then they used the hybrid MCDM method to evaluate China's renewable energy sources, the results indicated that more policies to support photovoltaic power generation should be implemented to promote the sustainable development of the entire renewable energy industry. Petinrin and Shaaban (2015) discussed Malaysia's renewable energy policy and current energy implementation strategy, and evaluated the sustainability of renewable energy from 2000 to 2015; the results show that biomass and solar energy are the most potential energy sources. Wang et al. (2018) used the Divisia index method to study the factors affecting the sustainable development of renewable energy in China, including supply structure, energy security, and carbon emissions and other factors. The results show that strong and sustainable renewable energy policies will help China's sustainable energy development. Zhao and Chen (2018) first identified 43 factors affecting the sustainable development of renewable energy in China through multi-facet content analysis; and then used questionnaires and relative importance index models to extract 33 key factors affecting the sustainable development of renewable energy within the context of China. In addition, the principal component analysis and driving force model were applied to determine the factors that have a greater impact on the sustainability of renewable energy.

2.4 The validity of EKC hypothesis

The EKC is a variant of the Kuznets curve hypothesis put forward by Simon Kuznets (1955) in which the author postulated a nonlinear inverted-U shaped relationship between economic growth and income inequality. The difference between these two hypotheses is that the EKC hypothesis replaces income inequality in the Kuznets curve hypothesis and comments on the changing patterns of environmental quality, emissions of GHG in the context of this paper, along with rising

national income level which is used to proxy for economic growth. The first empirical study that tested the validity of the EKC hypothesis for Mexico was pioneered by Grossman and Krueger (1991) in which the authors used sulphur and smoke emissions to quantify environmental quality within the EKC analysis. However, the findings condemned the existence of the EKC hypothesis in Mexico. Dong et al. (2018) the authors employed annual natural gas consumption data to assess the CO2 emission-induced EKC hypothesis in the context of 14 Asia-Pacific economies. The results inferred that greater consumption of natural gas attributed to smaller volumes of CO2 emissions within these economies while empirical evidence of the existence of the EKC hypothesis was also confirmed. Similar findings were reported for the BRICS countries include Brazil, Russia, India, China, and South Africa. Nathaniel and Bekun (2020) examined the association between urbanization and GDP in Nigeria covering the period from 1971 to 2014 by employing the Bayer and Hanck co-integration test, ARDL, FMOLS, DOLS, CCR, and VECM Granger causality. They found that urbanization negatively inhibits GDP, and there is a bidirectional link between urbanization and GDP. Etokakpan et al. (2020) examined the association between gross capital accumulation and GDP in Malaysia covering the period 1980-2014, employing the Bayer and Hanck cointegration tests, ARDL, and Granger causality. The authors concluded that an increase in gross capital formation would increase GDP. Adebayo (2020) also employed the ARDL and wavelet coherence methods to examine the long-run and causal relationship between CO2 emissions and GDP in Mexico. The results showed a positive link between these variables. In terms of causality, they identified a two-way interaction between CO2 emissions and GDP.

Table 2.1: Summary of the literature review

Name of the article	Author name, year of	Nations, time frame	Methodology Variables	Findings
	publication			

CO2 emissions and financial development in an emerging economy: an augmented VAR approach	Abbasi and Riaz (2016)	Pakistan (1971–2011)	VECM, Granger, ARDL (FDI, CO2, FD, Stock market, GDP)	FDI ≠ CO2 GDP→ CO2 (+) Financial development does not aid in mitigating CO2 emissions rather it increases it. CO2 emissions rise as per capita income rises. Government should devise comprehensive and realistic mitigation strategies
How urbanization affects CO2 emissions in Malaysia? The application of STIRPAT model	Shahbaz et al. (2016)	Malaysia (1970Q1– 2011Q4)	Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT), ARDL, VECM Granger causality (EC,GDP, URB, CO2, TO)	EC → CO2 (+) GDP→ CO2 (+) URB → CO2 (-) TO→CO2 (+) Economic growth is a major contributor to CO2 emissions. Energy consumption raises emissions intensity and capital stock boosts energy consumption. Trade openness increases CO2 emissions. The relationship between urbanization and CO2 emissions is Ushaped i.e. urbanization initially reduces CO2 emissions, but after a threshold level, it increases CO2 emissions.
The effects of financial development, economic growth, coal consumption and trade openness on CO2 emissions in South Africa	Shahbaz et al. (2013)	South Africa, (1965–2008)	ARDL, ECM (CC, EE, FDI, TO, CO2)	CC → CO2 (+) EE → CO2 (+) FD→ CO2 (-) Rise in economic growth increases energy emissions. Financial development lowers energy emissions. Coal consumption significantly deteriorate environment.

				Trade openness improves environmental quality. Existence of EKC is also found.
Impacts of urbanization and industrialization on energy consumption/CO2 emissions: does the level of development matter?	Li and Lin (2015)	Low, middle, and high-income countries (1971–2010)	Dynamic panel threshold regression models (Y, URB, EN, CO2)	In low-income nations $Y \rightarrow CO2 (+)$ EN $\rightarrow CO2 (+)$ URB $\rightarrow CO2 (+)$ In middle-income nations $Y \rightarrow CO2 (+)$ EN $\rightarrow CO2 (+)$ URB $\rightarrow CO2 (+)$ In high-income nations $Y \rightarrow CO2 (+)$ EN $\rightarrow CO2 (+)$ EN $\rightarrow CO2 (+)$ URB $\rightarrow CO2 (+)$
Testing the EKC hypothesis by considering trade openness, urbanization, and financial development: the case of Turkey	Ozatac et al. (2017)	Turkey (1960–2013)	ARDL, causality (Y, EN, TO, URB, FD, CO2)	EKC holds $GDP \rightarrow CO2(+)$ $EN \rightarrow CO2 (+)$ $URB \rightarrow CO2(+)$ $TO \rightarrow GDP(+)$
Economic growth, financial development, urbanisation and electricity consumption nexus in UAE	Sbia et al. (2017)	UAE (1975–2011)	ARDL, VECM (Y, EC FD)	URB → EC (+) Y → EC (+) FD → EC (+) The relationship between urbanisation and electricity consumption is an inverted U-shaped. This implies that urbanisation increases electricity consumption initially and, after a threshold level of urbanisation, electricity demand falls.

CO2 emissions, energy consumption, economic growth, and financial development in GCC countries: Dynamic simultaneous equation models	Bekhet et al. (2017)	Gulf countries (1980–2011)	ARDL, causality (Y, ENE, FD, CO2)	CO2 → ENE in Saudi Arabia, UAE, and Qatar FD → CO2 in UAE, Oman, and Kuwait There is a existence of a long- term equilibrium relationship among CO2 and real GDP per capita, energy consumption, and financial development in all GCC countries except UAE.
The impact of income, trade, urbanization, and financial development on CO2 emissions in 19 emerging economies	Saidi and Mbarek (2017)	19 emerging economies (1990–2013)	GMM model Panel regression (Y, TO, URB, FD, CO2)	EKC is hold FD → CO2 (-) URB → CO2 (-) Financial development has a long-run negative impact on carbon emissions, implying that financial development minimizes environmental degradation. This means that financial development can be used as an implement to keep the degradation environmental clean by introducing financial reforms
The process of peak CO2 emissions in developed economies: a perspective of industrialization and urbanization.	Dong et al. (2019)	Developed economies (1960–2012)	threshold regression model (Y, URB, EN, CO2)	EN → CO2 (+) URB → CO2 (+) An assessment of the threshold effects of urbanization indicates that the effect of urbanization on carbon emissions differs at different urbanization levels.
Testing validity of the EKC hypothesis in South Korea: role of renewable energy and trade openness.	Koc and Bulus (2020)	South Korea (1971–2017)	ARDL (GDP, ENE, TO, CO2,REN)	N-shaped relationship GDP \rightarrow CO2 (+) ENE \rightarrow CO2 (+) TO \rightarrow CO2 (-) REN \rightarrow CO2 (-)

				The N-shaped relationship between per capita CO2 emissions and GDP per capita implies that although some environmental gains will be achieved after the first turning point, an increase in environmental degradation may be seen from a second turning point.
Dynamic linkage among industrialisation, urbanisation, and CO2 emissions in APEC realms: evidence based on DSUR estimation.	Wang et al. (2020)	APEC nations (1990–2014)	Dynamic- unrelated seemingly regression (Y, IND, EN, CO2)	IND \rightarrow CO2 (+) Y \rightarrow CO2 (+) URB \rightarrow CO2 (+)
Fresh insight into the EKC hypothesis in Nigeria: accounting for total natural resources rent.	Bekun et al. (2020)	Nigeria (1971–2015)	ARDL (Y, Y2, FDI, EC, CO2)	EKC is hold GDP \rightarrow CO2 (+) EC \rightarrow CO2 (+) FDI \rightarrow CO2 (-)
The effects of energy consumption, economic growth and financial development on CO2 emissions in China: a VECM Approach. Sustainability	Jian et al. (2019)	China (1982–2017)	VECM, impulse response (Y, FD, EN, CO2)	FD \rightarrow CO2 (+) Y \rightarrow CO2 (-) EN \rightarrow CO2 (+) EN \rightarrow FD
The impact of energy intensity, urbanization, industrialization, and income on CO2 emissions in South Africa: an ARDL	Nondo and Kahsai (2020)	South Africa (1970–2016)	ARDL, VECM (Y, URB, ENE, IND)	URB \rightarrow CO2 (+) ENE \rightarrow CO2 (+) IND \rightarrow CO2 (+)

bounds testing approach. The nexus between renewable energy, economic growth, trade, urbanization and environmental quality: a comparative study for Australia and Canada	Rahman and Vu (2020)	Australia and Canada (1960–2015)	ARDL, VECM causality (Y, EN, URB, CO2)	In Australia $Y \rightarrow CO2(+)$ In Canada $Y \rightarrow CO2 (+)$ URB $\rightarrow CO2 (+)$
The impact of economic structure to the environmental Kuznets curve (EKC) hypothesis:	Dogan and Inglesi-Lotz (2020)	European countries (1980–2014)	Panel OLS, FMOLS, FE (Y, EN, CO2)	EKC does not hold GDP → CO2 (-) The EKC hypothesis is not confirmed – but a U-shaped relationship is confirmed. The industrial share decreases emissions through the development and absorption of technologies that are energy efficient and environmental friendly. EKC hypothesis is confirmed when the aggregate GDP growth is considered, taking into account the improvement of the overall economic conditions of the countries regardless of the economic structure and role of industrialization
Testing the EKC hypothesis for the top six hydropower energy-consuming countries: evidence from Fourier bootstrap ARDL procedure	Pata and Aydin (2020)	Brazil, China, Canada, India, Norway and the USA (1965–2016)	Fourier bootstrap ARDL, Fourier TYGC (Y, EN, HEC, CO2)	EKC hypothesis is not valid HEC → GDP in Brazil HEC ↔ GDP in China HEC alone is not sufficient to reduce EF in the six countries

Rediscovering the EKC hypothesis for the 20 highest CO2 emitters among OECD countries by level of globalization	Leal and Marques (2020)	OECD countries (1990–2014)	FMOLS, DOLS, AMG, CDS (Y, TO, CO)	EKC hypothesis is not valid OP→CO2 (+) REN → CO2 (+) Renewable energy consumption is ineffective for mitigating CO2 emissions in the long-run in the LGC (low globalized countries)
Dynamic relationship between oil price and inflation in oil exporting economy: empirical evidence from wavelet coherence technique	Adebayo et al. (2020)	Mint nations (1980–2018)	Pedroni, Westerlund Coint., PMG, CDS, panel causality (Y, TO, URB, EN, CO2)	GDP \neq CO2 TO \rightarrow CO2 (-) TO \rightarrow ENE (+) URB \rightarrow CO2 (+)
International tourism, social distribution, and environmental Kuznets curve: evidence from a panel of G-7 countries	Anser et al. (2020)	G-7 countries (1995–2015)	Random effect, panel causality (CO2, ITR, FDI, GEE, HEXP, INEQ, EG)	ITR \rightarrow CO2 (+) GDP \rightarrow CO2 (+) FDI \rightarrow CO2 (+) GEE \rightarrow CO2 (+)
Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies	Khattak et al. (2020)	BRICS (1980–2016)	CCEMG technique (CO2, GDP, RE, YPC, YPC)	EKC hold YPC \rightarrow CO2 (+) IN \rightarrow CO2 (+) RE \rightarrow CO2 (-)
The nexus between renewable energy, economic growth, trade, urbanization and environmental quality: a comparative study for Australia and Canada	Rehman et al. (2020)	Australia and Canada (2000–2018)	GRA Model, Hurwicz method (CO2, EC, GDP, PG)	GDP \rightarrow CO2 (+) EC \rightarrow CO2 (+) PG \rightarrow CO2 (+)

Innovation, financial development, and transportation infrastructure matter for environmental sustainability in China?	Umar et al. (2020)	China (1971–2018)	Bayer-Hanck cointegration, wavelet coherence (CO2, IN, FD, TO, GDP)	IN \rightarrow CO2 (+) FD \rightarrow CO2 (-) TO \rightarrow CO2 (+)
An empirical analysis of the determinants of CO2 emissions in GCC countries.	Zmami and Ben-Salha (2020)	GCC countries (1980–2017)	STIRPAT model, PMG (CO2, GDP, EC, URB, TRA, FDI)	EKC valid EC \rightarrow CO2 (+) FDI \rightarrow CO2 (+)
Effect of foreign direct investment on CO 2 emission with the role of globalization, institutional quality with pooled mean group panel ARDL	Teng et al. (2020)	10 OECD economies (1985–2018)	PMG-ARDL	CO2 → GDP (+) FDI showed a negative relationship with CO2 i.e mean an increase in FDI will lead to decrease in CO2 emissions
Sustainability of the moderating role of financial development in the determinants of environmental degradation: evidence from Turkey	Rjoub et al. (2021)	Turkey (1960–2018)	FMOLS, DOLS	CO2 → GDP (+) The study also found the significant moderating role of "financial development" in the relationship between "economic growth" and carbon emissions, capital formation and carbon emissions, and urbanization and carbon emissions
Modeling CO 2 emissions in Malaysia: an application of Maki cointegration and wavelet coherence tests	Zhang et al. (2021)	Malaysia (1960–2018)	Cointegration, wavelet, and gradual shift	GDP → CO2 (+) GDP → CO2 The Maki co-integration and ARDL bounds tests reveal evidence of cointegration among the variables. The ARDL test reveals that economic growth, gross capital formation, and urbanization exert a positive impact on CO2 emissions.

Modeling CO2 emissions in South Africa: empirical evidence from ARDL based bounds and wavelet coherence techniques	Odugbesan and Adebayo (2020)	South Africa (1971–2016)	ARDL & wavelet coherence	CO2 → GDP (+) The ARDL long- and short-run estimates a positive and significant link between growth and CO2 emissions.
Oil consumption, CO2 emission and economic growth in MENA countries	Al-Mulali (2011)	Turkey (1980–2009)	Panel Granger causality	CO2 ← GDP (+) oil consumption plays an important role in the economic growth of the MENA countries
The symmetrical and asymmetrical effects of foreign direct investment and financial development on carbon emission: evidence from Nigeria	Odugbesan and Adebayo (2020)	Nigeria (1980–2016)	ARDL, NARDL	CO2 → GDP (+) The fndings for the linear (symmetric) efect shows that foreign direct investment (FDI), and energy consumption have a long-run relationship with CO2 in Nigeria, while only FDI has a short-run linear relationship with CO2.
Reinvestigating the determinants of environmental degradation in Nigeria	Ayobamiji and Kalmaz (2020)	Nigeria (1971–2015)	ARDL, FMOLS, DOLS, wavelet coherence	CO2 → GDP (+)
An empirical investigation between CO2 emission, energy consumption, trade liberalization and economic growth: a case of Kuwait	Wasti and Zaidi (2020)	Kuwait (1990–2014)	ARDL	CO2 → GDP (+)
Effect of economic growth on CO2 emission in developing countries: evidence from a	Aye and Edoja (2017)	emerging nations	Panel techniques	CO2 → GDP (-)

dynamic panel threshold model				
Modeling CO 2 emissions in an emerging market: empirical finding from ARDL-based bounds and wavelet coherence approaches	Kalmaz and Kirikkaleli (2019)	Turkey	ARDL, FMOLS, DOLS, wavelet coherence	CO2 → GDP (+)
Do renewable energy consumption and financial development matter for environmental sustainability?	Kirikkaleli et al. (2020)	China	Maki cointegration, wavelet, and gradual shift	CO2 → GDP
CO2 emission and economic growth in Algeria	Bouznit & Pablo- Romero (2016)	Algeria	ARDL	CO2 → GDP (+)
Evaluating the role of renewable energy, economic growth and agriculture on CO2 emission in E7 countries	Aydoğan and Vardar (2020)	E-7 (1990–2014)	Panel VECM	CO2 → GDP
Decoupling analysis of world economic growth and CO2 emissions: a study comparing developed and developing countries	Wu et al. (2018)	World PRISMA (1995–2017)	ARDL	CO2 ↔ GDP
Natural resource abundance, technological innovation, and	Khan et al. (2020)	China (1987–2017)	GMM	CO2 → GDP (+)

human canital sauce				
human capital nexus with financial				
development: a case				
study of China	A al a la a	N. 4	ADDI Olat	CO2 () CDD ()
Revisiting the EKC	Adebayo	Mexico	ARDL & wavelet	$CO2 \leftrightarrow GDP (+)$
hypothesis in an	(2020)	(1971–2016)	coherence	
emerging market: an				
application of ARDL-				
based bounds and				
wavelet coherence				
approaches				
Energy consumption,	Jafari et al.	Bahrain	TY causality	CO2 → GDP
emissions and	(2015)	(1980–2007)		
economic growth in				
Bahrain				
Determinants of	Li et al.	20 provinces	Panel CSARDL	CO2 → GDP
carbon emission in	(2021)	in China		
China: how good is				
green investment?				
The effects of	Salahuddin	South Africa	ARDL	CO2 ≠ GDP
electricity	et al.	(1980–2017)		
consumption,	(2018)			
economic growth,				
financial				
development, and				
foreign direct				
investment on CO2				
emissions in Kuwait				
Determinants of CO	Awosusi et	MINT		CO2 ≠ GDP
2 Emissions in	al.	economies		
Emerging Markets:	(2020)	(1980–2018)		
An Empirical				
Evidence from MINT				
Economies				
Investigating the	Akinsola	Thailand	ARDL & wavelet	CO2 → GDP (+)
causal linkage among	and	(1971–2016)	coherence,	CO2 → GDP
economic growth,	Adebayo		Granger and	
energy consumption	(2021)		Toda-	
and CO2 emissions in			Yamamoto	
Thailand: an			causality	
application of the				

wavelet coherence approach				
Trivariate modelling of the nexus between electricity consumption, urbanization and economic growth in Nigeria: fresh insights from Maki Cointegration and causality tests	Ali et al. (2020)	Top 10 emitter countries (1990–2017)	Panel CSARDL	CO2 → GDP (+)
Does biomass energy consumption mitigate CO2 emissions? The role of economic growth and urbanization: evidence from developing Asia.	Gao and Zhang (2021)	13 Asian developing countries (1980–2010)	FMOLS and panel Granger causality tests	CO2 → GDP Energy consumption and economic growth
The energy consumption and economic growth nexus in top ten energy consuming countries: fresh evidence from using the quantile-on-quantile approach	Shahbaz et al. (2018)	Top 10 energy- consuming countries (1960Q1– 2015Q4)	Quantile-on- quantile (QQ) approach	EC → GDP (+)
The relationship between energy consumption, economic growth and carbon dioxide emission: the case of South Africa	Khobai and Le Roux (2017)	South Africa	Johansen cointegration and VECM Granger causality tests	EC ↔ GDP
Revisiting the relationship between energy consumption and economic	Ha and Ngoc (2020)	Vietnam (1971–2017)	ARDL and Toda- Yamamoto causality	EC ↔ GDP

growth nexus in Vietnam: new evidence by asymmetric ARDL cointegration A disaggregated level analysis of the relationship among energy production, energy consumption and economic growth: Evidence from China	Rahman et al. (2020)	China (1981–2016)	Hatemi-J and FMOLS	EC → GDP (+)
Energy consumption and economic growth nexus: new evidence from Pakistan using asymmetric analysis	Baz et al. (2019)	Pakistan (1971–2014)	NARDL	EC → GDP (+)
Energy consumption, electricity, and GDP causality; the case of Russia, 1990-2011	Faisal et al. (2016)	Russia (1990–2011)	Toda- Yamamoto causality	No causal link
Energy consumption, carbon emissions, and economic growth in India: evidence from directed acyclic graphs	Yang and Zhao (2014)	India (1970–2008)	Granger causality and DAG	EC → GDP
A bootstrap panel Granger causality analysis of energy consumption and economic growth in the G7 countries	Mutascu (2016)	G7 economies (1970–2012)	Granger causality tests	EC ↔ GDP
Energy consumption, CO2 emissions and economic growth in developed, emerging and Middle East and	Muhammad (2019)	Pakisthan (2001–2017)	ARDL	EC → GDP (-)

North Africa				
countries Electricity consumption, urbanization, and economic growth in Nigeria: new insights from combined cointegration amidst structural breaks	Nathaniel and Bekun (2020)	Nguyen and Nguyen (2018)	Bayer and Hanck cointegration tests, ARDL, FMOLS, DOLS, CCR, and VECM Granger causality	URB ↔ GDP (-)
The relationship between urbanization and economic growth	Nguyen and Nguyen (2018)	ASEAN (1971–2014)		URB → GDP (+)
International trade and environmental performance in top ten-emitters countries: the role of eco-innovation and renewable energy consumption	Ali et al. (2020)	Nigeria (1971–2014)	Maki cointegration, FMOLS, DOLS, CCR, and VECM Granger causality	URB → GDP (-)
Testing the EKC hypothesis in Indonesia: empirical evidence from the ARDL-based bounds and wavelet coherence approaches	Adebayo (2021)	Japan (1971–2015)	Wavelet coherence, ARDL, FMOLS, DOLS	URB → GDP (+)
An analysis of the implications of China's urbanization policy for economic growth and energy consumption	Yang et al. (2017)	China (2000–2010)	Pooled ordinary least squares (POLS), fixed effects (FE), and random effect	RE URB → GDP (+)
Economic growth, urbanization and energy consumption—a	Zheng and Walsh (2019)	29,provinces in China (2001–2012)	FE and sys- GMM estimated methods	URB → GDP (+) Gross capital formation and economic growth

provincial level analysis of China				
Global evidence from the link between economic growth, natural resources, energy consumption, and gross capital formation	Topcu et al. (2020)	124 countries (1980–2018)	PVAR	GCF → GDP (+)
Modeling natural gas consumption, capital formation, globalization, CO2 emissions and economic growth nexus in Malaysia: fresh evidence from combined cointegration and causality analysis	Etokakpan et al. (2020)	Malaysia (1994-2020)	Bayer and Hanck cointegration tests, ARDL and Granger causality	GCF → GDP (+)
An analysis of the implications of China's urbanization policy for economic growth and energy consumption	Yang et al. (2017)	China (2000–2010)	Pooled ordinary least squares (POLS), fixed effects (FE), and random effect	RE URB → GDP (+)
Economic growth, urbanization and energy consumption—a provincial level analysis of China	Zheng and Walsh (2019)	29,provinces in China (2001–2012)	FE and sys- GMM estimated methods	URB → GDP (+) Gross capital formation and economic growth
Modeling natural gas consumption, capital formation, globalization, CO2 emissions and economic growth nexus in Malaysia: fresh evidence from combined	Etokakpan et al. (2020)	Malaysia (1980–2014)	Bayer and Hanck cointegration tests,ARDL	GCF → GDP (+)

cointegration and				
causality analysis				
Revisiting the	Hang et al.	Vietnam	ARDL	URB → GDP (+)
relationship between	(2021)	(1980–2014)		
energy consumption				
and economic				
growth nexus in				
Vietnam: new				
evidence by				
asymmetric ARDL				
cointegration				
Financial depth,	Boamah et	18 Asian	POLS	GCF → GDP (+)
gross fixed capital	al.	nations		
formation and	(2018)	(1990–2017)		
economic growth:				
empirical analysis of				
18 Asian economies				
Scrutinizing the	Kong et al.	39 African	AMG and	Urban → GDP(+)
complex relationship	(2020)	countries	CCEMG	Urban ↔ GDP (+)
between financial		(1997–2017)		
development gross				
fixed capital				
formation and				
economic growth in				
Africa by adopting				
CCEMG and AMG				
estimation				
techniques				
Investigating the	Akinsola	Thailand	ARDL & wavelet	CO2 → GDP (+)
causal linkage among	and	(1971–2016)	coherence,	CO2 → GDP
economic growth,	Adebayo		Granger and	
energy consumption	(2021)		Toda-	
and CO2 emissions in			Yamamoto	
Thailand: an			causality	
application of the				
wavelet coherence				
approach				
Trivariate modelling	Ali et al.	Top 10	Panel CSARDL	CO2 → GDP (+)
of the nexus	(2020b)	emitter		
between electricity		countries		

consumption, urbanization and economic growth in Nigeria: fresh insights from Maki Cointegration and causality tests		(1990–2017)		
Does biomass energy consumption mitigate CO2 emissions? The role of economic growth and urbanization: evidence from developing Asia	Gao and Zhang (2021)	13 Asian developing countries (1980–2010)	FMOLS and panel Granger causality tests	CO2 → GDP Energy consumption and economic growth
The energy consumption and economic growth nexus in top ten energy consuming countries: fresh evidence from using the quantile-on quantile approach	Shahbaz et al. (2018)	Top 10 energy- consuming countries (1960Q1– 2015Q4)	Quantile-on- quantile (QQ) approach	EC → GDP (+)
The relationship between energy consumption, economic growth and carbon dioxide emission: the case of South Africa	Khobai and Le Roux (2017)	South Africa (1988-2020)	Johansen cointegration and VECM Granger causality tests	EC ↔ GDP
Revisiting the relationship between energy consumption and economic growth nexus in Vietnam: new evidence by asymmetric ARDL cointegration	Ha and Ngoc (2020)	Vietnam (1971–2017)	ARDL and Toda- Yamamoto causality	EC ↔ GDP

A disaggregated level analysis of the relationship among energy production, energy consumption and economic growth: Evidence from China	Rahman et al. (2020)	China (1981–2016)	Hatemi-J and FMOLS	EC → GDP (+)
Energy consumption and economic growth nexus: new evidence from Pakistan using asymmetric analysis	Baz et al. (2019)	Pakistan (1971–2014)	Non linear ARDL	EC → GDP (+)
Assessing the sustainability of renewable energy: An empirical analysis of selected 18 European countries	Wang, Q. & Zhan, L. (2019)	18 European countries (2007-2016)	RAGA PP (total energy demand, energy taxes, carbon dioxide emissions, sulfur oxides emissions, and nitrous oxides emissions)	The sustainability of renewable energy in Germany, the UK, France, and Italy is better than that the other. Whereas, Bulgaria, the Czech Republic, and Romania were the worst. The 17 indices selected by the 3E model the factors of total energy demand, energy taxes, carbon dioxide emissions, sulfur oxides emissions, and nitrous oxides emissions exert a stronger impact on the sustainability of renewable energy

2.5 Research Gap

- ♣ Over the last several years, economists and researchers have undertaken sincere efforts to study and analyse the impact of ecological footprint. The scopes of most of the existing studies are limited to the impact of human activity on natural environment. Limited studies have been done to study the level of optimal energy mix for environment sustainability.
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- limited to the impact of human activity on natural environment. Limited studies have been done to study the level of optimal energy mix for environment sustainability.
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- ♣ Over the last several years, economists and researchers have undertaken sincere efforts to study and analyses the impact of ecological footprint. The scopes of most of the existing studies are limited to the impact of human activity on natural environment. Limited studies have been done to study the level of optimal energy mix for environment sustainability.

2.6 Research Question

- Q1. What is the impact of energy on economy and environment?
- Q2. Does the Environmental Kuznets Curve hypothesis holds true in the present scenario?
- Q3. Are the different types of energy sustainable?
- Q4. What are the policy measures that the government can take to reach sustainability?

2.7. Objectives

- **RO1:** To study the nexus between energy, economy and environment
- **RO2:** To study the impact of conventional and non-conventional energy sources on environment and economy
- **RO3:** To suggest a combination of technology and policy mix that ensure reliable, affordable and clean energy
- **RO4:** To suggest policy measure to the government

2.8. Publication for fulfilling the Research Objectives

- RO1 Singh, A. & Kumar, N. "Assessing the relationship among Published Scopus energy, economy, and environment with special reference to India"
- RO2 Singh, A. & Kumar, N. "Analysing the long run Published Web of Science relationship between CO2emissions and Energy use of United Kingdom", Published ISSN 0971–765X 2024; pp.
- RO3 Singh, A. & Kumar, N. "Analysis of renewable energy and Published Web of Science economic growth of Germany, Published (2024) Vol. 15 (2): 2349-2355"
- RO4 Is CCUS technology be a better choice for India's net zero Communic SCIE carbon emission mission by 2050: Evidence from Fuzzy ated Analytical Hierarchy Process

CHAPTER 3

RESEARCH METHODOLOGY

The research methodology for studying the interrelationship among energy, economy, and environment involves a comprehensive approach that combines quantitative and qualitative methods. The goal is to analyse how energy consumption influences economic performance and environmental outcomes, and how economic policies, energy technologies, and environmental considerations interact.

3.1. Data Collection

Data for studying the interrelationship can be collected through various methods, depending on the scope of the study:

a. Quantitative Data

- ♣ Energy consumption data: From national or international energy agencies (e.g., International Energy Agency [IEA], U.S. Energy Information Administration [EIA], or national statistical bureaus).
- Economic data: GDP, industrial production, inflation rates, and other macroeconomic indicators, available from national economic agencies (e.g., **World Bank**, IMF).
- ♣ Environmental data: Data on emissions (CO₂, SO₂, etc.), air quality indices, resource depletion rates, deforestation, and biodiversity loss from environmental monitoring organizations (e.g., UN Environment Programme, World Resources Institute).

b. Qualitative Data

- Interviews with policymakers, energy experts, economists, and environmental scientists to gather insights on the practical aspects of the energy-economy-environment relationship.
- Case studies of specific countries, regions, or industries that have undergone energy transitions or have innovative policies for balancing economic growth and environmental sustainability.
- Document analysis of policy papers, government reports, and strategic plans related to energy policy and sustainable development.

3.2. Modeling the Interrelationship

Several models can be used to analyze the interrelationships between energy, economy, and the environment. The choice of model depends on the specific research focus:

- Input-Output Models: These models help understand the flow of energy, economic activity, and environmental impact across different sectors of the economy. They are useful for examining the direct and indirect effects of energy consumption on various industries and vice versa.
- Computable General Equilibrium (CGE) Models: These models simulate the entire economy, including energy sectors, environmental constraints, and economic activities. They can show how changes in energy policies (e.g., carbon pricing or renewable energy subsidies) affect the economy and environment simultaneously.
- Environmental Kuznets Curve (EKC): This model explores the relationship between economic growth and environmental degradation. It hypothesizes that environmental degradation increases with economic growth up to a certain point, after which it decreases as societies adopt cleaner technologies and improve environmental governance.

- System Dynamics Models: These models are useful for simulating the feedback loops and dynamic interactions between energy, economy, and environment. They help assess long-term trends and evaluate the impact of different policies (e.g., promoting renewable energy or imposing carbon taxes) on sustainability.
- Energy-Economic-Environment Nexus Frameworks: This is a holistic, systems-based approach to understanding the complex interconnections between energy use, economic performance, and environmental health. It integrates the physical, economic, and environmental dimensions of energy systems to create scenarios that help policymakers understand potential trade-offs and synergies.

3.3. Analysis Techniques

Depending on the data and modeling approach, several analysis techniques can be employed:

- ♣ Statistical Analysis: Techniques like regression analysis, correlation analysis, or econometric modeling can be used to quantify relationships between energy consumption, economic indicators (GDP, industrial output, etc.), and environmental outcomes (e.g., emissions, resource depletion). For example, regression models can examine the causal impact of energy consumption on GDP growth, controlling for other factors such as technological innovation or policy changes.
- Scenario Analysis: Scenario modeling can help assess the potential outcomes of different energy policies on economic and environmental factors. For example, examining "business-as-usual" scenarios versus aggressive renewable energy adoption strategies.
- Life Cycle Assessment (LCA): This method helps to evaluate the environmental impact of energy technologies, considering the entire lifecycle of energy production, from raw

material extraction to disposal. It's particularly useful in assessing renewable versus nonrenewable energy sources.

Multi-Criteria Decision Analysis (MCDA): This technique helps to evaluate different energy policies or projects based on multiple criteria (economic, environmental, and social) and can assist in identifying optimal solutions for sustainable development.

3.4. Data Interpretation and Discussion

- Comparative Analysis: Results from different countries, regions, or industries are compared to understand the different pathways to achieving a balance between energy use, economic growth, and environmental sustainability.
- ♣ Policy Implications: The findings of the research will be analyzed in the context of policy implications. For example, identifying how different government policies (e.g., carbon taxes, renewable energy subsidies) influence the interrelationship among energy, economy, and environment.

3.5. Ethical Considerations

- Ensure that all data used, especially from interviews and surveys, is collected with the consent of participants and that it is used responsibly.
- Consider the equity implications of energy policies, particularly how they impact different socio-economic groups, regions, or countries, especially in developing economies.

The research methodology for studying the interrelationship among energy, economy, and environment should be interdisciplinary, combining quantitative analysis, qualitative insights, and systems thinking. By using robust models and data-driven analysis, this approach can help inform evidence-based policies that promote sustainable development while balancing energy needs, economic growth, and environmental health.

CHAPTER 4

THE NEXUS BETWEEN ENERGY, ECONOMY AND ENVIRONMENT

In this chapter the complex relation is between energy, economy, and environment is presented. The relationship between energy, economy, and environment is complex and dynamic. Energy production and consumption are central to economic activity but come with significant environmental costs, especially from fossil fuels. In order to achieve long-term sustainability, countries must transition to cleaner energy systems, balance economic growth with environmental protection, and develop policies that promote innovation, efficiency, and sustainability. Understanding this interrelationship is essential for crafting effective strategies for a sustainable and resilient future. A study of the interrelationship among energy, economy, and the environment is a multifaceted analysis of how these three elements influence each other, and how their interactions shape policies, societal well-being, and the future of sustainable development. This relationship can be broken down into several key aspects:

4.1. Analysis of the relationship between three Es

- a. Energy and the Economy
- **Economic Growth and Energy Consumption**: Energy is a fundamental driver of economic activities. The production of goods and services, transportation, communication, and most industries rely on energy. Economic growth is often correlated with increased energy demand. More energy use can fuel expansion in sectors like manufacturing, agriculture, and services.
- Energy Costs and Economic Stability: Energy prices, particularly fossil fuels like oil, natural gas, and coal, directly impact economic performance. High energy costs can increase

production costs and reduce the purchasing power of consumers, potentially leading to inflation, reduced growth, or even recession. On the other hand, affordable energy prices support business competitiveness and economic stability.

Investment in Energy Infrastructure: The energy sector itself is a significant part of the economy, with investments in power plants, renewable energy technologies, and transmission networks. Such investments can create jobs, stimulate technological innovation, and promote economic development.

b. Energy and the Environment

- Environmental Impact of Energy Production: The method of energy production has significant environmental consequences. Fossil fuels, such as coal, oil, and natural gas, contribute to air pollution, climate change, and ecosystem degradation due to carbon emissions, sulfur dioxide, and other pollutants. In contrast, renewable energy sources like wind, solar, and hydroelectric power are considered environmentally cleaner options with less harmful impact.
- Climate Change and Energy Transition: The continued use of non-renewable energy sources exacerbates global warming and climate change, threatening ecosystems, food security, and human health. This has led to an international push for decarbonizing the energy sector and transitioning to sustainable energy solutions. Governments are focusing on policies such as carbon taxes, renewable energy incentives, and emissions trading systems to encourage cleaner energy production and consumption.
- Resource Depletion and Environmental Sustainability: Extracting and consuming finite resources like coal, oil, and natural gas leads to resource depletion. This poses long-term

environmental challenges and may increase the environmental costs associated with energy extraction (e.g., habitat destruction, water contamination).

c. Economy and the Environment

- Sustainable Development: Economic growth and environmental sustainability are often seen as competing goals. Traditionally, economic development has been associated with increased environmental degradation. However, sustainable development seeks to balance these concerns by fostering economic growth that does not exhaust natural resources or harm ecosystems.
- Environmental Regulation and Economic Activity: Governments implement environmental regulations (such as pollution controls, emissions standards, or biodiversity protection laws) to mitigate the negative impacts of economic activities. These regulations can influence economic decision-making by imposing costs on businesses and industries that rely on environmentally harmful practices. However, well-designed environmental policies can also create new economic opportunities, such as green jobs and innovations in clean technologies.
- Green Economy: The idea of a "green economy" advocates for decoupling economic growth from environmental degradation. This includes promoting energy efficiency, the adoption of renewable energy sources, sustainable agriculture, and responsible consumption. A green economy focuses on creating jobs and wealth while ensuring environmental protection.

d. Interlinkages and Feedback Loops

Feedback between Energy Use and Environmental Impact: Increased energy use often leads to greater environmental degradation, particularly in the case of fossil fuels. However, shifting towards cleaner energy sources can mitigate this impact. For instance, renewable

- energy technologies (solar, wind, etc.) can reduce dependence on fossil fuels and lower greenhouse gas emissions.
- Energy Efficiency and Economic Benefits: Improving energy efficiency can reduce overall energy consumption and lower costs for businesses and consumers. Energy-saving innovations (e.g., energy-efficient buildings, appliances, or industrial processes) contribute to economic competitiveness while reducing the environmental footprint.
- The Role of Policy: Government policies can guide the balance between these sectors. For example, policies that promote renewable energy can boost both the economy (through job creation in new industries) and the environment (through reduced emissions). Conversely, subsidies for fossil fuels may stimulate short-term economic growth but increase long-term environmental costs.

e. Globalization and the Global Energy-Environment-Economy Nexus

- International Trade and Energy: Global trade and globalization have expanded the demand for energy resources and intensified the environmental footprint of energy use. International supply chains, particularly in manufacturing and shipping, rely heavily on energy, and emissions from these sectors contribute to climate change. A shift toward international agreements on energy use and environmental protection is essential for addressing global challenges.
- International Cooperation on Climate Change: The interrelationship among energy, economy, and environment is a global issue. Solutions like the Paris Agreement aim to align international efforts to mitigate climate change, promote sustainable energy use, and ensure economic resilience in a world facing ecological challenges.

f. Energy Transition Challenges

- Social and Economic Impacts of Energy Transition: Transitioning from fossil fuels to renewable energy sources poses social and economic challenges, such as job losses in traditional energy sectors (e.g., coal mining or oil drilling) and the need for retraining workers. However, it also creates new opportunities in clean energy sectors and the development of green technologies.
- **Technological Innovation and Investment**: A transition to cleaner energy requires substantial investment in research and development of new technologies. This includes improving energy storage solutions (e.g., batteries), advancing smart grids, and scaling up renewable energy infrastructure. Technological innovation can help overcome many of the challenges posed by the energy-environment-economy nexus.

4.2. Case Study for assessing the relationship of Energy, Economy, and Environment with a Special Reference to India

In this chapter the complex relation is between energy, economy, and environment is presented. The coupling and coordination development of energy, economy and environment would help to analyze their relationship and it would further help to provide the basis of rational use. In this paper coupling and co-ordination is developed for India's energy, economy, and environment for the time period from 2006. It is evaluated and analyzed the results, which expressed into four patterns such as: (1) The coupling coordination development between energy and economy improved with passing year, it started with mild disorder category in 2006 and reached to intermediated coordination in 2018; (2) The coupling and coordination development between economy and environment showed that frequently unbalanced category repeated most often and only once, in

2016 it improved and reached to primary coordinated category; (3) The coupling and coordination development between energy and economy started with a mild disorder category in 2006 and improved in 2008 to barely coordinates, it was stable until 2016 when it further improved to primary coordinated development; (4) The coupling and coordination development between energy, economy, and environment repeated barely coordinated category most often, although there was an improvement in 2016 to primary coordinated but again in 2018 it deteriorated to barely coordinated. There exists a complex relation between the energy, economy, and environment in which they interact, promote and limit each other but through proper coordination between them India can reach its sustainable development goals.

4.3. Literature Review

Energy, Economy and Environment (EEE pr 3Es) are the wheels to reach the goal for development of any country. To reach the equilibrium of environmental protection, energy security, and economic development and to accomplish a sustainable development agenda has verified to be the one of paramount trials in present era. We all need energy and its consumption increments to ensure a better quality social life and to support the economic development especially in developing countries. However we need to generate the more energy to fulfill the modern energy demand and to ensure that the environment remains protected; regarding to this an existing relationship between the energy, economy and environment helps in the forecasting analysis. Therefore, 3Es have an important role in all past, present and future era, and have importance role in sustainable development. It is important to know the relationship of the 3Es to reach the desired equilibrium. The SDG7 affordable and clean energy, SDG12 responsible consumption and production, and SDG13 climate action can only be reached when all the 3Es are being

balanced. [1] Presented the remanufacturing and assessment of energy, environment, and economy based on LCA described systematically, to better understand and apply LCA and promote remanufacturing.

[2] Studied the New exergy metrics for energy, environment, and economy nexus and optimum design model for nearly-zero exergy airport (nZEXAP) systems. It was applied the second law of thermodynamics to analyze the relationship between energy, environment, and economy. [3] Used Lotkae Volterra model to examine the competitive interactions among energy, environment, and economy in the U.S. The study was emphasis on the existence of the environment Kuznets curve therefore the GDP is affected by the use of renewable and fossil energy while it interacts indirectly with emissions. [4] Examined the impact of energy consumption, economic growth on environmental degradation in the United States by using the wavelet technique. It was stated that in the short, medium and long run the energy consumption has a positive influence over carbon emissions. [5] Analyzed the relationship between social economy and environment energy of countries by using the coupling coordinates and panel data approach and observed that the status of the research zone has been improved. [6] Evaluated the decoupling relationship and its influencing factors between economic growth and carbon emissions in China. [7] Developed a Ternary coupling model to show the relationship between energy, economy and environment. The observations drawn based on the panel data of Hebei province and showed an upward trend. [8] Analyzed the rational use of the 3Es for the protection of ecological environment. [9] Analyzed the coupling relationship by establishing a coupling model of energy-economy-environment. [10,11] Calculated the average coupling coordination degree of China's energy, economy, and environment systems is lower compared to the international standard. [12] Studied and rationally contributed the situation and development trend of China's energy, economy and environment

systems. [13, 14] drawn a coupling and coordination model analysis of the complex relationship between urbanization, economy and environment. [15] Considered the development of an integrated environmental sustainability index and its application in the case of the Czech Republic. [16] Examined the effect of environment and economic variables on logistic performance in India using ARDL model on a time series data from 2007 to 2018. The development of economy and the ecological environment were mainly unbalanced whereas the trends between energy and ecological environment and energy and economy were coordinated. It showed a complex relation between the energy, economy and environment where they interacted, promoted and restricted each other.

[17] studied the major global concern today is climate change that has triggered due to the increasing population's increasing demand for energy consumption, food production and economic development. The author examines the relationship between economic growth, food, biomass, and greenhouse gas emission. The results showed that there exist an inverse U- shaped relationship between them; the author also reveals some conceptual tools that can be applied for decision making. [18] studied clean energy and renewable energy remains a major concern for most of the countries, the author suggest how biogas can be purified through combined UV irradiations and thermal annealing treatments as it increases the selectivity and permeability of membrane in CO₂ / CH₄ gas separation. It also enhances the performance of monohybrid PESnano silica CO₂ / CH₄ separation. As there is an increase in the pace of developmental work around the world increased the petroleum consumption majorly for transportation, industrial application and electrification that has increased the air pollution, which in turn degraded the environment. [19] The author suggests ways to reduce NO_X emission by adding hydrogen-rich synthesis gas

generated by plasma-assisted fuel reformer. By using the technique, it was observed that approximately 50% of harmful pollution was reduced.

[20] Even renewable energy has some disadvantages like voltage instability in wind and solar energy. The author reviews the important of optimal location and sizing distributed generation units for voltage stability. [21] The challenges in renewable energies of instability in solar and wind energy were addressed by designing a new hybrid power plant that converted solar and wind energy into electricity. The energy obtained from solar and wind was stored in accumulators and as soon the accumulators were full the energies were transferred to a plateau houses or to the network for production. The author outlines ways to select the location and make a high efficiency wind solar hybrid power plant. [22] The author examines the air pollutions emission patterns from oil refineries of Kuwait by using the AERMOD software and Industrial source complex short-term model. It observed that all the pollutants were higher than the predicted, the results also showed that oilfields and oil refineries were the major contributors.

This paper contributes to the literature in several ways firstly to the best of my knowledge no literature has stated the relationship among energy, economy and environment using coupling coordination in the Indian context secondly the world at present is in the energy transition phase hence it's very important to know the relationship between the 3Es for the policy makers so that they can take decision in the right direction. The author examines the coupling and coordination of development between energy, economy and environment of India between the years 2006 to 2019. The level of coupling and coordination development of the three E's exhibited an increasing trend.

4.4. Material and Methods:

a. Index selection:

The selection of indicators was such that they can mostly represent and reflect the development degree of energy, economy, and environment.

Energy

The energy use per \$1000 GDP is the commercial energy use measured in units of oil equivalent per \$1000 GDP converted from national currencies using the purchasing power parity. Energy use refers to using primary energy before transformation to other end-use fuels, equal to native manufacture plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. The energy data have been taken from World Bank date as shown in table 4.1. Energy production: It refers to the value of how much primary energy the country obtains from nature. It does not include any exports or imports and is just the total of what is extracted from nature. Total primary energy supply: The total amount of primary energy that a country has at its disposal. The total primary energy supply includes the imported energy minus the exported energy. It also consists of the energy obtained from natural resources. Electricity final consumption: Electricity consumption serves as an essential measure for a country's electric power development. Electric consumption usually grows faster during the development and industrialization phase.

Table 4.1: Energy Data

Unit	Million tons of Oil Equivalent	Million tons of Oil Equivalent	Terawatt- Hour
Year	Energy Production	Total Primary Energy Supply	Electricity Final Consumption
2006	405.77	532.99	584.45
2007	424.73	568.1	632.18
2008	445.26	603.83	670.79
2009	483.6	663.17	720.47

2010	503.78	700.76	785.81
2011	521.46	733.66	856.44
2012	524.18	766.26	907.19
2013	522.04	778.81	965.45
2014	532.76	822.05	1059.21
2015	537.3	834.53	1116.86
2016	550.84	852.22	1199
2017	551.62	882.88	1258.19
2018	573.56	919.44	1309.44
2019	593.5	973.7	1345.41

Source: World Bank Database

Leanner Economy

Table 4.2 represents the economy data referenced from World Bank database. Gross Domestic Product It is a standard measure for measuring the value-added of the total goods and services produced in a nation during a specific period. Although GDP is the single most crucial indicator of economic growth, it does not indicate anything about its material well-being in a country. The GDP growth rate: It tells us about the percentage growth of a country's GDP. It is calculated by finding the percentage increase in the GDP year on year. GDP per capita is the value obtained by dividing the country's population from its total GDP. Its growth rate is an indication of the economic growth of the country concerning the increase in population. The GDP output approach: It is occasionally referred to as GDP (O), is the amount of output or production in the economy. It covers the entire economy and uses the same data that makes up the index of production, output in the construction industry, retail sales index, and services index. The output approach to calculate GDP sums the gross value added of various sectors, plus taxes and less subsidies on products. The final consumption expenditure: It is the residential units' expenditure, including households,

enterprises, and other consumers whose economic interests lie in the particular economic region.

The goods and services used are for the direct satisfaction of individual wants and needs and the community.

Table 4.2. Economy Data

Unit	US \$	US \$ Trillion	Percentage	Percentage	INR Billion
	Trillion				
Year	GDP	FINAL	GDP Growth rate	GDP per capita	GDP Output
		Consumption		growth	approach
		Expenditure			
2006	0.94	0.619	8.061	6.403	40486
2007	1.217	0.798	7.661	6.048	47142
2008	1.199	0.805	3.087	1.588	54562
2009	1.342	0.904	7.862	6.351	59895
2010	1.676	1.101	8.498	7.042	72938
2011	1.823	1.227	5.241	3.894	84871
2012	1.828	1.227	5.456	4.165	96370
2013	1.857	1.261	6.386	5.135	108981
2014	2.039	1.398	7.41	6.187	122142
2015	2.104	1.461	7.996	6.797	133907
2016	2.295	1.597	8.256	7.083	149452
2017	2.653	1.851	7.044	5.912	166226
2018	2.713	1.91	6.12	5.024	185792
2019	2.901	1.97	6.34	5.891	189275

Source: World Bank Database

Environment

The environment plays a fundamental role in healthy living and existence of life. Over the years we have been witnessing an increased number of abnormal situations related to the environment. The weather is becoming extreme, increase in number of tropical storms, the sea level rising and deterioration in air and water quality. The environmental factors that are important to track and the

critical indicators are Air quality, waste management, country's green cover, and deforestation rate. The environmental performance Index: EPI provides a data-driven summary of the status of sustainability of several countries around the world. The index uses 32 performance indicators in 11 different categories. The data provided a straightforward way to identify problems, set targets, and identify best policy practices. The overall EPI rankings indicate which countries are the best in addressing environmental issues that the world is experiencing. The score provided is based on different factors used to analyze the performance in various categories like waste management, sanitization and drinking water, air quality, and biodiversity.

b. Model Construction and Index normalization

Indicators can be positive or negative indicators. A positive indicator correlates with increasing values, while a negative indicator correlates with decreasing values. A typical example of an indicator used to measure economic direction is the GDP per capita or nominal growth rate. Indicators have units associated with them and are thus prone to all the biases that come with non-standardized variable calculus and are therefore difficult to group with other indicators, to effectively compound different indicators, these variables need to be converted into a normalized standard index.

The given indicators are used to construct indices between 0 and 1 as lower and upper boundary values respectively, but in some cases, these bounds can be increased (or decreased) with the original minimum (or maximum) values in order to diminish the influence of extreme outliers. The natural logarithmic values of these bounds are used in some cases this takes care of probable deviations brought on by non-linear and exceptionally skewed indicator values' distribution. We first convert an indicator value (V) into an index score (I) by:

$$I = \frac{V - \min}{\max - \min}$$
 (1)

To avoid linearization, we can use the lognormal transform and standardize the transform

$$I = \sqrt{\frac{V - \min}{\max - \min}}...(2)$$

Standardization to check for outliers

$$I' = \frac{I - \mu}{\sigma} \tag{3}$$

c. Coupling Development

Coupling is a physical concept, a process in which the interaction between two or more elements affects each other. Coordination and development are two critical levels of coupling. Coupling is a simple but powerful probabilistic tool and is therefore of importance both in teaching and research. The basic idea is the joint construction of two or more random elements (variables, processes), usually to deduce the individual elements' properties. Coordination is the degree of close interaction between systems, and development is the process of continuous improvement of the level of interaction between systems.

H Binary Coupling (Coordination Coefficient)

For a statistic X & Y, the coupling or coordination coefficient C is given by

$$C = \frac{xy}{\left(\frac{x+y}{2}\right)^2}...(4)$$

The corresponding development is given by

$$D = CT$$
....(5)

Where C stands for coordination and T is a weighted index of X &

$$T = \alpha X + \beta Y \dots (6)$$

With α , β being the appropriate weights

Tertiary Coupling (Coordination)

Here coordination C' for statistics X, Y & Z is equal to

$$C' = \frac{3(XY + YZ + ZX)}{(X + Y + Z)^2}...(7)$$

The development D' is equal to

$$D' = C'T'$$
....(8)

Where,

$$T' = \alpha X + \beta Y + \gamma Z \dots (9)$$

And
$$\alpha = \beta = \gamma = \frac{1}{3}$$

4.5. Results and Discussions

Table 4.3. Represents the comprehensive index of energy, economy, and environment where the value of energy and economy was formulated by using equation 1, 2 and 3 whereby environment index was obtained from epi.yale.edu. Table 4.4. represents the judgment criteria table based on which the results were formulated of the 3Es. Table 4.5. Represents the results of the 3Es using equation 4 to 9, where D is the development index and T is a weighted index of X & Y.

Table 4.3: Comprehensive Index of Energy, Economy, and Environment

Year	Energy(X)	Economy(Y)	Environment(Z)
2006	0.277189136	0.468615693	0.477
2007	0.367030754	0.508199605	0.54
2008	0.437007993	0.348110576	0.603
2009	0.532282842	0.54625564	0.543
2010	0.591973325	0.608634013	0.483
2011	0.643224312	0.543528903	0.42265
2012	0.672915897	0.560308965	0.3623

2013	0.690717768	0.601823314	0.3373
2014	0.737801927	0.655672615	0.3123
2015	0.758341222	0.684423193	0.42405
2016	0.791876136	0.715503978	0.5358
2017	0.814440162	0.721088501	0.42075
2018	0.852549672	0.709972969	0.3057
2019	0.885482712	0.719756213	0.4057

Source: Authors 'estimation energy and economy index, environment index from (epi.yale.edu)

Table 4.4: Comprehensive Index of Energy, Economy, and Environment

Coordination level	Criterion	Types
I	0-0.09	Extremely imbalanced
П	0.10-0.19	Sever disorders
III	0.20-0.29	Moderate disorder
IV	0.30-0.39	Mild disorder
V	0.40-0.49	Frequent imbalanced
VI	0.50-0.59	Barely coordinated
VII	0.60-0.69	Primary coordinated
VIII	0.70-0.79	Intermediate coordinated
IX	0.80-0.89	Good coordinated
X	0.90-1.00	Highly coordinated

Source: Authors' estimation energy and economy index, environment index from (epi.yale.edu)

The figure 4.1 shows the trends of comprehensive index the 3Es from 2006 to 2018 where by the environment index shows the downward trend until 2014 and after that there exist an improvement in the trend between energy economy and environment. Figure 4.2 represents the coupling coordination between energy and economy (X-Y) and shown the rising trend. Similarly figure 4.3 shows the coupling coordination between energy and environment (X-

Z), it is observed that in 2014 it reached the level 0.83 is the value and put in to the barely coordinated. In 2016 the relationship was improved. Figure 4.4 represents the trends of coupling coordination between economy and environment (Y-Z) and observed that dip was observed in 2014. Figure 4.5 shows the trends of coupling coordination among energy, economy and environment (X-Y-Z) and it is presented that after 2014 the riding trends was observed in relation and after 2016 it was started to decline the coordination. The figure 4.6 explained the combined trend of coupling coordination between energy, economy (XY, energy environment (XZ), economy environment (YZ) and energy, economy environment (XYZ). The figure 4.7, represent the trend of 3Es development in India from 2006 to 2018.

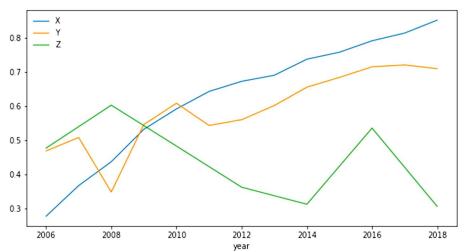


Fig. 4.1. The trend of the comprehensive index of 3Es in India

Table 4.5: Coupling and Coordination Development degree of energy, economy and environment of India

Year:	XY	YZ	ZX	XYZ	T	D	Types
2006	0.9337	0.999928	0.92964	0.974284	0.407	0.397	Mild Disordered
2007	0.974	0.99906	0.96361	0.987306	0.471	0.465	Frequent imbalanced
2008	0.9871	0.928102	0.97452	0.973917	0.462	0.45	Frequent imbalanced
2009	0.9998	0.999992	0.99989	0.999938	0.539	0.54	Barely Coordinated
2010	0.9998	0.986686	0.98971	0.995055	0.56	0.558	Barely Coordinated
2011	0.993	0.984343	0.9574	0.985949	0.536	0.529	Barely Coordinated
2012	0.9916	0.953882	0.90971	0.970776	0.531	0.516	Barely Coordinated
2013	0.9952	0.920355	0.88141	0.961711	0.542	0.522	Barely Coordinated
2014	0.9965	0.87371	0.83539	0.947338	0.568	0.538	Barely Coordinated
2015	0.9973	0.944936	0.92015	0.973487	0.621	0.605	Primary Coordinated
2016	0.9974	0.97933	0.96283	0.987588	0.68	0.672	Primary Coordinated
2017	0.9963	0.93099	0.89873	0.966923	0.651	0.63	Primary Coordinated
2018	0.9916	0.84188	0.77725	0.930883	0.622	0.579	Barely Coordinated
2019	0.9934	0.85623	0.77564	0.948543	0.634	0.586	Barely Coordinated

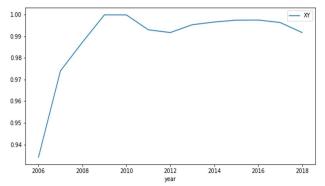


Fig. 4.2. Trends of Coupling of Energy-Economy(XY)

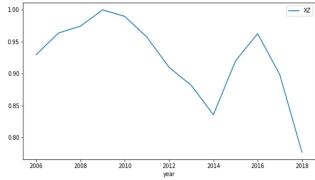


Fig.4. 3. Trends of Coupling of Energy-Environment (XZ)

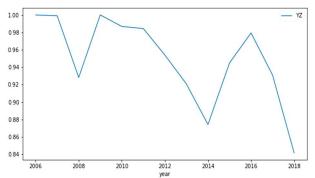


Fig. 4.4. Trends of Coupling of Economy-Environment (YZ)

Fig. 4.5. Trends of Coupling of Energy-Economy-

Environment(XYZ)

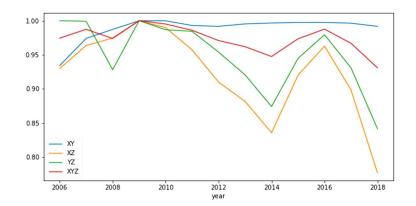


Fig. 4.6: Combine trends of Coupling of Energy-Economy (XY), Energy-Environment(XZ), Economy-Environment(YZ), and Energy-Economy-Environment(XYZ)

There was a mild in the coordination of economy and energy in the year 2006, India has a huge population and to provide energy to all citizens demanded huge investments in the energy sector. The National Grid system was yet not established in 2006 that could facilitate electricity to all. As the National Grid or Central Grid system was established in 2013 and since then India's energy supply has increased unfold by 18% from 2013 to 2018. Whereas, the overall energy supply from 2006 to 2018 has increased by 55%. The coordination between energy economies also improved from barely coordinated to primary coordinated in 2012. Whereas, it moved to intermediately coordinated in 2015 and showed stability by maintaining the coordination degree. The coordination between economy and environment has been very unstable and has majorly had

frequent imbalanced coordination only once in 2016 it improved to primary coordinated. The reason for this was India's strong average economic growth rate and the ever-rising population of the country, created pressure on the biosphere, which has led to environmental degradation.

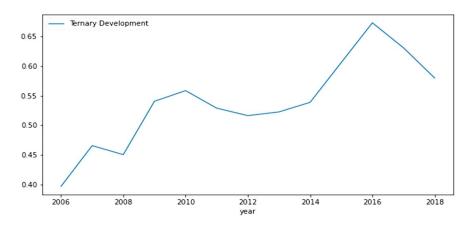


Fig. 4.7. Trends of development India

The Indian energy sector has steadily increased its production. The domestic energy production is dominated by coal and bioenergy. If we go back to 1973 the domestic energy production was largely dominated by bio-energy and waste around three fourth share of the total energy production. But the exploration of coal mines in the last three decades has made coal a prime material for the production of energy and its share has increased ever since. Therefore, the coordination between energy and environment was in a mild disorder in 2006. In 2008 at the conference of the parties15, India announced to reduce the emission intensity by 20-25% of its GDP against 2005 levels by 2020. Therefore we can see an improvement in the coordination between energy and environment from mild disordered to barely coordinate and for seven consisting years it maintained the same coordination. In 2016 after Paris Agreement India focused on achieving the NDC's built target of reducing emissions by 33-35% of GDP against 2005 emissions by 2030, to increase the cumulative electric power by 40% from non-fossil fuel based energy and to increase the forest and tree cover to increase carbon sink by 2030 (IEA 2020).

Therefore, there is an improvement in the coordination between energy and environment from barely coordinated to primary coordinated. In 2018 as electrification work in the country was going on due to which there was a huge gap between demand and supply of energy and the coordination again deteriorated to barely coordinate.

4.6. Conclusion

Energy, Economy and Environment are the components of a complex system that interact, promote and restrict one another. The three Es' systematically evaluated by constructing a coupling coordination and development model of India from 2006 to 2018. In the years from 2006 to 2018 the development trends between energy, economy and environment has been in recession or mild disorder category in 2006 but in 2009 it improved and moved up to barely coordinated and maintained the same for six years. This was mainly due to the Indian government was driven to reduce the energy's intensity, also to provide electricity to all the citizens while the growth rate of the economy was also maintained. Hence, there was further improvement in the coordination with 0.6049 to primary coordinated in 2015 and was stable till 2017. Again in 2018 it dipped back to barely coordinated with 0.579 score. This was due to the humongous pressure on the environment due to the ambitious targets of government to provide electricity to all, which mostly met by coal that was the reason for increase in the emission of greenhouse gases.

The coupling coordination between economy and environment has mostly been unstable. It has shown a declining trend since 2010 till 2014, mainly due to the increase in demand of energy that was majorly met by coal. The use of unclean energy degraded the environment. In 2015, we see an improvement in the coordination but it was short lived and again declined after 2016. It was due to increase in the pace of developmental work. The coupling coordination between energy and environment has been most often in barely coordinated category. It started with mild disorder in

2006 and in 2018 it was still in frequent imbalanced category only once in 2016 it was in primary coordinated category due to growing environmental concern internationally. The EPI was at its worse on 2018 with score of 0.306. The energy, economy, and environment are interlinked with each other to an extent that changes in one E affect both the Es'. In India the coupling coordination and development between energy, economy, and environment has been very unstable. There is a need for efficient polices and research& development and deployment for positive coupling coordination between the energy, economy, and environment.

The impact of Conventional and Non-Conventional on Environment and Economy

5.1. The impact of Energy on Environment and Economy

The impact of conventional (fossil fuel-based) and non-renewable energy sources (such as nuclear energy) versus renewable energy sources (RES) on the environment and economy is a critical topic in today's discourse on sustainable development. Both types of energy have significant implications for environmental sustainability, economic growth, and long-term global well-being. Below is an analysis of the impacts of conventional (non-renewable) and renewable energy on the environment and the economy.

a. Environmental Impact of Conventional Energy Sources (Fossil Fuels)

Conventional energy sources include coal, oil, and natural gas. These energy sources have significant negative environmental impacts due to their high levels of greenhouse gas (GHG) emissions and other pollutants.

Greenhouse Gas Emissions:

The combustion of fossil fuels is the primary source of carbon dioxide (CO₂) emissions, the most significant greenhouse gas contributing to global warming and climate change. Fossil fuel power plants are responsible for about 40% of global CO₂ emissions, contributing to global warming, rising sea levels, extreme weather events, and disruptions in ecosystems.

Air and Water Pollution:

Coal and oil burning release a wide range of pollutants, including sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM), which contribute to acid rain, smog, respiratory diseases, and cardiovascular problems. Fossil fuel extraction and processing can lead to water contamination. For example, mining for coal and drilling for oil can result in water table contamination, affecting local ecosystems and communities.

Resource Depletion:

Fossil fuel extraction is unsustainable as these resources are finite. Their depletion leads to higher costs of extraction and environmental degradation due to more invasive methods like deep-water drilling, fracking or mountaintop removal mining. The infrastructure required for fossil fuel extraction, such as drilling platforms, pipelines, and refineries, can lead to deforestation, habitat loss, and biodiversity reduction, particularly in sensitive ecosystems like rainforests.

b. Environmental Impact of Non-Renewable Energy Sources

Nuclear energy is considered a low-carbon energy source, but it still has environmental risks:

Radioactive Waste due to Nuclear Energy:

The major environmental concern with nuclear energy is the disposal and storage of radioactive waste, which remains hazardous for thousands of years. The safe management of nuclear waste is a significant challenge and a source of public concern. While rare, nuclear accidents like the Chernobyl disaster (1986) and Fukushima (2011) can have catastrophic environmental consequences, including the contamination of large land areas, long-term health risks for humans, and severe ecological damage. Nuclear power plants require substantial amounts of water for cooling, which can deplete local water resources and affect aquatic ecosystems.

Under Renewable Energy Sources (RES)

Renewable energy sources, including solar, wind, hydro, biomass, and geothermal energy, are generally considered environmentally friendly alternatives to fossil fuels. However, they still have some environmental impacts, albeit less severe.

- Lower Carbon Emissions: RES contribute little to no carbon emissions during energy production, making them vital in mitigating climate change. Wind and solar power, for example, are considered near-zero emissions technologies.
- Land and Resource Use: Solar and Wind: Large-scale solar farms and wind turbine installations require significant land space, potentially displacing agricultural land or natural habitats. However, these impacts are generally less disruptive compared to fossil fuel extraction. Hydropower: Dams and reservoirs for hydropower can lead to habitat disruption, fish migration disruption, and ecosystem changes, especially in river systems.
- Energy Storage: The intermittent nature of some renewable energy sources (e.g., wind and solar) requires the use of energy storage systems, which can involve resource-intensive processes and materials (e.g., lithium for batteries).
- Environmental Footprint of Manufacturing: The production of renewable energy systems (such as solar panels, wind turbines, and batteries) involves resource extraction, energy use, and emissions. However, their lifetime carbon footprint is still much lower than fossil fuels.

c. Economic Impact of Conventional Energy Sources (Fossil Fuels)

Fossil fuel industries have traditionally been the backbone of global economic growth, particularly in terms of energy production, jobs, and national revenue. However, their economic impact is

increasingly seen as unsustainable due to environmental degradation, resource depletion, and volatility in global energy markets.

- **Job Creation and Economic Output**: The fossil fuel industry creates millions of jobs globally in extraction, transportation, and refining, and remains a significant contributor to GDP in many oil and gas-dependent economies (e.g., Middle East, Russia, and the U.S.).
- ♣ Volatility and Price Instability: Fossil fuel prices are subject to global market fluctuations
 due to geopolitical instability, supply chain disruptions, and global demand shifts, leading
 to economic instability, especially in economies dependent on fossil fuel exports.
- Subsidies and Hidden Costs: Governments often subsidize fossil fuel industries to maintain low energy prices, which can lead to fiscal inefficiencies and market distortions.

 The economic costs of fossil fuel use also include healthcare costs due to pollution and environmental damage, which are not always factored into the price of energy.
- Long-term Unsustainability: The increasing cost of extraction, declining reserves, and external environmental costs make fossil fuels an unsustainable source of economic growth. Transitioning to renewable energy is seen as necessary for long-term economic stability.

d. Economic Impact of Non-Renewable Energy Sources

- ♣ The economic impacts of nuclear energy: Nuclear energy has its own economic considerations, particularly around infrastructure investment, operational costs, and public acceptance.
- → **High Initial Costs**: Nuclear power plants are expensive to build, requiring significant capital investment. However, once built, they provide a stable and reliable source of electricity at relatively low operational costs.

- **↓ Job Creation and Innovation**: The nuclear industry provides specialized jobs in engineering, operation, and maintenance of nuclear facilities. It also drives technological innovation in energy production and safety.
- ♣ Cost of Decommissioning and Waste Management: The decommissioning of nuclear plants and management of nuclear waste are costly and long-term liabilities. These costs often exceed initial construction costs and pose long-term economic challenges for countries relying on nuclear power.

e. Economic Impact of Other Renewable Energy Sources (RES)

Renewable energy sources are increasingly becoming a central pillar of the global energy transition, with significant benefits for both the environment and the economy. However, there are also economic challenges associated with the shift from fossil fuels to renewables.

- **Job Creation in Green Technologies**: The renewable energy sector has become a significant driver of job creation in solar, wind, battery storage, and clean technology manufacturing. Renewable energy industries are labor-intensive, creating a wide range of jobs in installation, maintenance, and research and development.
- Reduced Long-Term Energy Costs: Although the initial capital investment for renewable energy infrastructure can be high (e.g., wind turbines or solar panels), the operational costs are lower than fossil fuel plants, and the price of renewable energy continues to decline due to technological advancements.
- ♣ Energy Independence and Security: Renewables can reduce dependency on imported fossil fuels, enhancing energy security for countries, especially those with limited fossil fuel resources. This can lead to greater economic resilience and reduce geopolitical risks tied to fossil fuel imports.

- **♣ Energy Access and Rural Development**: Renewable energy can provide electricity to rural and off-grid areas, stimulating economic growth in underserved communities. This can support small businesses, improve healthcare, and enhance educational opportunities.
- ♣ Subsidies and Investment: While renewable energy technologies are becoming more cost-competitive, subsidies and government investment (e.g., tax incentives for solar or wind projects) are still required in many regions to make the transition feasible and attractive for private investors.
- f. Environmental Impact: Conventional energy sources, particularly fossil fuels, have significant negative environmental consequences, including climate change, air and water pollution, and resource depletion. Nuclear energy offers a low-carbon alternative but introduces challenges related to waste disposal and accident risks. Renewable energy sources are the most environmentally friendly but still have some environmental trade-offs, such as land use and manufacturing impacts. Fossil fuels have historically driven economic growth but are becoming less sustainable due to environmental costs and price volatility. Nuclear energy offers stability but requires substantial investment and faces public opposition. Renewable energy is increasingly economically competitive, with benefits such as job creation, energy independence, and lower long-term costs, though it requires initial investments and infrastructure development. The shift towards renewable energy is essential for creating a sustainable future, both environmentally and economically, by reducing the dependence on polluting fossil fuels and investing in clean, renewable alternatives. However, this transition requires careful planning, investments, and policy frameworks to balance economic and environmental goals.

5.2. Case study of analysing the long run relationship between CO₂ emissions and Energy use of United Kingdom

In this case study, the time series data of the United Kingdom from 1965 to 2021 for energy usage, total reserves, manufacturing, GDP and total carbon emission have been examined using autoregressive distribution lag (ARDL) model. The results revealed that energy usage, manufacturing and GDP have a positive relation with CO2 emission both in the short run and long run raising environmental concerns on the contrary only total reserves have a negative relation in the short and long run. United Kingdom increasing energy efficiency have been a top priority in the recent era, in order to achieve the target of net zero carbon emission by 2050, government need to promote policies for energy mix which would increase the usage of other renewable energy as the challenges remain for manufacturing and transportation industry because the overall emission from these sector remains largely unchanged despite advancements in fuel efficiency because the results indicates that a percentage increase in energy usage increase the CO2 emission by 0.23% whereas 1% increase in manufacturing leads to 0.25% increase in the CO2 emission.

5.3. Literature Review

Over time, the UK has significantly reduced its carbon dioxide (CO₂) emissions as shown in fig.7.1. Between the early 1990s and 2019, emissions had decreased by about 43%, largely as a result of a move away from coal-based energy production, improved energy efficiency, and the expansion of renewable energy sources. The energy industry has significantly reduced its emissions. This reduction was greatly aided by the closure of coal-fired power stations and their replacement with natural gas and renewable energy sources like wind and solar. A challenge has been the transportation industry. The overall emissions from this sector remained largely unchanged because of a rise in road traffic, despite advancements in fuel efficiency and the use

of electric vehicles. The United Kingdom government has established challenging goals for emissions reduction. The goal is to achieve net-zero emissions by 2050, which is legally required. The UK has introduced a number of policies, including carbon pricing and subsidies for renewable energy, to achieve this.

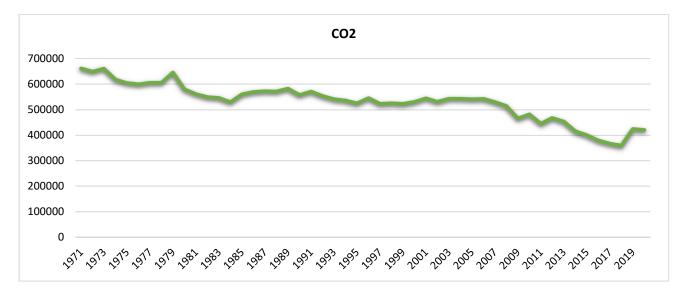


Fig. 5.1 CO₂ emission

The United Kingdom's energy mix has evolved over time, fig. 7.2 shows the total energy usage of UK. While natural gas, nuclear power, and renewable energy sources have gained popularity, the amount of coal used to generate electricity has significantly decreased. The UK is now a global leader in offshore wind energy because to the significant increase of wind power in particular. In the UK, increasing energy efficiency has been a top goal. This covers metrics for building, appliance, and industrial process energy efficiency. To promote more energy-efficient housing, initiatives like the Energy Performance Certificate (EPC) have been introduced. Energy production has become more decentralized in the UK, where more homes and businesses are using solar energy and small-scale wind power to generate their own electricity. This trend to decentralized energy production has helped to cut down on transmission losses. Although there have been oscillations in energy use in the household and industrial sectors, there has been an

overall trend towards increased energy efficiency. Government incentives and policies have contributed to the promotion of sustainable practices and energy efficiency.

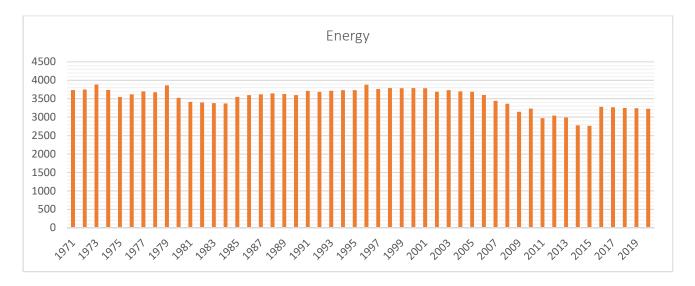


Fig. 5.2 Energy Usage

Emissions reduction in the transport industry is still a difficult task. It will take significant infrastructural investments to make the switch to electric vehicles and lessen reliance on fossil fuels. It will take time and effort to increase the housing stock's energy efficiency in the UK, particularly renovating older structures. In this study, we looked at the connections between CO₂ emissions, economic expansion (GDP, manufacturing value), total reserves and energy use. A multivariate model is used to investigate the causation, short and long sighted interdependence between CO₂ emission, economic growth (GDP, Manufacturing), total reserves and energy usage. The goal of the study is to identify the factors that are beneficial to environment sustainability so that we can advance in a more sustainable way.

A significant number of studies show that, despite the fact that economic growth does result in an increase in energy consumption, carbon emissions are not permanently reduced as a result. Some scholars use econometric models to look at the short- and long-term dynamic interactions between factors like carbon emissions, financial growth, suburbanization, and international trade in order

to offer direction for the sustainable development of a region or a nation. According to the environmental Kuznets curve (EKC) theory, there is an inverse U-shaped relationship between environmental pollutants like CO₂ and GDP (Jebli et al. 2016, Leal & Marques. 2020, Rafiq et al. 2016, Dong et al. 2017, Shahbaz et al. 2019).

Time series data for the three major nations of the USA, France, and Japan were studied from 1965 to 2020 using the Fourier ARDL, Fourier bootstrap Toda-Yamamoto, and wavelet coherence methods. According to this analysis, France crossed the breakeven threshold in 1978, demonstrating that CO₂ levels decreased as nuclear energy use increased (Singh et al. 2023). The South Asian EKC hypothesis was also confirmed, demonstrating the beneficial effects of LPG use on the environment (Murshed M. 2021).

GDP and CO₂ emissions are inversely correlated, according to research on 31 developing countries with subpar clean energy development Aye et al. (2017). While few studies (Teng et al.2021, Ahmed et al.2019, Ahmed et at.2020, Odugbesan and Adebayo.2020, Pablo et al.2016, Wasti et al.2020) found a positive link between GDP and CO₂ emissions. The most modern econometric approaches, like as ARDL, Wavelet coherence, and Fourier analysis, have been used in several research to analyse the causal relationship and unidirectional connectivity between energy, GDP, and CO₂ emissions. [Yang and Zhao (2014), Adebayo et al. 2020, Adebayo et al. 2021, Khobai and Roux (2017), Toda-Yamamoto Al-Mulali, U. 2011, Wu et al. 2022, Adebayo TS. 2020, Gao & Zhang. 2021, Faisa et al. 2016, Jafari et al. 2015, Wang et al. 2019, Aydoan & Vardar. 2020, Kirikkaleli et al. 2020, Kirikkaleli, & Adebayo. 2021].

A study that looked at the effects of ethanol and biodiesel in Latin America using life cycle analysis (LCA) recommended converting 5% of pastureland into energy crops to increase biofuel production for low carbon emissions and significant economic benefit Canabarro et al. 2023. The

study found that using biofuels instead of fossil fuels reduces greenhouse gas emissions by 70%. The economic potential of biofuels was studied between 2001 and 2022 using bibliometric analysis. The research revealed that while the US, China, India, and Europe have the largest biofuel markets, many other developed and developing countries still have smaller and less developed markets for sustainable biofuels (Hasan and Coworkers, 2023).

7.4. Methodology

To test our hypothesis and accomplish our objective, we used secondary time series data that we obtained from the World Bank Development Indicators (WDI). Equation 1 was created to analyse the relationship between CO2 emissions, GDP, energy use (EU), manufacturing value (MV), and total reserves (TR) in the context of the United Kingdom from 1965 to 2021.

$$ln CO2 = f (lnGDP, lnEU, lnMV, lnTR)...$$
 (1)

Here, ln is the natural log in the equation above, and Table 1 defines the variable description has definitions of the variables.

$$\Delta \ln CO2_{t} = a_{0} + \sum_{i=1}^{n_{1}} a_{1i} \Delta \ln GDP_{t-i} + \sum_{i=1}^{n_{1}} a_{2i} \Delta \ln EU_{t-i} + \sum_{i=1}^{n_{2}} a_{3i} \Delta MV_{t-i} + \sum_{i=1}^{n_{3}} a_{4i} \Delta \ln TR_{t-i} + \beta_{1} \ln GDP_{t-1} + \beta_{2} \ln EU_{t-1} + \beta_{3} \ln MV_{t-1} + \beta_{4} \ln TR_{t-1} + \mu_{t} \dots (2)$$

The letters a1 to a3 in the equation above reflect the short-run relationship, b1 to b3 represent the long-run relationship, and a0 the drift component. While ni is the optimal lag and t is the error term.

$$\Delta \ln CO2_{t} = \beta_{0} + \sum_{i=1}^{n_{1}} \beta_{1i} \Delta \ln GDP_{t-i} + \sum_{i=1}^{n_{2}} \beta_{2i} \Delta \ln EU_{t-i} + \sum_{i=1}^{n_{3}} \beta_{3i} \Delta \ln MV_{t-i} + \sum_{i=1}^{n_{3}} \beta_{4i} \Delta \ln TR_{t-i} + \theta ECM_{t-1} + \mu_{t}......(3)$$

In the equation above, the letters all to a 4 stand for the short-run relationship, bl to b4 for the long-run connection, and a0 for the drift element. While t is the error term and ni is the ideal lag.

5.5. Results and Discussions

The study is conducted on time series data for 57 years so ADF unit root test was applied to check the Stationarity of the variables, the results indicated that the variables were stationary at first difference, ARDL model is applicable if variables are stationary at level or first difference or a mixture of both and as the variables were stationary at first difference ARDL model was well suitable for this study. The table below illustrates the results of ADF unit root test.

Table 5.1. ADF unit root test

Variables	I(0) t-stats	I(0) p-value	I(1) t-stats	I(1) p-value
CO2	-2.897	0.1713	-8.379	0.0018***
GDP	-1.591	0.78	-7.015	0.002***
EU	-2.703	0.239	-7.567	0.018***
MV	-1.488	0.822	-7.525	0.003***
TR	-2.83	0.1931	-8.618	0.0098***

***, ** &*denotes 1%, 5% & 10% significance level.

The long-term relationship between the dependent and independent variables is assessed using the Auto Regressive Distributed Lag bond (ARDL) bound test. The upper bound and lower bound are two critical variables that the test displays. The lower bound assumes that all the variables are equal, while the upper limit assumes that there is a first difference for all of them in this situation. The null hypothesis is rejected and co-integration is shown to exist if the upper limit value is less than the F statistic. ARDL bound test is used to check the cointegration between the variables, the finding reveals that the dependent variable CO₂ and the independent variables GDP, manufacturing, energy usage and total reserves are cointegrated as the F statistic is 4.26 which is greater than 3.49 the upper bound and 2.56 the lower bound at 5% significance level. Table 5.2 illustrates the results of the ARDL bound test.

Table 5.2. ARDL bound test

Variables	F-Statistics		
F (CO2,GDP,EU,MV,TR)	4.264781**		
Critical Value	1%	5%	10%
Lower Bound	3.26	2.56	2.2
Upper Bound	4.47	3.49	3.09

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level.

Table 5.3 The results of the ARDL short run estimates are indicated in table 5.4 indicating that energy usage and GDP is significant at 1% and is positively correlated with CO₂ emission, a 1% increase in the GDP will increase CO₂ by 1.12% whereas one percentage increase in energy usage will increase the CO₂ emission by 0.23% on the other hand manufacturing also has a positive relation and is significant at 10%, in all the independent variable only total reserves is negatively correlated with CO₂ emission indicating that a percentage increase in the reserves leads to 0.04 reduction in the CO₂ emission.

Table 5.3. ARDL short run

Variables	Probability	t-Statistics	Coefficients
GDP	0.0001***	4.5845	1.1222
MV	0.0701*	1.8598	0.2589
EU	0.0049***	2.9732	0.2321
TR	0.0239**	-2.345	-0.0483

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level

Table 5.4 displays the results of ARDL long run estimates where the results of ARDL long run estimates where the results indicates that GDP, manufacturing and energy usage are significant at 1%, 10%, and 1% respectively and has a positive relationship with CO₂ emission hence it would be advisable to use more of green energy both for manufacturing process and energy use which would also impact the GDP on the other hand total reserves is significant at 5% and has a negative relation with the CO₂ emission.

Table 5.4. ARDL long run

<u>Variables</u>	<u>Probability</u>	<u>t-</u>	Coefficients
		Statistics	
GDP	0.0000***	4.5845	1.1222
MANUFACTURING	0.0701*	1.8598	0.2589
ENERGY	0.0049***	2.9732	0.2321
RESERVES	0.0216**	-2.388	-0.0589

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level

Table 5.5 displays the results of diagnostic test Jarque-Bera normality test was employed to check whether the residual are normally distributed or not and the result reveal that the residuals are normally distributed (0.20 > 0.05). Ramsey Reset test was used to check the specification error and the result revealed that there was no specification error in the model (0.40 > 0.05). Breusch-Godfery serial correlation, LM test revealed that there exist no serial correlation among the error components in the model (0.38 > 0.05). Lastly, the outcomes of heteroscedasticity Breusch-Pagan-Godfery test demonstrate that the data is homoscedastic.

Table 5.5. Diagnostic tests

JB Normality Test	2.02	0.66
Ramsey RESET test	10.25	0.318
Breusch-Godfery serial Correlation	16.68	0.122
Heteroskedasticity B.P.G. test, Observed R-squared	5.46	0.325

Granger causality test is used for the time series data to predict whether one variable has potential prediction impact on the other variable. The results reveals that there exist unidirectional causation between CO₂ emission-GDP, total reserves- manufacturing and CO₂ emission-reserves at 10%

significance level whereas manufacturing-CO₂ and GDP-reserves have a unidirectional causual linkage at 1% and 5% respectively. The Granger causality test results are shown in Table 5.6.

Table 5.6. Granger causality test

Direction of Causality	F-statistics	Probability
CO ₂ - GDP	3.1667	0.0507*
MANUFACTURING- CO ₂	5.07605	0.0098***
GDP-RESERVES	3.22392	0.0482**
RESERVES- MANUFACTURING	2.89367	0.0647*
CO ₂ -RESERVES	3.02068	0.0577*

***, **& *denotes 1%, 5% & 10% significance level

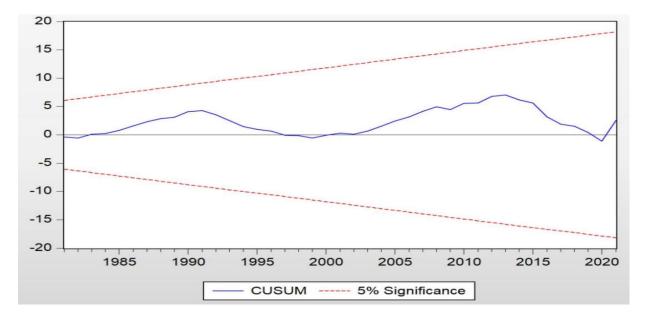


Fig.5.3 CUSUM test

The stability of the model was checked by the cumulative sum of the recursive residuals stability test (CUSUM) and as the statistics were found to be between the critical bounds the model was found stable as shown in Fig.5.3.

5.6 Conclusion

This study uses data from 1965 to 2021 to examine the relationships between carbon emissions, economic growth (GDP, Manufacturing, Reserves), and energy consumption of the United Kingdom. The findings reveal that energy use, GDP and manufacturing are positively related whereas total reserves have a negative relation with CO₂ emission both in the short run and long run respectively. The short and long run impact of GDP, energy usage and manufacturing on CO₂ emission is unfavourable that is a concern for the environment. Estimates of the linkages between economic expansion, CO₂ emissions, and energy consumption reveal that the United Kingdom has a wide range of options for establishing its energy policy toward alternative and renewable energy sources in an environmentally friendly and long-term manner. They could diversify their energy strategies in this direction, reducing environmental pollution while steadily and reliably increasing the energy supply over time. By supporting the development and widespread use of alternative and renewable energy technologies, it may also play a leading role in ensuring that future generations inherit a more habitable and cleaner environment.

CHAPTER 6

The Combination of Technology and Policy mix that ensure Reliable, Affordable and Clean Energy

Achieving reliable, affordable, and clean energy requires a careful combination of technology and policy to ensure a sustainable energy future. This combination must address the challenges of energy security, affordability, and environmental sustainability while promoting economic growth. The study in this chapter is a comprehensive analysis of the technologies and policy mix necessary for ensuring these three critical goals.

6.1. Technological Solutions for Reliable, Affordable, and Clean Energy

The renewable energy sources like solar, wind, hydro and nuclear are the clean energy resources and some methods can also be used to save the carbon pollution by adoption of these technologies such as: smart grid, battery storage and carbon capture & storage. These are described with support of type policy as follows:

a. Clean Energy Technologies

- Solar Power: Solar photovoltaic (PV) have become one of the most cost-effective and scalable renewable energy technologies. With advancements in efficiency and a reduction in manufacturing costs, solar energy is increasingly affordable and capable of meeting local and national energy needs. Policies like subsidies, tax credits, and feed-in tariffs (FITs) have spurred the adoption of solar power globally, making it a mainstream energy source.
- Wind Power: Both onshore and offshore wind turbines provide a significant portion of clean energy in many regions. Offshore wind farms, in particular, offer high energy yields

due to stronger, more consistent winds at sea. Long-term government commitments, such as renewable portfolio standards (RPS), can create market certainty and attract private investments in wind energy infrastructure.

- Energy Storage Technologies: Battery Storage (e.g., lithium-ion, solid-state batteries):

 Storage systems are crucial for balancing intermittent renewable energy sources like solar and wind. Energy storage helps smooth out supply and demand fluctuations and ensures a reliable power supply. Governments can incentivize battery storage deployment through grants, tax incentives, and funding for research and development (R&D) to accelerate technological breakthroughs and reduce costs.
- Grid Modernization and Smart Grids: Modernizing the electricity grid and incorporating smart grid technologies enables better management of electricity flow, integrates diverse energy sources, and enhances grid stability. Policies that promote investments in grid infrastructure, such as smart meters and advanced control systems, are crucial for enabling demand response, optimizing energy distribution, and increasing resilience to disruptions (e.g., extreme weather events).
- **Hydropower and Geothermal: Hydropower** (both large-scale and small-scale) and geothermal energy are reliable, clean, and cost-effective options for providing baseload power. Policies such as power purchase agreements (PPAs) or long-term contracts for renewable energy generation encourage investments in hydropower and geothermal projects, particularly in regions with abundant natural resources.
- ♣ Carbon Capture and Storage (CCS): CCS technologies capture carbon dioxide emissions from power plants and industrial sources, preventing them from entering the atmosphere. This is especially important for decarbonizing industries that are difficult to

electrify, such as steel and cement manufacturing. Governments can facilitate CCS adoption by offering subsidies, tax credits (e.g., the 45Q tax credit in the U.S.), and financing for pilot projects.

Nuclear Energy (Next-Generation Reactors): Nuclear power provides a low-carbon, high-output energy source. New technologies, such as small modular reactors (SMRs), promise to reduce costs, enhance safety, and provide more flexible energy production. Strong government policies are necessary to promote nuclear energy, including research into next-generation reactors, financing for new plants, and the management of nuclear waste.

b. Energy Efficiency Technologies

The energy efficiency technologies for building, industries and transportation sections are summarized as follows:

- Building Energy Efficiency: Technologies such as LED lighting, high-efficiency HVAC systems, and smart building technologies can significantly reduce energy consumption in residential and commercial buildings. Energy efficiency standards for buildings (e.g., LEED certification) and incentives for energy-efficient appliances and retrofits can drive the adoption of these technologies.
- Industrial Efficiency: Energy-efficient industrial technologies, including advanced manufacturing processes, automation, and waste heat recovery systems, can reduce energy consumption in manufacturing. Policies like energy efficiency standards, tax breaks for energy-saving investments, and industrial energy audits can help industries transition to low-energy, low-carbon operations.

Transportation Efficiency and Electrification: Electric Vehicles (EVs) and public transportation electrification (e.g., electric buses) significantly reduce the demand for fossil fuels, particularly in urban areas. Policies such as EV purchase incentives, investments in charging infrastructure, emissions standards, and subsidies for public transport electrification are critical in scaling up adoption.

c. Regulatory and Market Frameworks

♣ Carbon Pricing (Carbon Tax or Cap-and-Trade Systems): Pricing carbon incentivizes the reduction of carbon emissions by making fossil fuels more expensive relative to clean energy sources. It internalizes the environmental cost of carbon emissions, encouraging businesses and consumers to choose low-carbon alternatives. Governments should implement carbon taxes or emissions trading systems to create market-driven incentives for clean energy deployment while ensuring the price of carbon is high enough to drive investment in green technologies.

Renewable Portfolio Standards (RPS) and Clean Energy Standards (CES):

These policies mandate that a certain percentage of electricity must come from renewable or clean sources. This guarantees demand for renewable energy and stimulates investment in clean energy infrastructure. Governments should increase renewable energy targets over time and provide financial support (subsidies, grants) to meet these goals.

Subsidies and Incentives for Clean Energy Technologies:

Subsidies for solar, wind, energy storage, and energy efficiency technologies have been instrumental in reducing their costs and accelerating their deployment. Governments should continue to support early-stage renewable technologies through direct subsidies, tax

credits (such as Investment Tax Credits for solar), and R&D funding. These policies help reduce the cost gap between clean energy and conventional fossil fuels.

d. Long-Term Energy Planning and Integration

- ♣ Integrated Energy Policy: Governments must integrate energy, environmental, and economic policies to create a cohesive strategy for energy transition. This includes setting long-term decarbonization targets, diversifying energy sources, and ensuring equitable access to energy. National energy plans should include timelines for phasing out fossil fuels, promoting renewable energy, and ensuring a just transition for workers in fossil fuel industries.
- ♣ Investment in R&D and Innovation: Government support for energy innovation through R&D funding accelerates the development of new technologies and helps overcome barriers to the adoption of clean energy solutions. Governments should provide funding and create innovation hubs (e.g., energy research labs) focused on next-generation energy technologies like advanced storage, nuclear fusion, and next-gen solar cells.

e. International Cooperation and Policy Coordination

Global Agreements on Climate Change (e.g., the Paris Agreement): International agreements help coordinate global efforts to reduce emissions and transition to clean energy. Countries must align their energy policies to meet global climate goals. National policies should align with international climate commitments and promote cross-border collaboration on technology sharing, emissions reductions, and clean energy deployment.

Financing and Support for Developing Countries:

Many developing nations lack the infrastructure and resources to transition to clean energy. International financial support, technology transfer, and capacity-building are necessary to help these countries adopt clean energy solutions. Developed countries should increase financial aid to support clean energy projects in developing nations, in line with commitments such as the Green Climate Fund (GCF).

f. Social and Behavioral Policies

- ♣ Public Awareness and Education: Educating consumers and industries about the benefits of clean energy, energy efficiency, and sustainable practices is critical in driving demand for clean energy. Governments should invest in public awareness campaigns, educational programs, and training for workers transitioning to clean energy jobs.
- **♣ Energy Access Policies**: Ensuring that energy transitions are equitable and that all populations have access to affordable, clean energy is vital for social stability and economic development. Governments should develop programs that provide energy access to underserved communities, such as off-grid renewable energy solutions and subsidies for low-income households.

6.2. Case Study on CCUS technology can enhance the COP-28 Carbon Neutrality Target of India: Evidence from Fuzzy Analytical Hierarchy Process

The trajectory of India's energy system is a combination of technology and policy mix which extends to reliable, affordable and attainable. More than 60% of electrical power is generated by coal in India as well as globally. The major air pollution take place due to the thermal power plants and the country needs to deploy carbon capture, utilization, and storage (CCUS) technology in thermal power plants that can help to decarbonize the economy. In present era, the CCUS is a cutting edge technology for the power plants and Industries. The paper is validate the use of CCUS technology as a better option for India in the present scenario. The Fuzzy AHP multi-decision

criteria method is used to compare the potential of CCUS and renewable energy. The value of CCUS is evaluated by 0.981 and the value of REW is 0.609 in India. Present study suggests that CCUS has an advantage over REW in comparison to time taken for CO₂ reduction and present energy mix is in favourable for CCUS whereas REW has a cost advantage over CCUS. The BAU estimation is also forecasted the future energy demand and CO₂ reduction till 2050.

6.3. Literature Review

Paris climate agreement stated the countries to drive for net zero carbon emission by 2050. This lead to the race of developing renewable energy sources and by far the European Union countries are a way ahead then the other countries. Presently India is facing triple challenge of increasing energy demand while simultaneously reducing the cost of renewable energy and greenhouse gas emissions. Therefore, there is a need to identify the plausible pathways and technology to meet the challenges. As India's coal, generating capacity is higher than its peak demand and it needs to adapt a technology that can reduce the carbon emission while using the conventional sources. India's electricity demands by 2020-21 will be more than double the level in 2011-2012. Hence, it is an urgent need to explore and develop the different sources of renewable energy. The total energy demands in the year 2022 will 6551 TWh/yr and out of 974TWh meant by renewable energy as projected by the government of India. India has committed to reduce its carbon emission concentration by approximately 30-35% by 2030 at the UNFCCC Paris Summit. To achieve the targets it is expected to develop a proper CCUS technology, if it is able to develop an efficient CCUS technology it can reduce 50-85% of the GHGs by 2050 by constructing its way to achieve the net zero CO₂ emission by 2050 [IRENA 2020]. The Transition in energy consumption can be accomplished by proper policy implementations and Technological innovation.

Xu et al. [2021] focused on CCS technology for the reduction of CO₂ emission for becoming

carbon neutral by 2060. It has outlined the present status CCS of selected countries. The paper has discussed the potential of china in the development and application of CCS technology. It has also highlighted that china has highest potential for CCS, as the good compatibility with CO₂ emission, as China is one of the largest emitter of CO₂. [Kumar et al., 2020] analysis the challenges in implementation of CCS technology in India while demonstrating the breakdown of CCS technologies within the country. The various methods of carbon dioxide capture and separation, as India's power market is responsible for the half of CO₂ emission. Zhang [2020] reviewed research on Carbon Capture Utilization and Storage (CCUS) and concluded the need to prevent large quantities of CO₂ emission by implementing sound policies that can lead to positive results. More investment in the area of research and development is need of the hour. Moreno et al. [2019] reflected how carbon dioxide can be used as a source of carbon that can be used as raw materials for manufacturing of fuels, chemicals and carbonates. Carbon can also be used as recovery agent enchasing coal bed methane. It also explains the recent advancement of each technology. Life cycle assessment showed that among all the process, carboxylation is the best as it a synthesis of carbonates and carboxylates. The production of salicylic acid, dimenthyl and mineral carbonation are most likely application for reduction of CO₂ emission in short run.

Pearce et al.[1996] provided a theoretical framework of sustainability indicators to sustainable development. It is the study of two approach carrying capacity and Resilience and concludes that even though the economy operates under strong sustainability regime, saving are still a key indicator, regarding the measure of resilience more research is needed. Cantor [2011] develops a composite index, the (SDMI) Sustainable Development Measurement Index, which can be used in various countries. The study integrates social, economic and environmental components in assessing the sustainability for development. Then through juxtaposition of SDMI with HDI and

GDP developmental techniques, the paper highlighted a series of contemporary and important issues in the field of political and economic areas. SDMI breaks SD into three distinct components: social, economic, and environment factors. The list of specific components are defined under three baskets of development, data is collected for a period of 13 years of 30 countries using multiplicative excel formulas a score is calculated for each orient or on a point scale of 10 and all the three parameter of the basket is added on 0-30 scale of Sustainable Development.

Zeng et al. [2020] examined the performance of different renewable energy schemes and tried to develop an optimal design of two stage i.e., firstly Evaluation stage and secondly optimization stage. In the first stage multiple indexes taken into consideration and then using intuitionistic fuzzy qualitative index and lastly super efficiency Data Envelopment Analysis (DEA) is used to overcomes the short- coming of the traditional model and provides beneficial results. Doukas et al., [2010] highlighted that renewable energy sources are more qualitative in nature. SD and renewable energy sources related using linguistic variable for this numerical multi-criteria method (TOPSIS) used to show that stability interval are not continuous but discrete in nature hence the policy makes can easily identified variables that are more sensitive to Sustainable Development. Wang and Yang [2020] focused on analyzing the sustainability index of 27 EU Countries by employing drivers, pressures, state impact and response model of intervention (DPSIR), by integration social energy environment aspects because of multidimensional dataset a nonlinear multifactor assessment model has been developed. The results showed that Denmark and Sweden have strong sustainability, as CO₂ emission is comparatively less and emphasis that good policy implementation closely related to strong sustainability. Mastrocinque et al. [2020] used AHP for case study in photovoltaic energy the framework was based on the triple bottom line approach. Gundogdu and Kahraman [2020] used spherical fuzzy analytic hierarchy process for the location

selection of Renewable energy.

Mangla et al. [2020] highlighted the importance of sustainable energy development in the present era and the importance of energy in the developed and developing countries. It evaluates the important indicators for sustainable development in emerging economy like India. The author has used grey based decision making trial and evaluation laboratory techniques for causal relationship between variable adoption of energy management system has highest relation score hence is more significant but awareness is comparatively less among India. Chen et al. [2010] discussed the correct modeling approach development in order to achieve the energy requirement between the developed and developing nations but this paper on contrary focus on the implementation aspect of energy system. One of the major challenges is in the area of fossil fuels their mitigation aspect of resultant carbon emission and impact on climate change.

Kumar et al. [2010] examine importance of renewable energy resources like wind, geothermal, biomass and countries are facing shortage of energy requirement and this to find the optimal level of how energy should be used, the focus should be more on renewable than non-renewable India in particular need 3-4 times more energy in order to meet its requirement. India has started taking positive steps like reduced carbon emission for more sustainable future potential- renewable energy certification (REC) could be used in future. Naqvi et al. [2010] linked the REC, FD and real income to ecological footprint by APGM (augmented panel algorithm method). The observation gives positive and negative relation- FD is positively linked however PCI (per capita income) for RI (real income) and HCG (high-income group) have a negative result. Majid [2020] presented the challenges, investment and employment opportunities in the field of RE in India. There are various obstacle faced by the energy sector like skewed regulation policy, lack of awareness, poor R&D and delay in the project of private sector. There is an urgent need to provide

affordable, reliable energy for the citizen hence the government should design policies to attract foreign investment to increase the phase of renewable energy market in India.

Mainali et al. [2010] developed a methodology to evaluate the energy sustainable for rural household in developing countries through Energy Sustainability Index (ESI). Social, Economic and Environmental factor combined using principal Component Analysis (PCA). The results shows that South Africa's sustainable rural energy index is the highest, the Countries like China, India, Sri Lanka has also shown improvement because of use of green electricity and clean cooking fuels. Mukherjee et al. [2020] expessed a continuous increasing trend in CO₂ emission due to the rapid industrial growth for enhanced the economic development, which has a direct harmful impact on the environment sustainability. It was suggested the need to develop industries that has less carbon emission for a better future one way to achieve it through use of clean coal technology for carbon neutral industrial economy. A holistic macro and micro level analysis is essential for a cost sensitive economy like India. It was identified some key sectors which enables to using coal gasification and carbon capture model. Khan et al. [2021] examined the relationship between energy consumption, population and natural resources on CO₂ emission of the United States. It was developed a comprehensive empirical analysis and applied unit root test for stationarity analysis. The data shows that there exists a long run relationship among variables other finding were that there exist an inverse relationship of renewable energy consumption and ecological footprints whereas population and bio-capacities are positively related with ecological footprint for non-renewable energy consumption. In addition, Granger causality presented bidirectional causality between CO₂ emissions and natural resources while unidirectional causality for population growth to energy consumption and CO₂ emissions. Policy maker suggested making policy that reduces over utilization of natural resources so that sustainable future can be reached.

Harjanne et al. [2019] presented that the Policy makers are always of the view that country should switch to renewable energy sources for better sustainability but renewable energy itself has certain drawbacks and therefore cannot be considered as a key solution to climate challenges. The policy makers need to understand that renewable is not sustainable as renewable itself is a question mark. Rather we need to switch to more practical approaches like cost benefit analysis for low carbon, more accurate concept needs to be created. "Bait and Switch" approach used by politician and industrialist ought to be stopped i.e., selling questionable energy sources in the name of renewable energy.

The work on CCUS and various methods applied for the analysis by the researchers is presented in table 6.1. The variable are dependent on the conditions and geographical and type of application hierarchy CCUS. The various models like MILP, MINLP, AHP, FAHP, FGRA, MCDM, ANP, FANP, PCJM, DEA, MCS, MCDA, IECM, WSM ate are the most feasible methods which can be used for the fuzzy analysis of CCUS in any country

Table 6.1: Summary of various studies for AHP and other methods used in CCUS analysis by researchers

Author	Country	Model	Variables	Finding
Tan et al	Philippines	MINLP, MILP	CO ₂ source and sink, Time,	applicable where CCS is to be
(2012)			Power Loss	worthwhile
Gumus et al.	Turkey	FAHP, FGRA,	Weightlessness, capacity,	used for hydrogen energy
(2013)		MCDM	reliability, cost	storage
Dai et al.	China	IMFCP	CO ₂ , Resources (PP, PRP,	IMFCP is verify the good
(2014)			SP), DOF, DCC, SF	relation and can get the CCUS
Tapia and	Philippines	FMILP	CO ₂ , Time, flow rate,	CO ₂ capture can be planned to
Tan (2014)			Source, Sink, No. of Power	man-age the technical risk of
			plant	overestimating the sink
				parameters.
Angelo et	Philippines	FANP, PCJM	CO ₂ , EN, EC, TE, SO, HE,	most preferred low-carbon
al. (2014)			WE, GE, SE, BE, NE, FC	technologies are geothermal,
				wind and hydroelectric energy

Krishna et	India	CCUS in TPP	CO ₂ , H2, Algae oil	CO ₂ will be reduced by using
al. (2018)				CCUS in TPP
Tapia et al.	Philippines	AHP, HAHP,	CO ₂ (Supply and	The strategy simultaneously
(2017)	, Japan	DEA, MCS,	Transportation captured),	allows the use of
		MCDA	Cost, Earth reservoir, CO2	
			flooding, Physical security	
Datta and	India	IECM	CO ₂ , oil, Gas, RE, HE, NE,	Good result of CCUS
Krishnamoo			O&M cost	
rti (2019)				
Chauvy et	Belgium	MCDA,	RE, CO ₂ , TM, GC,FFO, SM,	CO ₂ utilization products
al. (2020)		WSM, AHP,	CT, RAV	
Jalali et al.	Iran	MCDM,	CO ₂ , IMT, AT, MK, EAS,	TOPSIS decision-making
(2020)		TOPSIS	TCO ₂ , PCO ₂ , ACO ₂ , IC,	method to find the best
			OMC, RR, Alternatives	application of CO ₂ emitted from
				ethane treatment units of the
				Asalouyeh gas
				Processing plant.
Lu Y.	China	AHP	CO ₂ , CIPR, TEOR, APT,	TMC Benefits in CO ₂ flooding
(2021)			SEF, BT	in the water drive petroleum
				reservoir
Cai et al.	China	FCM	A_d , $S_{t,d}$, S_{tcf} , V_{daf} , M_t , ST ,	overall quality of coal is better
(2022)			Q _{gr,d} , S _{daf} , H _{daf}	
Rahman et	Pakistan	MCDM, AHP,	No. of Cars, Smart Parking,	CO ₂ Reduction due to SCP
al. (2022)		WSM, EDA	GPS Position, present value	
			(Cost0, CO ₂ , sentiments,	
			security, Organisation	
Sun Et al.	China	DEMATEL-	EO, TO, PO, MO, SO, CO ₂	Commercialization of CCUS
(2022)		ANP(DANP)		

Adenle [2020] assessed the solar energy in South Africa to goal of the energy demand till 2030 and CO₂ reduction by solar energy technologies. The patent related to CCUS technology has been discussed and framed out in a single paper by Zhu et al.[2023]. Some of the researchers have reviewed the literature of CCUS [Moreno et al. (2019), Frederich et al. (2017, Shaw et al. (2022), Vishal et al. (2021), Haszeldine etal. (2018)] which can help us to understand the past work on

CCUS and shall present the new idea and work in future. Wicaksono et al. [2019] analyzed the Gaussian FAHP for the analysis of benefit, cost and risk in the oil and gas processing in Indonesia. Jov et al. [2019] utilized the 3PL with MCDA and Fuzzy approach in the third party logistic selection and similar studies have been carried out by Jovcic and Prusa [2021]. The AHP is the similar decision support tool which was used by KIm et al. [2021] in its study on CO₂ capture technologies. The CO₂ reduction technologies and renewable energy options are required for sustainability and it approved by the Narula et al. [2017] in the study related to the sustainable energy security for India and another study of Sarangi et al. [2019]. Nassef et al. [2023] used Runge Kutta optimization method to maximize the CO₂ capture capacity.

This technology is a new technology by which the carbon content and CO₂ can be captured, store and utilized in various applications. The methods can be applied as an attachment to any plant which generated the CO₂. The AHP method is the most feasible method and can be used in any analysis and which required minimum three variables. It can be applied for the assessment of renewable energy options feasibility in the country. It has been used the AHP methods using fuzzyfication and defuzzification in the CCUS analysis for this research work. India is developing country and most industrialization country that's why the necessity of CCUS in all the coal thermal power plants as well as in the small power generations.

6.4. Materials and Methods

a. Model Construction and criteria selection

The Fuzzy AHP model is constructed with the nine steps and the tree diagram of the same is shown in figure 6.1. The model construction steps are included by Step 1: Goal identification, Step 2: Criteria selection, Step 3: Alternatives available, Step 4: Assigning weights to selected criteria, Step 5: Assigning fuzzy weights, Step 6: Checking the consistency ratio, Step 7: Assigning weights

to alternatives, Step 8: Measuring the fuzzy weights with alternatives weights, Step 9: Assigning rank to the best alternative.

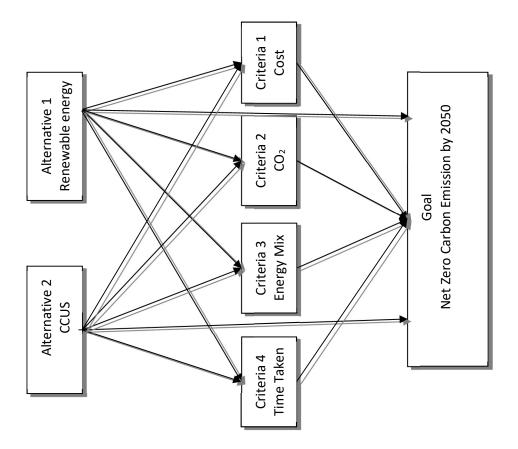


Figure 6.1. Model construction

The cost for deploying particular alternatives taken into account as one of the criteria, the country has shortage of finance. The reduction of CO₂ is the prime motive of the goal and given the highest priority. The present Energy Mix of India is very important as it reflects the nature of the country's energy source, which the policy makers should consider before choosing any technology. Finally, the time taken was one of the criteria, as the measures taken in the particular period can benefit otherwise the environmental degradation would reach to an extent from where it cannot be reversed. In addition, the Period laid down on the Paris climate agreement. The alternatives considered according to the present scenario of the country. The weights were assigned according

to importance of particular criteria after an intensive literature review. Very few literature reviews exist in CCUS technology as it is still in its research phase.

b. Mathematical Fuzzy methodology:

The method to reciprocal in fuzzy reciprocal

$$\tilde{\mathbf{A}}^{-1} = (\mathbf{I}, \mathbf{m}, \mathbf{u})^{-1} = (1/\mathbf{u}, 1/\mathbf{m}, 1/\mathbf{I})$$
 (1)

The Fuzzy Geometric mean value

$$\hat{\mathbf{r}}_{i} = \tilde{\mathbf{A}}_{1} \otimes \tilde{\mathbf{A}}_{2} = (\mathbf{l}_{1}, \mathbf{m}_{1}, \mathbf{u}_{1}) \otimes (\mathbf{l}_{2}, \mathbf{m}_{2}, \mathbf{u}_{2})$$

$$(\mathbf{l}_{1} \otimes \mathbf{l}_{2}, \mathbf{m}_{1} \otimes \mathbf{m}_{2}, \mathbf{u}_{1} \otimes \mathbf{U}_{2})$$
(2)

Fuzzy weights

$$\hat{\mathbf{w}} = \hat{\mathbf{r}}_i \otimes (\hat{\mathbf{r}}_1 \oplus \hat{\mathbf{r}}_2 \oplus \dots \hat{\mathbf{r}}_n) \tag{3}$$

Fuzzy add $\tilde{A}1 \oplus \tilde{A}2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2)$

$$(\mathbf{l}_1 \oplus \mathbf{l}_2, \mathbf{m}_1 \oplus \mathbf{m}_2, \mathbf{u}_1 \oplus \mathbf{U}_2) \tag{4}$$

De-fuzzyfication

Centre of area (COA)
$$\mathbf{W_i} = (l + m + u) \div 3$$
 (5)

Where l, m, u are the fuzzy triangular numbers and Wi represents a non-fuzzy number and if it need to be normalize it can be normalize.

Maximum Eigen value= λ_{max}

Consistency Index (CI) =
$$(\lambda_{max} - n) \div (n - 1)$$
 (6)

After that get the random index (RI) for the number of attributes used in the decision making for net zero carbon goals

Consistency Ratio (RC) = Consistency Index (CI)
$$\div$$
 Random Index (RI) (7)

c. Fuzzy Analytical hierarchy process

Fuzzy Analytical hierarchy process (AHP) methodology used to formulate the decision criteria as it has advantage over the basic AHP. AHP is a method that helps decision makers to choose between two alternatives whereas Fuzzy logic deals with uncertain data and imperious knowledge. Fuzzy AHP method helps the decision makers to take decision in ambiguous circumstances. Through AHP priorities are quantified for given alternatives, by calculating weights of criteria and alternatives. Based on the weights alternatives are ranked and the top ranked alternative is preferred by the decision makers, the consistency of the comparison of alternatives are also checked through Consistency Index. Fuzzy logic comes in play when there is an uncertainty and incomplete information. It quantifies the linguistic terms and has robust algorithms. Therefore, Fuzzy AHP method is used in the research to choose between the best alternatives according to the present scenario. The goal is to achieve net zero carbon emission by 2050. The alternatives are Carbon Capture Utilization and storage (CCUS) and Renewable Energy Sources (RES). The criteria's are cost, energy mix, CO₂ reduction and Time.

The AHP pairwise comparison scale is given in table 8.2 where scale 1 to 9 represents the preference level [Satty, 1980]. Table 8.3 shows the fuzzy comparison scale in which the ratings scale is presented by number from 1 to 9; the fuzzy ratings for the various judgments are also presented. The [1,1,1] is represented by the equal judgment, for moderate it represents by [1,2,3], for strong [2,3,4], very strong is represented by [3,4,5] and next to this the extremely strong is presented by [4,5,6]. Others are the intermediate representations till 9 rating [Chang, D. Y. 1996].

Table 6.2: AHP pairwise comparison scale

Ratings	Judgments
1	Equally preferred
	Equally to moderately preferred
3	Moderately preferred

4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strong preferred
7	Strong preferred
8	Strong to extreme preferred
9	Extremely preferred

Table 6.3: Fuzzy comparison scale

	Fuzzy	Judgments
Ratings	Ratings	
1	1,1,1	Equal
2	1,2,3	Moderate
3	2,3,4	Strong
4	3,4,5	Very Strong
5	4,5,6	Extremely Strong
6	5,6,7	Intermediates
7	6,7,8	Intermediates
8	7,8,9	Intermediates
9	9,9,9	Intermediates

The random consistence or ratio (RC) is required to find out the number of attributes which can be used in the decision making for net zero carbon goals. The values of RC are shown in table 6.4 for the number 1 to 10 as per design matrix [Rao, 2007].

Table 6.4: Random Consistency Ratio

Design of matrix	1	2	3	4	5	6	7	8	9	10
RC	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

d. Present status of Renewable energy and CCUS

Since the year 2010, India has been undertaking significant economic transformations to explore and develop new renewable energy sources. Although the generation of energy from this form has shown an upward trend in recent years but the development is still in single units. To achieve its net zero carbon dioxide emission by 2050 and to limit the global warming to 1.5% it needs to work in strategically to make effective policy and increase technological innovations. As India generates its maximum energy from conventional source mainly coal it is important to develop an efficient technology that can treat CO₂ emission. Simultaneously, increase the share of renewable energy in the total primary energy generation. Carbon capture utilization and storage technology is still very uncommon in the nation.

Share of energy from renewable sources in gross final consumption of energy from all sources. Gross final energy consumption means the use of energy in households, agriculture, public services, industry, transport, forestry, and fisheries, together with losses of electricity and heat during transmission and distribution [GUS 2018]. It India Renewable energy accounts for 12% of the total installed power generation capacity and approximately 5% of the total generation. India has set a target of 175 GW of renewable energy by the year. 2022. That target will be achieved by four sources Solar, Wind, Small hydro and Bio-energy i.e., 100 GW, 60GW, 5GW, 10GW respectively. According to the report of the Expert group on 175 GW RE by 2022, there is possibility of India achieving 479 GW of solar PV and 410 GW of wind by 2047.

India and China shares 26% of the global emission reduction potential through the implication of Carbon capture and storage i.e. 10GtCO₂/year by 2050 [IEA, 2021]. The total cost of emission reduction would increase to 70% by 2050 without Carbon capture and storage technology, to achieve the goal of temperature control to 2°C would be impossible. As there is a good compatibility between Carbon capture and storage (CCS) and the fossil energy, it gives CCS room for development in India since last decade India has seen a sharp rise in CO₂ emission due to the increasing development. One experimental CCUS system was developed in NIT Bhopal for experimental analysis purposes. The present status of CCUS facilities in India summarized in table 6.5 as given below [Global CCS report 2018].

Table 6.5: CCUS facilities in India

Name	Tutuicorin CCU Project(Carbon	Carbon Clean Solutions Solvay		
	Clean Solutions)	Vishnu Capture Project		
Category	Utilization Facility	Pilot and demonstration CCS facility		
Status	Operational	Completed		
Operation date	2016	2012		
Facility	Power Generation	Chemical Production		
Capture Capture(Mtpa)	0.06	0.00		

6.5. Results and Discussion

a. Fuzzyfication and Defuzzification for CCUS and Energy Mix

The association between two or more variables that tend to vary together in a systematic way is referred to as correlation. It is a statistical metric used to quantify the strength and direction of the association between two or more variables. The correlation coefficients range found from -1 to +1, where, -1 representing a perfect negative correlation (as one variable increases, the other

decreases), +1 representing a perfect positive correlation (as one variable increases, the other increases), and 0 representing no correlation as shown in table 6.6.

Table 6.6: Correlation matrix

CO ₂ , (MT)	Electricity demand	Renewable energy generation
	(bkWhs)	(bkWhs)
1.000000	0.967451	0.875221
0.967451	1.000000	0.743803
0.875221	0.743803	1.000000

Table 6.7: Descriptive stats

Variables	CO ₂ emission	Electricity generation	Renewable energy generation
Mean	1380.91211	46.61267	932.21613
Median	1202.13637	24.40000	888.40000
1. Quartile	880.15159	10.37500	502.45000
3. Quartile	1887.34022	51.85000	1317.50000
Minimum	613.13041	0.68000	275.40000
Maximum	2471.94617	216.80000	1765.50000
Sum	42808.27536	1444.99280	28898.70000
Variance	376200.51376	3247.71527	228336.32607
St. dev	613.35187	56.98873	477.84550
Skewness	0.43758	1.63947	0.17836
Kurtosis	-1.33008	1.68362	-1.43436

Descriptive statistics describe how widely distributed the data is shown in table 6.7. The most frequent metrics of variability are range, variance, and standard deviation. The range is defined as

the difference between the highest and lowest values in the dataset. The variance is the average of the squared variations between each value and the mean, whereas the standard deviation is the square root of the variance. Descriptive statistics can also provide information on the shape of the data distribution. It depicts the data distribution as well as any outliers or skewness. The degree of asymmetry of a distribution is referred to as its skewness. The skewness of a symmetric distribution is zero. If the distribution is skewed to the left (negatively skewed), the tail is longer on the left side of the distribution, and the mean is smaller than the median. If the distribution is skewed to the right (positively skewed), the tail is longer on the right side, and the mean exceeds the median. Kurtosis is the degree to which a distribution is peaked or flat. The kurtosis of a normal distribution is 0. Kurtosis is positive if the distribution is more peaked than normal (leptokurtic), and negative if the distribution is less peaked than normal (platykurtic). Descriptive statistics are useful in academic research and everyday life. They can assist researchers and decision makers in understanding the major features of a dataset, identifying outliers or extreme results, and making informed judgments based on the data. Furthermore, descriptive statistics can be used to compare different datasets or to find patterns and trends in data.

Setup a triangular fuzzy number (TFN) as shown in figure 6.2 where the scale has three values name as L, m, u. These are representing the Lowest value (L), median value (m) and the highest value or called upper value (u). Therefore each set is divided into 2 except the same comparison set.

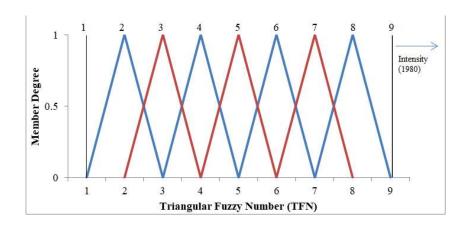


Figure 6.2: Graph of Fuzzy Triangle Set

The pairwise comparison of four criteria cost, energy mix, CO₂ reduction and time is shown in table 6.8 be made in to a TFN set. The Cost, Time and CO₂ reduction are equally, strong and very strong criteria and the energy mix are equal to intermediate. If Energy mix is considering the criteria than the time will be the strong and CO₂ reduction will be the moderate criteria. In similar to that more results can be evaluated by the pairwise comparison. The estimated value of Cr is 0.02 which is very lower than the allowed value of 0.1 or 10%. The Fuzzy geometric mean is shown by matrix in equation 9 and the Fuzzy weights are shown by equation 10. The values can be evaluated by simple analytical methods.

Table 6.8: Pair wise comparison

Criteria	COST	Energy mix	CO ₂ reduction	Time
	L m u	L m u	L m u	L m u
COST	1 1 1	1/8 1/7 1/6	1/6 1/5 1/4	1/4 1/3 1/2
Energy mix	6 7 8	1 1 1	1 2 3	2 3 4
CO ₂ reduction	4 5 3	1/3 1/2 1	1 1 1	2 3 4
Time	2 3 4	1/4 1/3 1/2	1/4 1/3 1/2	1 1 1

CR = 0.02 which is much less than the allowed CR value of 0.1

Fuzzy geometric mean =
$$\begin{pmatrix}
0.269 & 0.312 & 0.380 \\
1.86 & 2.54 & 3.13 \\
1.19 & 1.65 & 2.21 \\
0.707 & 0.759 & 1
\end{pmatrix}$$
(8)

Fuzzy weights =
$$\begin{pmatrix}
0.040 & 0.059 & 0.094 \\
0.277 & 0.483 & 0.778 \\
0.177 & 0.314 & 0.548 \\
0.106 & 0.144 & 0.248
\end{pmatrix}$$
(9)

De-fuzzification =
$$\begin{pmatrix} 0.040 & 0.059 & 0.094 \\ 0.277 & 0.483 & 0.778 \\ 0.177 & 0.314 & 0.548 \\ 0.106 & 0.144 & 0.248 \end{pmatrix} = \begin{pmatrix} 0.193 \\ 1.537 \\ 1.039 \\ 0.498 \end{pmatrix} \div 3 = \begin{pmatrix} 0.064 \\ 0.512 \\ 0.346 \\ 0.166 \end{pmatrix}$$
 (10)

Index Normalization=
$$\begin{pmatrix}
0.064 \\
0.512 \\
0.346 \\
0.166
\end{pmatrix}
\div 1.088 = \begin{pmatrix}
0.059 \\
0.471 \\
0.318 \\
0.153
\end{pmatrix}$$
(11)

The defuzzification is shown by equation 10 and the index has to be normalized by equation 11. The pairwise simple comparison of cost, energy mix, CO₂ reduction and time is presented in table 6.9.

Table 6.9: Value wise comparison of the parameter

	Cost	Energy Mix	CO ₂ reduction	Time
Weights	0.059	0.471	0.318	0.153
CCUS	0.981	1	1	1
REW	1	0.5	0.714	0.571

$$CCUS = 0.059*0.981+0.471*1+0.318*1+0.153*1$$

$$REW = 0.059*1+0.471*0.5+0.318*0.714+0.153*0.571$$

CCUS = 0.981

REW = 0.609

India's Energy mix has fossil as the predominant factor in the final energy consumption. Around 70% of coal used for the generation of electricity for meeting the present rising demands. These coal mines have only been developed in the last decade and have a life of fifty to sixty years, if India plans to shut it down not only it will have an economic loss but also it won't be able to

support the social sector as there will be frequent power cuts due to the inefficiency and energy shortage.

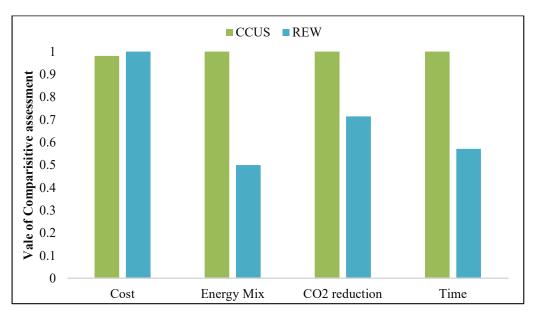


Fig. 6.3. Comparison of different parameters

The value of CCUS is evaluated by 0.981 and the value of REW is 0.609 in India as shown in figure 6.3. Presently Renewable energy has a 5% share in the final energy consumption and it will need a paradigm shift in the deployment of Renewable Energy for reaching the net zero carbon emission. Instead, the policy makers should take the present scenario of the country in consideration, as show in the results CCUS have an advantage over the renewable energy particularly in case of India. CCUS will not only reduce the carbon emissions but it will be used for the production of byproducts like low carbon hydrogen, soda and ink from the captured carbon. The costs of CCUS technologies can be supported by the profits from the byproducts. CCUS has an advantage over renewable energy as it directly capture the carbon for air, the time take reduce equal amount of CO₂ is also less.

The cost of CCUS is still high as it is still in its research phase in India. Whereas, renewable energy is in deployment phase and the cost have come down also because of ongoing innovation in renewable energy around the world. As shown in the results CCUS would be the best technology

for CO₂ reduction and would give a buffer time to renewable energy for its deployment. The energy transition could also be achieved without disturbing the economic, social and energy sector.

b. Carbon dioxide and BAU forecast

The combustion of fossil fuels causes 70% of global CO₂ emissions. India's share is 9.7% in the global CO₂ emissions. The global share of India slipped from 9.7 to 9.6 during the lockdown in the wake of COVID-19. The Kyoto basket comprises the six greenhouse gases: Carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and F-gases: Hydro fluorocarbons (HFCs), per fluorocarbons (PFCs), and sulphur hexafluoride (SF₆). Greenhouse gas emission ise defined as the aggregated emission of the six greenhouse gases listed above, weighted by global warming potentials on a 1988 basis equal to 100 [Kyoto Protocol]. The CO₂ equivalent would be 1 mg or an amount of another greenhouse gas equivalent to 1 mg of CO₂ calculated using global warming potentials, e.g., one ton of methane corresponds to 25 tons of CO₂. [Green Projects, 2020]. The BUA estimates shows that reaching Net zero carbon emission is impossible considering the present scenario. The development of CCUS is the best alternative for the country, as a decade investment in Renewable energy shows no reduction in the Carbon dioxide emission. The BUA estimate shows in figure 8.4 as an unprecedented rise in the carbon emission by the year 2050. The ever growing population and economic growth acts like a catalyst to increase the carbon dioxide emission year by year to 2050.

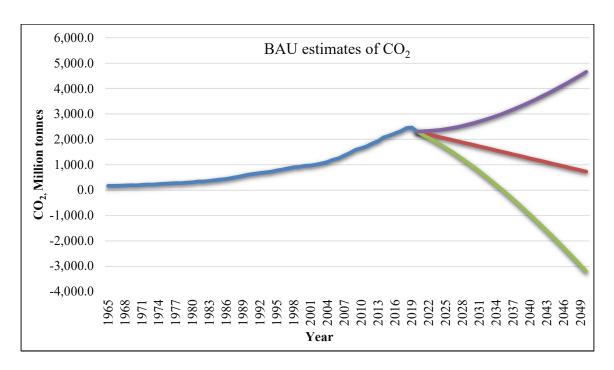


Fig. 6.4: BAU estimates of CO₂

India's primary energy sources are coal, natural gas, oil and RES like solar, wind, and hydroelectricity. Approximately 44% of India's total primary energy demand in 2019 was met by coal, with the next largest sources being oil (27%), natural gas (6%), and renewable energy (6%) which is clearly shown in figure 6.5.

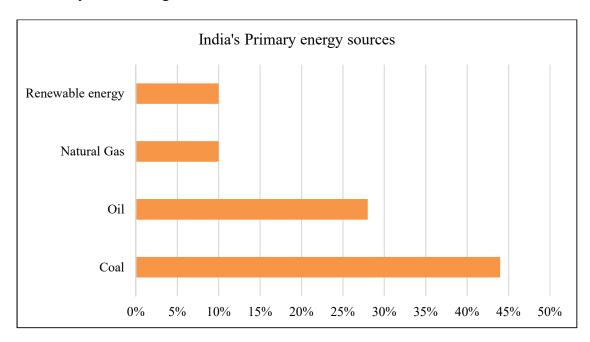


Fig. 6.5. Total energy mix of India

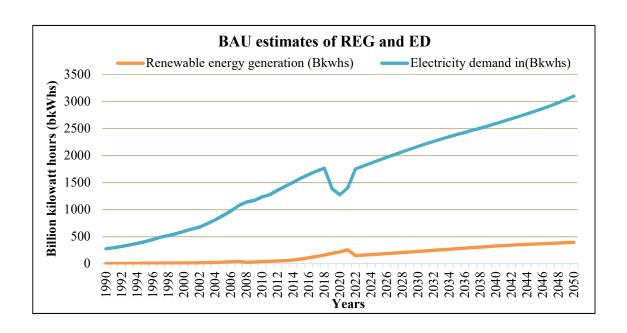


Fig. 6.6. BAU estimates of renewable energy generation and electricity demanded

Due to its fast growing economy and population, India is predicted to continue to experience high growth in energy demand. However, long-term reductions in the nation's reliance on fossil fuels and the promotion of sustainable development could result from the government's push for energy efficiency and renewable energy sources.

In recent years, the proportion of renewable energy in India's electrical generation has been substantially rising. The Central Electricity Authority (CEA) estimates that India's installed renewable energy capacity as of March 2021 was over 94 GW, or nearly 25% of all installed capacity in the nation. The proportion of renewable energy in India's mix for generating electricity has also been rising. In India, the share of renewable energy sources in total electricity generation increased from 6.6% in the financial year 2016–17 to 10.4% in the financial year 2020–21. India's installed solar capacity increased from roughly 2.6 GW in March 2014 to over 40 GW in March 2021, making solar energy the country's fastest-growing renewable energy source. But India's demand for electricity has been rising quickly in recent years due to factors like population growth, urbanization, and economic development. The Central energy Authority (CEA) predicted that

India's energy demand would increase by about 6% per year to 2,000 billion units (BU) by 2021–22. India has been spending extensively in its power sector, using both conventional and renewable sources of energy, to fulfill this rising demand. With nearly 70% of all energy produced in India as of 2021 coming from coal, this fuel type continues to be the country's principal source of electricity generation. The figure 6.6 shows the Business as usual forecast which reflects that the electricity demand of India will be 3098 bkWhs by 2050 and the renewable energy production will be only 395.168 bkWhs by 2050 which only the 10% of the total electricity demand therefore India will continue using coal to meet its electricity requirements. Therefore CCUS technologies can be the tool to reduce CO2 emission and reach the net zero carbon emission goals by 2050.

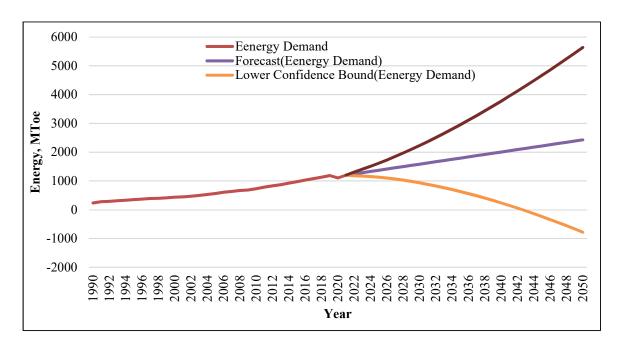


Fig. 6.7. BAU estimates of total energy demand

India ranked third in terms of global energy consumption in 2019 behind China and the US, according to the IEA (International Energy Agency). India's primary energy consumption in 2019 was over 1,200 million tons of oil equivalents (Mtoe), and the nation is significantly dependent on coal, which made up about 44% of the nation's total primary energy consumption. Providing 26%

and 6% of India's energy mix, respectively, oil and natural gas are also significant contributors. Nevertheless at present the Indian government has set itself some daring targets for the growth of renewable energy, hoping to reach 175 GW of installed capacity by 2022. Having installed over 93 GW of renewable energy capacity as of 2021, India has significantly advanced towards this goal. In spite of this, India will probably continue to rely on coal as a significant source of energy in the near future as it works to satisfy the demands of its expanding economy and population. Therefore to set off the emissions generated by coal the government can only rely on CCUS technologies. The figure 8.7 expressed that the India continues its developmental activity in the same pace than it will need 2427.81 Mtoe of energy in 2050 to meet its demand and if urbanization and developmental works outperforms than the demand for energy can also go up to 5638.07 Mtoe by 2050

How CCUS can support India's efforts

Carbon Capture, Utilization, and Storage (CCUS) technology has the potential to significantly enhance India's ability to meet its carbon neutrality target under the Paris Agreement, particularly in the context of its COP-28 commitments. Here's how CCUS can support India's efforts.

♣ Reducing Emissions from Hard-to-Abate Sectors

India's carbon emissions come from a mix of sectors, including energy production, industrial processes (e.g., cement, steel, and chemicals), transportation, and agriculture. Many of these sectors are difficult to decarbonize through renewable energy alone. CCUS can capture carbon dioxide (CO₂) emissions from these sources and store or repurpose them, reducing overall emissions.

- Industrial Emissions: Cement, steel, and chemical industries are major emitters of CO₂, with processes that are hard to electrify or transition fully to low-carbon alternatives. CCUS allows these sectors to capture and store carbon, thus reducing their direct emissions.
- Power Sector: While India is increasing its renewable energy capacity, fossil fuel power plants still contribute significantly to emissions. Integrating CCUS with thermal power plants can drastically reduce their CO₂ output while maintaining base-load power generation.

♣ Enhancing India's Net-Zero Pathway

India's net-zero goal is targeted for 2070. While renewable energy expansion (solar, wind, hydro, and hydrogen) is key to decarbonizing the energy grid, CCUS can play a complementary role in bridging gaps and reducing emissions faster.

- Interim Solution for Fossil Fuels: Given that fossil fuels like coal will likely remain part of
 India's energy mix for several years, CCUS can be an interim solution to decarbonize coalfired power plants and heavy industry.
- Scaling up Green Hydrogen: CCUS can facilitate green hydrogen production, which requires
 hydrogen from natural gas (through steam methane reforming) and capturing the associated
 CO₂ emissions.

Carbon Utilization for Economic Growth

CCUS doesn't just involve storing carbon underground—it also involves utilizing CO₂ in productive ways, which can have economic and industrial benefits.

• Enhanced Oil Recovery (EOR): Injecting captured CO₂ into oil fields can enhance oil recovery, generating economic value while sequestering carbon underground.

- Carbon to Value: CO₂ can be converted into useful products like synthetic fuels, chemicals, and building materials (e.g., carbonated concrete). This could foster new industries and create jobs, while also helping to offset emissions.
- Agricultural Benefits: Captured carbon can be used in agricultural practices, such as in enhancing soil health or for use in algae-based biofuels.

Facilitating Climate Finance and International Collaboration

India's climate commitments involve substantial financial and technological support from developed countries. As part of international cooperation, CCUS could serve as a mechanism for India to receive financial and technological assistance to implement carbon capture and storage infrastructure.

- Collaboration with Developed Nations: By leveraging global expertise and technology, India can fast-track CCUS deployment and share knowledge with other developing nations.
- Accessing Carbon Credits: CCUS technologies can contribute to carbon credit mechanisms (such as the Clean Development Mechanism under the Paris Agreement), allowing India to earn credits for captured CO₂ and potentially sell them in international carbon markets.

Scaling Up for Long-term Impact

While CCUS technologies are still in the early stages of large-scale deployment, there is growing interest in scaling them up to meet global emissions reduction targets. For India to integrate CCUS at scale, it will require substantial investment in infrastructure, regulatory frameworks, and public-private partnerships.

• Investment in R&D and Infrastructure: To make CCUS cost-competitive and scalable, investment in research and development (R&D) is critical. India could benefit from international collaboration to develop lower-cost solutions for CCUS.

 Policy and Regulatory Support: Establishing clear policies around the adoption of CCUS, including carbon pricing, emissions reduction targets, and incentives for industries, will help accelerate deployment.

6.6 Conclusion

CCUS has a key role to play in India's transition to a carbon-neutral future, particularly as part of a mixed strategy combining renewables, energy efficiency, electrification, and decarbonization technologies. By addressing hard-to-abate emissions, creating new economic opportunities, and leveraging global expertise, CCUS can help India meet its COP-28 commitments and work towards its 2070 net-zero target in a more cost-effective and feasible manner. However, successful implementation will require significant policy, financial, and technological support both domestically and from the international community. The massive ecological crises in the world construct CCUS technology a prime attraction, as most of the country uses energy produced by thermal sources. India's more than 60% of the electricity demand is currently met by fossil fuel based thermal power plants. As the developmental works are at its peak around the world the demand for energy is comparatively very high from the past decade. This increasing demand mostly met by conventional source creates havoc in biosphere by increasing the ecological footprints. The value of CCUS is evaluated by 0.981 and the value of REW is 0.609 in India. Development without increasing the carbon footprints can be achieved through increasing awareness of CCUS and developing an efficient CCUS technology.

What is the present status of renewable energy? Why should we go that way? India generates only 5% of total demand of energy from renewable source and it is still in its developmental phase. The debt cost of renewable energy India is very high around 12-14% whereas it is only 3-7% in the developed countries. As India is densely populated country the availability of land is concern for

solar and biomass energy generation. India needs a paradigm shift in the planning and government practices to generate energy from renewable sources.

India will remain dependent on fossil fuel and coal for a longer time as the coal plants in India are very young. The cost of renewable energy will make the delivery time longer. Therefore, there is an urgent need to develop CCUS technology in India to reverse the harmful impact of using conventional sources of energy. The benefits of CCUS will be much greater than depending entirely on renewable energy, as India will take longer time for energy transition. Industrial sector is the major polluter in India and accounts for 50% of all the greenhouse gas. CCUS is the only better option to significantly reduce emissions from coal, gas based power generation, steel, cements, chemical and manufacturing industry, as it will raise the cost to 10% when compared with the other options of electrolytic hydrogen [IEA, 2021]. The target is to achieve net zero carbon emission but government of India has made development of renewable energy as its primary target and main goal of net zero carbon emission shifted to the secondary target. A holistic strategy according to the present scenario of the country will be needed to achieve it. CCUS technology combined with the increasing share of renewable energy in the total energy composition would call for a win-win situation for the country.

Policies and Strategies for Energy, Economy and Environment

7.1. Economic Policies

Economic policies and strategies for sustainable energy development play a crucial role in transitioning towards low-carbon, efficient, and environmentally responsible energy systems. These policies aim to promote clean energy sources, reduce reliance on fossil fuels, and address climate change while fostering economic growth. Below are key economic policies and strategies that can drive sustainable energy development:

a. Carbon Pricing (Carbon Tax and Cap-and-Trade Systems)

A tax levied on carbon emissions, incentivizing businesses and individuals to reduce their carbon footprint by adopting cleaner energy sources or improving energy efficiency. The tax can be gradually increased to reflect the true environmental cost of fossil fuels. A market-based system where governments set a cap on total emissions and distribute or auction emissions permits. Companies can buy and sell permits, creating financial incentives to reduce emissions. The cap is gradually reduced over time to drive emissions down.

b. Subsidies and Incentives for Renewable Energy

Governments can offer financial incentives or subsidies to renewable energy projects (wind, solar, hydro, etc.) to make them more competitive with fossil fuel-based energy. These could include tax breaks, grants, or direct payments. Feed-in Tariffs (FiTs) and Power Purchase Agreements (PPAs)

these are long-term contracts guaranteeing a fixed price for renewable energy producers, ensuring stable revenue streams and encouraging investment in renewable technologies.

c. Investment in Research and Development (R&D)

Government Funding for R&D investing in research and development of renewable technologies can lower costs and increase efficiency. Public-private partnerships can accelerate innovation in energy storage, grid integration, and next-generation renewable technologies. Establishing innovation hubs for clean energy technologies can bring together universities, research institutions, and companies to collaborate on energy breakthroughs.

d. Energy Efficiency Standards and Regulations

Governments can establish building codes, appliance standards, and industrial regulations to ensure energy-efficient practices across sectors. These regulations can drive demand for energy-efficient technologies and reduce overall energy consumption. Encouraging regular energy audits for businesses and residential sectors can help identify opportunities for energy savings, which in turn fosters demand for energy-efficient technologies.

e. Green Financing and Investments

Issuing green bonds or creating investment vehicles focused on sustainable energy can mobilize capital for clean energy projects. These financial instruments offer investors an opportunity to support sustainable development while earning returns. Governments can encourage private sector investment by offering risk-reducing mechanisms, such as guarantees or co-investment, and ensure that clean energy projects receive fair access to capital markets.

Energy Market Reforms

Encouraging decentralized energy systems, like rooftop solar, small-scale wind farms, or community energy projects, can promote local clean energy generation and reduce transmission costs. Investing in smart grid infrastructure and energy storage solutions can enhance the integration of variable renewable energy (solar, wind) into the grid by enabling better demand response and energy storage. Promoting competition in energy markets can drive efficiency and lower costs. By removing monopolies and encouraging the entry of new energy suppliers, governments can promote a more diverse energy mix.

Cross-Sector Collaboration and International Cooperation

Since energy markets are interconnected, international collaboration on energy standards, grid integration, and technology sharing can help accelerate the transition to sustainable energy. Countries can share best practices and pool resources for large-scale renewable energy projects. Adherence to international climate agreements, like the Paris Agreement, encourages countries to set ambitious emissions reduction targets and develop national sustainable energy strategies.

Social Policies for Energy Access

Ensuring that affordable, clean energy is accessible to all, including rural and off-grid communities, can support economic development in emerging economies. Microgrids, solar home systems, and mini-grid solutions can expand energy access in remote areas. Supporting workers and communities impacted by the transition away from fossil fuels (e.g., coal miners, oil industry workers) through retraining programs, new job creation, and social safety nets is essential for ensuring equity in the energy transition.

f. Taxation and Financial Tools

Offering rebates or tax incentives for individuals or businesses investing in renewable energy systems or energy-efficient appliances can encourage widespread adoption. Governments can divest from fossil fuel investments, redirecting capital into sustainable energy infrastructure. Public pension funds, for example, can be reallocated to green technologies.

g. Carbon-Free Technology Deployment

Promoting the use of electric vehicles (EVs) through subsidies, infrastructure development (charging stations), and tax incentives can significantly reduce the demand for oil and encourage clean energy consumption in the transportation sector. Promoting clean energy adoption in industries and agriculture (e.g., through solar-powered irrigation, bioenergy, or green hydrogen) can make these sectors more energy-efficient and less carbon-intensive.

To achieve sustainable energy development, governments, industries, and civil society must collaborate to implement comprehensive economic policies. These policies should focus on reducing greenhouse gas emissions, fostering innovation, incentivizing clean energy investments, and promoting energy efficiency. With clear long-term strategies and the right economic tools, countries can transition to a sustainable energy future that balances environmental concerns with economic growth.

7.2 Case study for analysis of renewable energy and economic growth of Germany

The aims of this analysis is to investigate the effect of energy use, renewable energy consumption, nuclear energy consumption and air transport freight on CO₂ emissions in Germany. Auto Regressive Distributed Lag (ARDL) technique was used to establish the short and long-term correlations between the dependent (CO₂) and independent variables (Energy Use, Nuclear Consumption, Renewable Consumption, Air Transport freight) on a time series data from 1970 to 2021. The results demonstrated the dependence of energy use on non-renewable energy sources by revealing a significant and positive relationship between short and long-term energy use and CO₂ emissions. Similar to energy use, nuclear energy use and air transport freight was also found to be positively correlated with CO₂ emissions. On the other hand, despite the fact that there is a strong negative connection between carbon dioxide emissions and renewable energy, the results reveal that the correlation between the two is not

statistically significant. The study aims to investigate the effect of important economic factors on Germany's CO₂ emissions in order to move further in a sustainable manner. The data reveals an astonishing increase in the usage of nuclear energy for power generation between 1965 and 1985, which was followed by a fall in 2012 as a result of the Fukushima tragedy and growing social unease in Germany, which ultimately led to the phase-out of nuclear power. Nonetheless, BAU projections revealed that even with 200 nuclear power plants, CO₂ emissions would still be reduced to 278 by 2070, in part because of the additional power produced by other energy sources.

7.3 Review of Literature

One of the most important concern of mankind's today is perhaps climate change. This is clear from the fact that the world is no longer wasting time on theoretical debates and has turned its attention to concrete regulations and environmental laws. Therefore, it has become a matter of tremendous interest to spot and solve the challenges pertaining to reduction in carbon dioxide emission levels. Environmental degradation brought on by human activities that release CO₂ includes ecological problems, global warming, climate change and environmental pollution. According to BP statistics, the G7 nations contributed approximately 25% of global CO₂ emissions in 2019 and slightly less in 2020 to 23.2%. The world's most industrialised economies play a crucial role and their policies and practices are frequently imitated by other nations (B. Li and N. Haneklaus. 2022). We will examine the impact of macroeconomic variables on Germany's CO₂ emissions because it is one of the greatest energy consumers in the world and ranks third in the G-7 countries for overall CO₂ emissions, after the United States and Japan (M. Blesl., et al. 2006). Environmental issues are having a growing impact on German energy policy. The government has set the objective of lowering greenhouse gas (GHG) emissions by at least 55% by 2030 and by 85% by 2050 compared to 1990 emission levels as part of the German Climate Action Plan 2050.

(P. Markewitz., et al. 2019). Initiatives for energy efficiency and renewable energy have been promoted by the government. The Eco-tax was created in 1999 with the intention of promoting energy efficiency, renewable energy use, and conservation. The German Renewable Energy Act (EEG), which went into effect in 2000, established a feed-in tariff (FIT) system for all renewable technologies, which led to an astonishing increase in renewable energy capacity (C. Eui, C. Marcantonini, and A. D. Ellerman, 2013). However, only energy shift is not sufficient to reduce GHG emissions significantly. In order to meet the ambitious ideals, set by the German government, all sectors including energy, industry, transport, agriculture and homes will need to drastically reduce their GHG emissions. For a more comprehensive analysis, we have taken into account a number of sectors including consumption of renewable energy, nuclear energy and air transportation along with energy use.

As per popular belief, clean energy fuels have a direct impact on reduction of carbon dioxide level through production as well as consumption. In this paper, we have emphasised on consumption, so renewable energy consumption is a significant regressor in our analysis. Renewable energy must be able to supply the necessary energy for economic activity and lessen environmental issues brought on by the use of fossil fuels (Y. Fang, 2011). It is worthwhile to mention that clean fuels not only require energy innovation at its pinnacle, but also political and social commitment. Therefore, renewable energy consumption's impact may not be as direct and immediate as it seems. Trade is a crucial component of economic growth, which in turn implies that air travel is a crucial component as well. Despite its significance for the advancement of the nation and the creation of jobs, its unfavourable impact on GHG emissions is a serious concern. In fact, 915 million tonnes of CO₂ were created by flights globally in 2019, accounting for 12% of all transport-related CO₂ emissions. This leads us to the inclusion of air transport freight as an essential variable

in the study. In an effort to build alternative sources of energy and to avoid the price fluctuations associated with oil import, nuclear power plants have been set up in several countries. Nuclear energy is proposed to offer a significant advantage in terms of reducing CO₂ emission and curbing the effects of global warming (Y. Wolde-Rufael and K. Menyah, 2010). Hence, nuclear consumption of Germany has also been taken into account in this study. The use of recent statistics such as the BP statistics on G7 nations CO₂ emissions, adds credibility and relevance to the discussion. The mention of Germany's position in global CO₂ emission provides a focused context for the study.

Chang explored the relationships between energy use, carbon dioxide emissions and economic growth in China. The results of the study indicated that rising economic activity increases energy use and CO₂ emissions (C.C. Chang., 2010). Similar study on Russia's CO₂ emissions, energy use, and economic growth was analysed by (H.T. Pao., et al. 2011). They used the causality test and the co-integration technique to analyse the data between the period of 1990 and 2007. Empirical findings indicated that emissions appear to be elastic in terms of energy use but inelastic in terms of output in the long-run. (A. Singh., et al. 2022) used ARDL analysis on data from 2007 to 2018, the study looks at how economic and environmental factors affect logistic performance in India. The logistics performance index (LPI) is found to be positively impacted by foreign direct investment (FDI) and negatively impacted by the use of fossil fuels, both in the short and long term. While greenhouse gas emissions show a positive correlation with LPI, GDP per capita has a negative correlation, raising worries about the environment. The global economy suffered as India's logistic performance rating fell from 35th to 44th in the world. The report makes suggestions for how to enhance logistics and explains why India

Some of the other studies focussed on factors different from energy use. Apart from energy consumption Baek also investigated the effects of nuclear energy and income on CO₂ emissions in 12 major nuclear-generating countries. The research demonstrated that nuclear energy typically reduces CO₂ emissions (J. Baek, 2015). A related research by Al-mulali examined the impact of nuclear energy use on GDP growth and CO₂ emissions in 30 nations worldwide. But unlike the previous research the study's results revealed that nuclear energy use has no long-term impact on CO₂ emissions, but it has a positive long-term impact on GDP growth (U. Al-mulali., 2014) Some research also studied the relationships of renewable energy use. (K. Menyah and Y. Wolde-Rufael, 2010) investigated the relationship between nuclear and renewable energy use, and carbon dioxide emissions for the US from 1960 to 2007. The research showed no correlation connecting the renewable energy to CO₂ emissions, but it discovered a unidirectional causality between the consumption of nuclear energy and CO₂ emissions. (S. Kumari and N. Kumar., 2023) concludes that while renewable energy boosts the green economy, helps agriculture, and lowers CO2 emissions, it also highlights the need for better nuclear waste management to avoid environmental risks. (A. Singh., et al. 2023) the study assesses GDP, nuclear energy consumption, and CO2 emissions in the United States, France, and Japan from 1965 and 2020 in order to validate the Environmental Kuznets Curve (EKC) theory. It is demonstrated that nuclear energy greatly lowers CO2, SO2, and NOx emissions using the Fourier ARDL and FBTY causality tests. The report recommends boosting the generation of nuclear and tidal energy and making sure that radioactive waste is disposed of safely in order to reach the UN's 2050 net-zero carbon targets. Similar research was conducted which studied the causal association between renewable energy use and economic growth in Turkey from 1990 to 2010. The result revealed that there is a

unidirectional causal relationship linking economic growth to the renewable energy use (O. Ocal

and A. Aslan, 2013). Related research was investigated by Sebri for the BRICS countries between 1971 and 2010 using a multivariate approach. The research showcased that based on the ARDL estimations, empirical data demonstrates that there are long-run equilibrium relationships between the variables (M. Sebri and O. Ben-Salha, 2014) Similar techniques like ARDL and VAR methodology was used to examine the relationship between CO₂ emissions, economic growth, energy consumption and renewable energy consumption in Germany for the years 1975 to 2014 and suggested that the government should create and implement appropriate support programmes to encourage investment in new renewable energy technology by (S. khoshnevis Yazdi and B. Shakouri, 2018).

Different factors from energy use, nuclear energy use, and renewable energy use were analysed in some of the other research. (R. Waheed., et al. 2017) studied the impact of Pakistan's agricultural and forest production on carbon dioxide emissions in addition to the renewable energy use. The research showcased that, the use of renewable energy and forests have negative and significant effects on CO2 emissions, whereas agricultural production has a positive impact on CO2 emissions. (Y.Cai., et al. 2018) examined the nexus between clean energy usage, economic growth and CO2 emissions. The result revealed that in Canada, France, Italy, the US, and the UK there was no correlation between real GDP per capita, clean energy consumption and CO2 emissions. However, when real GDP per capita and CO2 emissions are the dependent variables co-integration occurs in Japan.

7.4. Methodology

The study establishes a relationship between CO₂ emissions and energy use, renewable energy consumption, nuclear energy consumption and air transport freight over the period 1970–2021 in Germany.

For the purpose of this study, we have used secondary data that was acquired from the World Bank Development Indicators (WDI). Equation 1 establishes the relationship of CO₂ Emission with Energy Use, Nuclear Consumption, Renewable Consumption and Air transport freight in the context of Germany during the period 1970-2021.

$$lnCO_2 = f(lnEnergy, lnNuclear, lnRenew, lnAir).$$
 (1)

The variables are described in table 1 and ln, the natural log, is used in the equation above.

$$\Delta \ln CO_{2} = \alpha_{0} + \sum_{i=1}^{n_{1}} \alpha_{1i} \Delta \ln ENERGY_{t-i} + \sum_{i=1}^{n_{2}} \alpha_{2i} \Delta \ln NUCLEAR_{t-i} + \sum_{i=1}^{n_{3}} \alpha_{3i} \Delta \ln RENEW_{t-i} + \sum_{i=1}^{n_{4}} \alpha_{4i} \Delta \ln AIR_{t-i} + \beta_{1} \ln ENERGY_{t-1} + \beta_{2} \ln NUCLEAR_{t-1} + \beta_{3} \ln RENEW_{t-1} + \beta_{4} \ln AIR_{t-1} + \mu_{t}..(2)$$

In equation 2 the short-run relationship is represented by α_1 to α_4 whereas the long-run relationship is represented by β_1 to β_4 where α_0 is the drift component and μ_t is the error term and n_i is the optimal lag.

$$\Delta \ln CO_{2t} = \beta_0 + \sum_{i=1}^{n_1} \beta_{1i} \Delta \ln ENERGY_{t-i} + \sum_{i=1}^{n_2} \beta_{2i} \Delta \ln NUCLEAR_{t-i} + \sum_{i=1}^{n_3} \beta_{3i} \Delta \ln RENEW_{t-i} + \sum_{i=1}^{n_4} \beta_{4i} \Delta \ln AIR_{t-i} + \theta ECM_{t-1} + \mu_t$$
 (3)

In order to create an error correction model, the co-integration of the variables was first tested whereas θ is the speed of adjustment of the long run equilibrium.

Table 7.1: List of Variables

Variables	Description
CO2	Carbon Dioxide Emissions (Million Tonnes)
ENERGY	Energy use (kg of oil equivalent per capita)
NUCLEAR	Nuclear Consumption (EJ)
RENEW	Renewable Consumption (EJ)
AIR	Air transport, freight (million ton-km)

Source: World Bank Database, 2020

The description of the variable is shown in Table 9.1 where ENERGY, NUCLEAR, RENEW and AIR are the independent variables affecting CO2 Emission. We discovered that the ARDL technique was best suited for our research since some variables were stationary at first difference and some at level.

7.5. Result and Discussion

a. Unit Root Test

A popular statistical test to determine whether a particular time series is stationary or not the Augmented Dickey Fuller test (ADF Test). In time series analysis, unit root test is used to determine if a time series is stationary or not, the null hypothesis states that time series have a unit root whereas alternative hypothesis states that time series are stationary. Therefore, we require the probability values to be smaller than 0.05 in orders to reject the null hypothesis. The outcome of the unit root test is shown in Table 7.2. The results proved the stationary of the dependent variable

CO₂ at level as well as 1st difference whereas the independent variables were stationary at 1st difference.

Table 7.2: ADF Unit Root Test

**	Level	Level	1st Difference	1st Difference
Variables	t-statistics	Probability	t-statistics	Probability
CO ₂	-4.278871	0.0070	-8.039970	0.0000
ENERGY	-3.318208	0.0748	-7.844101	0.0000
NUCLEAR	-2.700536	0.2408	-4.932591	0.0011
RENEW	-1.581440	0.7860	-1.615187	0.0995
AIR	-1.279795	0.8816	-9.082132	0.0000

b. Auto Regressive Distributed Lag bond test for co-integration

For the purpose of examining co-integration, Pesaran, Shin and Smith (PSS) created the ARDL bonds test. (A. Montenegro., 2019) The ARDL model is the most suitable for our study since it permits having a mixture of variables at level and first difference. Another advantage that ARDL test offers is that it is relatively more efficient in the case of small and finite sample data sizes (Belloumi, 2014). The ARDL bound test is used to evaluate the long-term connection between the dependent and independent variables prior to performing ARDL co-integration. The upper bound and lower bound are the two essential values that the bound test characterises. The lower limit assumes that all variables are at level, while the upper bound presumes that all variables are at first difference. The null hypothesis is rejected and co-integration is shown to exist if the upper bound value is less than the F statistic.

 Table 7.3: Auto Regressive Distributed Lag bond test for co-integration

Variable	F statistics	Co-integration	
F (CO2,ENERGY, NUCLEAR,RENEW,AIR)	4.445385***		
Critical Value	1%	5%	10%
Lower bound	3.29	2.56	2.20
Upper bound	4.37	3.49	3.09

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

Table 7.3 displays the results of the ARDL bound test; the findings reveal that the dependent and independent variables exhibit considerable co-integration because the F statistic is significantly higher than both the upper bound and lower bound statistic.

The findings of the ARDL short run test are shown in the table 9.4. Energy use (0<0.05), Air transport (freight) (0.002<0.05) are significant and have positive correlation with CO_2 emission whereas Nuclear Consumption also has a positive relation with the CO_2 emission and is significant at 10% (0.10>0.05). On the other hand, Renewable Energy has no significant correlation with CO_2 emission in the short run.

Table 7.4: Auto Regressive Distributed Lag Short-Run Estimates

Variables	Probability	t-statistic	Co-efficient
ENERGY	0.0000***	7.733957	0.892228
NUCLEAR	0.1056*	1.655687	0.038417

RENEW	0.1581	1.438348	0.039372
AIR	0.0002***	4.112279	0.135124

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

Table 7.5 describes the results of long-run ARDL test. Energy use is statistically significant and is positively correlated with the carbon dioxide emission. Similarly, Nuclear Energy is positively correlated with CO₂ emissions and is significant at 10%. Moreover, Air transport (freight) is again significant and has a positive correlation with CO₂ emission. On the other hand, Renewable energy an important variable of our study is not statistically significant and has a negative correlation with carbon dioxide emissions.

Table 7.5: Auto Regressive Distributed Lag Long-Run Estimates

Variables	Probability	t-statistic	Coefficient
ENERGY	0.0046**	3.000507	0.639761
NUCLEAR	0.1056*	1.655687	0.038417
RENEW	0.3594	0.927247	0.028450
AIR	0.0002***	4.112279	0.135124

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

c. Diagnostic tests

Table 7.6 illustrates the results of the diagnostics tests that were performed to validate our findings. The Jarque-Bera test, which has achieved widespread acceptability among econometricians, is one of the most well-known tests for determining the normality of regressors. (T. Thadewald and H. Büning., 2007) Since Normality is the most common presumption when using statistical

procedures, we applied the Jarque-Bera test, and the findings indicate that variables are normally distributed.

Homoscedasticity is a crucial presumption in statistical analysis. In order to determine if the data are homoscedastic or heteroscedastic, the heteroskedasticity Breusch-Pagan Godfrey test has been used; the results show that the dataset is homoscedastic.

Further Ramsey RESET test was used, and the outcome demonstrates that the model is free from specification error. Specification error means that at least one of the model's fundamental characteristic or presumption is erroneous. As a result, model estimation could produce inaccurate or deceptive results. Lastly, the Breusch-Godfrey Serial Correlation LM test demonstrated that our model's error component is not serially correlated.

Table 7.6: Diagnostic tests

Jarque-Bera Normality Test JB stat	0.2346	0.8893
Ramsey RESET test, Log likelihood ratio	1.0537	0.2985
Breusch-Godfrey serial Correlation, LM test	2.2290	0.3281
Heteroskedasticity Breusch-Pagan-Godfery test, Obs R-squared	15.3637	0.0814

d. Granger Causality Test

Table 9.7 shows the results of the Granger causality test, the test is applied to time series data to determine whether there is any pronounced predictive power from one variable to the other. In essence, it aids in determining if a variable is helpful or not and whether it is capable of predicting other factors or not. It describes a one-to-one relationship between variables. As per our results, CO_2 - Energy Use, CO_2 - Nuclear Consumption, CO_2 - Air, Energy Use - Nuclear Consumption, Energy Use - Renewable Energy Consumption, Energy Use - Air Transport (Freight), Renewable

Energy - Nuclear Consumption, Nuclear Consumption - Air Transport (Freight), Renewable Energy - Energy use have unidirectional causal relationships.

Table 7.7: Granger Causality Test

Direction of Causality	F-statistics	Probability
ENERGY - CO ₂	1.76577	0.1827
CO ₂ - ENERGY	6.13381	0.0044**
NUCLEAR - CO ₂	0.61963	0.5427
CO ₂ - NUCLEAR	4.48486	0.0167**
RENEW - CO ₂	1.76303	0.1832
CO ₂ - RENEW	2.27442	0.1146
AIR - CO ₂	2.59037	0.0861*
CO ₂ - AIR	0.18345	0.8330
NUCLEAR - ENERGY	4.08311	0.0235**
ENERGY - NUCLEAR	2.11688	0.1322
RENEW - ENERGY	5.07704	0.0103**
ENERGY - RENEW	0.28825	0.7509
AIR - ENERGY	6.70181	0.0028***
ENERGY - AIR	0.96116	0.3902
RENEW - NUCLEAR	2.2363	0.1186
NUCLEAR - RENEW	2.90893	0.0649*
AIR - NUCLEAR	5.03021	0.0107**
NUCLEAR - AIR	1.21720	0.3056

AIR - RENEW	5.13433	0.0098***
RENEW - AIR	0.81349	0.4497

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

e. CUSUM Test for stability assessment

Figure 7.1 demonstrate the result of cumulative sum of the recursive residual stability test (CUSUM). Brown et al. invented the CUSUM test in 1975, it is a common statistical tool for analysing and tracking structural changes in time series models (S. Otto and J. Breitung., 2022). The figure above implies that the model is stable because our graph is within the bounds of 5% significance level.

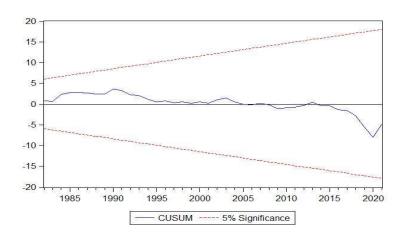


Figure 7.1: CUSUM Test

f. The BAU Estimates

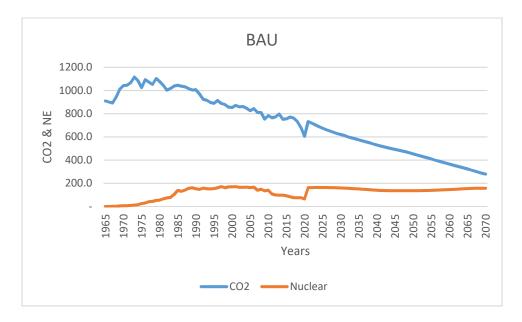


Fig.7.2. BAU estimates

According to the analysis a trend of sharp increase in the use of nuclear energy for power generation between the years 1965 to 1985. But the trend started declining from the year 2012 mainly because of the 2012 Fukushima accident and the concerns in German society regarding the nuclear accidents was deep, so the government had to completely phase out nuclear power generation. However the BAU estimates from 2022 to 2070 shows that even if the nuclear power generation would have maintained the 200 mark then also the CO2 emission would have dropped to the mark of 278 by year 2070, it's also because of the increase in power generation through other sources of renewable energy.

7.6 Conclusion

CO₂ emission is a major contributor to climate change and global warming. Substantial increase in CO₂ emission over the years has altered the proportions of our atmosphere and has given rise to global temperatures. The negative effects of this are currently being felt throughout the planet in the form of abrupt changes in weather patterns, extremely high temperatures, rising sea levels and

melting ice caps. In this era of widespread recognition of the current issue, countries all over the world are issuing laws and taking precautions, but before one can be sure that these actions are even effective, one must first determine whether or not they are even addressing the proper cause. In this paper, we analysed whether or not the theoretically stated variables had an impact on Germany's CO₂ emissions. One can make some inferences from the empirical testing carried out in this paper.

The focus of the study is to find out whether CO₂ emissions are affected by energy use, renewable energy consumption, nuclear consumption, and air transport (freight) in Germany from the period 1970 to 2021. The results show a substantial and positive correlation between short and long-term energy use and CO₂ emissions, demonstrating the dependence of energy use on non-clean energy sources. The amount of energy used nationwide directly affects carbon dioxide emissions. Similar there is a positive association between air transport (freight) and CO₂ emissions, indicating that the expansion of the aviation industry has contributed to increased emissions.

Consumption of nuclear energy is positively correlated with CO₂ emissions. It is obvious that Germany's CO₂ emissions will not decrease by switching to nuclear energy. As a result, the country's policy of using nuclear energy as a clean fuel has not been successful. On the contrary, we observe a rise in CO₂ emissions due to other factors such as energy use, industry, population etc. Although there is a negative correlation between carbon dioxide emissions and renewable energy, which is a significant variable in our analysis, the test findings show that this correlation is not statistically significant. This suggests that just implementing policies to increase the use of renewable energy has little effect on carbon dioxide emissions. The aforementioned two findings are quite important since they show that, in the case of Germany, the energy industry has no impact at all on CO₂ emissions. Significant CO₂ emissions are not being caused by energy generation or

consumption. CO₂ emissions are instead influenced by other economic sectors like transportation, industrialization, etc. As a result, the nation needs to change its focus on the source of CO₂ emission. In a complicated economic system, it is exceedingly difficult to comprehend the underlying causes of CO₂ emissions. We can never be certain that our efforts to conserve the environment will be successful if we don't understand the true cause. As a result, ongoing efforts are made in this area, and our work has been essential in understanding some of the real variables influencing Germany's CO₂ emissions. The data demonstrates a strong rise in the usage of nuclear energy for power generation between 1965 and 1985, which was followed by a fall in 2012 as a result of the Fukushima tragedy and growing social unease in Germany, which ultimately led to the phase-out of nuclear power. Due in part to enhanced power generation from other renewable energy sources, BAU projections show that even with 200 units of nuclear power generation, CO2 emissions will still be reduced to 278 by 2070. Further research can be done on managing the waste disposable generated by nuclear energy.

Conclusion, Recommendation and Future Scope

8.1. Conclusion

The synthesis of energy, economy, and environment is crucial for the attainment of sustainable development, the mitigation of climate change, and the assurance of enduring economic prosperity. The interplay among these three components has been extensively examined, and it is evident that attaining equilibrium between energy production, economic development, and environmental sustainability constitutes one of the most urgent challenges on a global scale. This conclusion integrates essential insights from recent research and provides a thorough understanding of the present circumstances, underpinned by pertinent data, while highlighting the necessity for ongoing innovation, enhancements in policy, and international collaboration.

♣ The difficulties in balancing the three E's

The integration of energy, economy, and environment presents a fundamental challenge characteristically the inherent tension among these components. Economic growth is characteristically energy-intensive, and the imperative to ensure energy access frequently compels nations to depend significantly on fossil fuels, thereby exacerbating environmental degradation, particularly through the emission of carbon. The analysis conducted in India reveals a clear evaluation of the coupling coordination among energy, economy, and environment from 2006 to 2018, highlighting distinct periods of instability. In 2018, India's coordination score concerning energy, economy, and environment fell to 0.579, indicating a state of "barely coordinated" efforts, primarily driven by the environmental challenges linked to the rising reliance on coal to satisfy

escalating electricity needs. Notwithstanding the government's initiatives aimed at diminishing energy intensity and enhancing energy accessibility for the populace, the environmental repercussions linked to these policies were substantial. The energy requirements of the nation were predominantly satisfied through coal, resulting in a substantial rise in greenhouse gas emissions. In a comparable manner, research undertaken in the United Kingdom from 1965 to 2021 revealed a detrimental long-term correlation among energy consumption, GDP, manufacturing, and CO2 emissions. The correlation between energy consumption and manufacturing with CO2 emissions highlights the critical concern of economic advancement leading to environmental harm, predominantly via the utilisation of non-renewable and polluting energy resources. The correlation between energy consumption and carbon emissions presents a significant issue in industrialised nations, characterised by elevated per capita energy usage. The data indicates that the United Kingdom's dependence on fossil fuels remains a significant contributor to its carbon dioxide emissions. Projections suggest that the adoption of renewable energy alone will be inadequate to completely offset these emissions unless there are fundamental changes in energy and industrial policies.

♣ The Role of Renewable Energy in Creating a Sustainable Future

The shift towards renewable energy represents a highly effective approach to alleviating environmental degradation, concurrently fostering economic development. The International Energy Agency (IEA) projects that global renewable energy capacity will increase by 60% by 2030, primarily fuelled by advancements in solar and wind energy, which are anticipated to achieve greater cost competitiveness. In India, renewable energy presently constitutes a mere 5% of the overall energy demand; however, the nation has established ambitious objectives to enhance this proportion. The objective set forth by the government to attain 500 GW of renewable energy

capacity by the year 2030 exemplifies the nation's dedication to mitigating its carbon emissions. Nonetheless, this transition encounters numerous obstacles, such as elevated debt costs (approximately 12-14% for renewable energy in India, in contrast to 3-7% in developed nations) and limitations regarding land availability for solar and biomass energy production, particularly in areas with high population density.

In light of these challenges, the prospective trajectory of renewable energy appears to be quite promising. The significant reduction in the costs associated with solar panels, wind turbines, and energy storage systems is poised to expedite the global transition towards renewable energy sources. For instance, the expense associated with solar photovoltaic (PV) technology has diminished by over 80% in the last ten years, thereby enhancing the accessibility and feasibility of solar power for extensive projects, including those in developing nations. The expansion of the solar sector in India, propelled by governmental initiatives and private sector investments, is anticipated to lead to a decrease in electricity costs and enhance energy accessibility in remote regions. The United Kingdom has effectively augmented its proportion of renewable energy, currently producing approximately 40% of its electricity from sustainable sources. The trajectory of this trend is anticipated to escalate, with wind energy serving a pivotal function, as the United Kingdom allocates resources towards the development of offshore wind farms. The policies and subsidies implemented by the nation regarding renewable energy initiatives have been instrumental in the reduction of carbon emissions, thereby illustrating the efficacy of aligning economic incentives with environmental objectives.

The Significance of Carbon Capture, Utilisation, and Storage (CCUS) as an EssentialTechnological Advancement

Renewable energy is essential for emission reduction; however, carbon capture, utilisation, and storage represents another vital technological advancement that can facilitate the shift towards a carbon-neutral future. CCUS presents a viable solution for mitigating emissions from sectors that pose challenges for electrification, including heavy industry (such as steel, cement, and chemicals) and fossil fuel-based power generation. In India, where more than 60% of electricity continues to be produced from coal, carbon capture, utilisation, and storage could serve a crucial function in alleviating the environmental consequences associated with coal consumption. The emphasis placed by the Indian government on the establishment of a CCUS infrastructure within the framework of its carbon-neutral strategy represents a significant advancement in the endeavour to mitigate the country's greenhouse gas emissions. The International Energy Agency posits that carbon capture, utilisation, and storage has the potential to mitigate as much as 40% of global carbon dioxide emissions originating from industrial processes, thereby establishing it as a crucial instrument in the pursuit of international climate objectives. Furthermore, carbon capture, utilisation, and storage (CCUS) has the potential to generate novel economic prospects, exemplified by enhanced oil recovery (EOR), a practice currently operational in nations such as the United States and Norway. The dual function of CCUS, serving as both an emissions reduction technology and an economic facilitator, underscores its capacity to enhance renewable energy investments and play a significant role in the global shift towards a net-zero future.

Economic Effects and Sustainability over Time

The relationship between economic growth and energy consumption is intricate, necessitating a careful balance of technological advancements and robust policy frameworks to effectively

manage this dynamic. As nations embrace clean energy technologies and integrate energy-efficient practices, they will not only mitigate emissions but also achieve considerable economic advantages. For example, implementing energy efficiency strategies, including the enhancement of industrial processes, the retrofitting of buildings, and the modernisation of infrastructure, has the potential to reduce energy expenditures for businesses by as much as 20%. In a comparable manner, India's UJALA LED initiative, having disseminated more than 800 million LED bulbs, has culminated in an annual savings of 47 billion kWh, thereby contributing to a reduction in both energy expenditures and emissions. Furthermore, initiatives such as carbon pricing and green taxation have demonstrated favourable outcomes in advancing sustainable energy consumption while simultaneously generating revenue for governmental bodies. In Sweden, the implementation of a carbon tax since the early 1990s has resulted in a 25% reduction in emissions, all while the GDP has experienced continuous growth. This evidence supports the notion that economic development can indeed be separated from environmental degradation.

The Necessity for Holistic Policy Frameworks and Global Collaboration

The shift towards a sustainable energy economy necessitates comprehensive national policies, global cooperation, and substantial investment in research and development initiatives. Numerous governments globally are establishing ambitious climate objectives, with more than 130 nations pledging to achieve net-zero carbon emissions by the middle of the century. Achieving these targets necessitates global cooperation, especially regarding technology transfer, funding, and the sharing of knowledge. International initiatives such as the Paris Agreement and the Green Climate Fund provide structured frameworks for nations to engage in collaborative efforts aimed at mitigating climate change, all while considering their individual development requirements. In India, the intricate challenge involves reconciling developmental objectives with the imperative of

environmental conservation. The escalating industrial and energy requirements of the nation compel a sustained dependence on coal; concurrently, the government is dedicated to augmenting the proportion of renewable energy sources and advancing clean technological innovations. India's comprehensive strategy must encompass a dual approach: fostering domestic innovation in energy technologies while simultaneously engaging in international collaboration to secure access to cleaner technologies at competitive prices.

8.2 Recommendations

To achieve sustainable development, coordinated efforts are necessary due to the intricate relationship between the environment, economy, and energy. This necessitates the careful integration of economic development, energy reliability, and ecological preservation, all while confronting the complexities introduced by climate change, energy accessibility, and environmental degradation. Drawing from a comprehensive analysis of energy trends, economic development, and environmental concerns as evidenced by case studies in India, the United Kingdom, and Germany, the ensuing recommendations are meticulously crafted to inform and direct future initiatives aimed at fostering a sustainable and equitable framework for energy, economic, and environmental management.

Expediting the Shift towards Sustainable Energy Sources

A pivotal recommendation is to expedite the transition from fossil fuels to renewable energy sources. The predominant role of energy consumption in greenhouse gas emissions necessitates an urgent transition to cleaner energy sources, which is essential for minimising carbon footprints and addressing the challenges posed by climate change. India has established an ambitious objective of attaining 500 GW of renewable energy capacity by the year 2030. Nevertheless, the present

contribution of renewable energy in India constitutes merely approximately 5% of the overall energy demand. In order to realise this ambitious objective, it is imperative for India to concentrate on enhancing investments in solar, wind, and hydropower technologies. The reduction in the cost of solar energy by more than 80% in the last ten years has significantly enhanced its accessibility. However, the nation encounters obstacles related to land availability, financing, and the adoption of technology. India ought to investigate novel financing strategies to reduce the expenses associated with renewable energy initiatives and enhance energy accessibility in rural and remote areas. Investment in wind and solar energy presents a substantial opportunity for India, leveraging its inherent potential in these renewable resources. The National Institute of Wind Energy posits that the wind energy potential in India may exceed 100 GW. India possesses extensive regions in states such as Rajasthan and Gujarat that can be utilised for the generation of solar energy. Through the implementation of incentives including tax reductions, subsidies, and extended power purchase agreements (PPAs), governmental action can effectively catalyse private sector investment in renewable energy initiatives.

The United Kingdom's approach to wind energy demonstrates significant advancements in the realm of renewable resources, particularly through the development of offshore wind energy, which presently constitutes 30% of the country's overall electricity generation. The government has pledged to produce 50 GW of offshore wind energy by the year 2030. India has the opportunity to emulate the United Kingdom by harnessing its offshore wind potential along both its eastern and western coasts.

Advancing and Advocating for Carbon Capture, Utilisation, and Storage (CCUS)Technologies

The imperative shift towards renewable energy is crucial; however, it is anticipated that the global energy composition will continue to rely on fossil fuels for a number of decades to come. In nations such as India, where more than 60% of electricity generation relies on coal, the implementation of CCUS technologies will be essential in addressing emissions from sectors that are challenging to decarbonise. The capacity of CCUS to mitigate global CO2 emissions by as much as 40% is of paramount significance. In India, the reliance of heavy industries like cement, steel, and power generation on coal presents a significant opportunity for carbon capture, utilisation, and storage (CCUS) technologies to mitigate environmental impact by capturing and sequestering CO2 emissions prior to their atmospheric release. The Indian government has initiated measures to advance CCUS by designating \$50 million for research in the 2020-2021 budget; however, further actions are necessary to enhance the scalability of this technology.

Public-Private Partnerships: The deployment of Carbon Capture, Utilisation, and Storage necessitates substantial investments in research, infrastructure, and regulatory frameworks. To address financial constraints, the establishment of public-private partnerships (PPPs) may facilitate the co-financing of large-scale carbon capture, utilisation, and storage (CCUS) initiatives. The Carbon Capture and Storage Association in the United Kingdom has been instrumental in promoting government investment aimed at advancing the development of carbon capture, utilisation, and storage technologies. In a comparable manner, India stands to gain from the establishment of a robust regulatory framework and the implementation of specialised financial instruments for carbon capture, utilisation, and storage. India has the potential to engage in the export of CCUS technology, capitalising on its expanding proficiency in this domain. Through

strategic collaboration with international organisations and the facilitation of technology transfer, India has the potential to establish itself as a frontrunner in the domain of carbon capture solutions.

Strengthening Sustainable Practices and Energy Efficiency

Energy efficiency represents a highly economical approach to mitigating energy consumption and emissions. It is imperative for both developed and developing nations to prioritise the implementation of energy efficiency measures across all sectors, with particular emphasis on the industrial and building sectors. India's Energy Efficiency Program has demonstrated notable advancements in enhancing energy efficiency, particularly through the implementation of the Perform, Achieve, and Trade (PAT) scheme alongside the Energy Efficiency Financing Platform (EEFP). Nevertheless, it is imperative that more assertive policies be implemented to achieve the nation's energy efficiency objectives. India ought to prioritise the enhancement of energy efficiency initiatives across critical sectors, including agriculture, manufacturing, and transportation. The implementation of energy-efficient pumps, irrigation systems, and lighting technologies can lead to a substantial decrease in energy consumption within the agricultural sector, which plays a pivotal role in India's economy.

Smart Buildings and Urban Planning: Within the urban sector, India must prioritise the retrofitting of existing structures and the enhancement of urban planning strategies to facilitate more sustainable energy consumption. The International Energy Agency (IEA) reports that buildings account for 30% of global energy consumption. The implementation of energy-efficient technologies in existing buildings, including LED lighting, smart meters, and enhanced insulation, has the potential to significantly decrease energy consumption and mitigate carbon emissions. This initiative has the potential to generate millions of environmentally sustainable jobs while making a substantial impact on the economy. In the realm of industrial efficiency, it is imperative for India

to embrace cleaner technologies and facilitate the widespread adoption of electric vehicles (EVs) as a means to mitigate oil dependency and lower emissions. The enhancement of industrial energy efficiency can be achieved through the implementation of lean production methodologies, the integration of waste heat recovery systems, and the utilisation of high-efficiency boilers. The International Energy Agency's energy efficiency scorecard indicates that nations prioritising industrial energy efficiency initiatives have the potential to realise annual energy cost savings ranging from 15% to 20%.

Enhancing Policy Frameworks for a Sustainable Low-Carbon Economy

An extensive and anticipatory policy framework is crucial for steering the transition towards a low-carbon economy. It is imperative for governments to establish not only ambitious targets for renewable energy and emission reductions but also to underpin these objectives with sustained policy commitments, investment incentives, and mechanisms that are conducive to market dynamics. The implementation of carbon pricing mechanisms, including carbon taxes and emissions trading systems (ETS), serves to create financial incentives for businesses aimed at reducing their emissions. This approach facilitates the attainment of environmental objectives while simultaneously providing industries with a financial motivation to shift towards cleaner energy alternatives. India may consider emulating the European Union's approach, which established an emissions trading system in 2005 to regulate carbon emissions. This system has demonstrated its efficacy as a mechanism for promoting the adoption of cleaner technologies among businesses.

Subsidy Shifts: The allocation of energy subsidies in India predominantly favours fossil fuels, with government expenditures exceeding \$22 billion each year on these subsidies. The provision of these subsidies results in market distortions and perpetuates the reliance on environmentally

detrimental energy sources. Redirecting financial support towards renewable energy technologies has the potential to foster a more sustainable energy landscape. For instance, the government of the United Kingdom has implemented subsidies aimed at offshore wind energy and solar power, thereby enhancing the affordability of these technologies for consumers. The stability of long-term policies is essential for fostering investor confidence. The renewable energy sector in India has garnered significant investments; however, fluctuations in policy may impede prospective investments. It is imperative that long-term renewable energy objectives are aligned with robust regulatory frameworks and financial incentives, as this will facilitate the attraction of both domestic and international investments in clean energy initiatives.

International Collaboration for Sustainable Advancement

The complex and interconnected issues of climate change and energy demand a collaborative approach and the sharing of expertise across borders. It is imperative for nations to engage in collaborative efforts to exchange best practices, technologies, and financial resources, thereby expediting the transition towards a low-carbon economy.

International technology transfer is essential, particularly as developed nations possessing advanced clean energy technologies must prioritise the dissemination of these innovations to developing countries such as India, where there exists a substantial demand for energy infrastructure development. The United Kingdom's advancements in offshore wind technology present a valuable framework for fostering collaboration with nations such as India and other developing countries.

International Climate Agreements: It is imperative for India and other developing nations to maintain robust engagement in international climate agreements, including the Paris Agreement, to guarantee that the increase in global temperatures is confined to 1.5°C. International funding

mechanisms, such as the Green Climate Fund, serve to furnish financial assistance for climate mitigation and adaptation initiatives within developing nations.

8.3. Future work

The interplay among energy, economy, and environment is undergoing significant transformation as countries grapple with the escalating challenges posed by climate change, energy security, and the imperative of economic sustainability. The ongoing increase in the global population, coupled with the expansion of economies, underscores the pressing necessity for sustainable development. Despite the considerable advancements achieved in comprehending the complex interrelations among these three domains, there exists a substantial opportunity for additional inquiry, technological innovation, and policy development. This future scope examines the prospective domains for enhancement, innovation, and policy development aimed at optimising the interconnections among energy, economy, and environment in the forthcoming decades.

■ Developing Technologies for Energy Storage and Grid Modernisation

The integration of renewable energy sources, including solar and wind, into the current power infrastructure necessitates advancements in energy storage and grid modernisation. Given the intermittent nature of these energy sources, it is imperative to develop efficient energy storage systems that can effectively capture and retain surplus power generated during times of elevated renewable output for subsequent utilisation. The prospective advancements are centred on enhancing energy storage technologies and modernising grid infrastructures to enable more seamless integration of renewable energy sources into the overall power mix.

Energy Storage Solutions: Presently, existing battery technologies, including lithium-ion batteries, exhibit constraints regarding efficiency, cost, and capacity. Nonetheless, recent advancements, including solid-state batteries, flow batteries, and grid-scale storage systems such as pumped hydro

storage, present significant potential for improving energy storage capacities. The International Renewable Energy Agency (IRENA) posits that, contingent upon suitable investments, energy storage has the potential to fulfil approximately 5-10% of global energy demand by the year 2030. India, characterised by its ambitious renewable energy objectives, stands to benefit from investing in large-scale storage solutions to enhance grid stability and guarantee a reliable energy supply, particularly in areas heavily reliant on solar and wind resources.

Smart grids and decentralised energy systems necessitate a future-oriented approach, emphasising flexibility, resilience, and the capacity to integrate diverse energy sources. The advancement of intelligent grid systems, which leverage information and communication technology (ICT) for the oversight and administration of electricity distribution, will facilitate enhanced integration of renewable energy sources, demand response mechanisms, and energy efficiency initiatives. By the year 2030, projections indicate that the global market for smart grid technology will reach \$61.5 billion, with smart meters, sensors, and distributed energy resources serving as pivotal components in this expansion. The potential for substantial advantages exists for India and other developing nations through the enhancement of their electrical grids, enabling the integration of cleaner and more decentralised energy sources.

Expanding Technologies for Carbon Capture, Utilisation, and Storage (CCUS)

In light of the ongoing dependence on fossil fuels for energy production, industrial applications, and transportation, carbon capture, utilisation, and storage (CCUS) technologies are poised to be pivotal in mitigating carbon emissions, especially within challenging sectors such as cement, steel, and chemicals that are difficult to decarbonise. The prospective advancements in CCUS are centred around enhancing its efficiency, minimising costs, and expanding its implementation, particularly in nations with significant reliance on fossil fuels, such as India. The current state of

technological advancements in carbon capture, utilisation, and storage (CCUS) reveals that the efficiency of existing technologies is still suboptimal, while the financial implications associated with the capture and sequestration of carbon dioxide continue to be considerable. Nonetheless, the exploration and advancement of direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) have the potential to greatly enhance the feasibility of these technologies. The Global CCS Institute reports that there are presently more than 30 large-scale CCUS projects functioning globally, with projections indicating that carbon capture capacity may rise by 40% by 2030, contingent upon the proactive measures undertaken by governments and industries.

The deployment of carbon capture, utilisation, and storage (CCUS) in India is critical, as the nation's energy sector stands as one of the foremost contributors to CO2 emissions, largely attributable to its significant dependence on coal-fired power generation. A considerable fraction of the nation's electricity requirements continues to be fulfilled by coal, representing 60% of the total electricity generation. The implementation of carbon capture, utilisation, and storage (CCUS) technologies has the potential to diminish emissions from these facilities by up to 90%. India has the potential to advance the establishment of extensive CCUS demonstration projects, aligning them with its strategies for expanding renewable energy. Such initiatives may be executed within industries such as steel production, cement manufacturing, and power generation. The advancement of CCUS technologies necessitates significant financial backing, alongside robust research initiatives, infrastructure development, and comprehensive regulatory frameworks. To ensure the economic viability of CCUS, it is imperative for governments to establish conducive policies, which encompass carbon pricing, subsidies, and financial incentives aimed at encouraging businesses to integrate these technologies. The U.S. Department of Energy has designated substantial financial resources for research and pilot initiatives related to carbon

capture, utilisation, and storage. India has the potential to replicate these initiatives by establishing a comprehensive policy framework that fosters both domestic and international investments in carbon capture, utilisation, and storage.

Advancing Electrification and Decarbonisation within the Transportation Sector

Transportation represents a significant factor in the global emissions of greenhouse gases, especially in nations that heavily rely on internal combustion engine (ICE) vehicles. The electrification of the transportation sector and the advancement of zero-emission vehicles (ZEVs) are essential for mitigating carbon emissions and addressing air pollution. The prospective developments within this domain centre on the proliferation of electric vehicle (EV) adoption, the augmentation of charging infrastructure, and the advocacy for alternative fuels such as hydrogen. The adoption of Electric Vehicles (EVs) is anticipated to experience a compound annual growth rate (CAGR) of 22.6% from 2023 to 2030, with projections indicating that total EV sales will surpass 40 million vehicles annually by the year 2040. In nations such as India, the transportation sector accounts for 13% of total CO2 emissions. Therefore, encouraging the adoption of electric vehicles can substantially contribute to mitigating the carbon footprint. Estimates from the industry suggest that the proportion of electric vehicle sales in India will rise from 3% of total sales in 2022 to 15% by the year 2030. Nonetheless, the nation encounters obstacles including elevated battery expenses, inadequate charging infrastructure, and a lack of consumer awareness. Future initiatives ought to prioritise the reduction of electric vehicle costs via subsidies and incentives, the expansion of charging infrastructure, and the promotion of advancements in battery technologies.

Hydrogen and Fuel Cells: Vehicles powered by hydrogen represent a compelling alternative to traditional petrol and diesel options. Hydrogen fuel cells yield solely water as a byproduct, positioning them as a sustainable alternative for the decarbonisation of transportation systems.

Although the adoption of hydrogen remains in its nascent phases, projections from the Hydrogen Council suggest that hydrogen has the potential to fulfil as much as 18% of the global energy demand by the year 2050. The potential for India to enhance its transportation sector through the adoption of hydrogen-powered vehicles is substantial, given the country's extensive fleet of commercial and industrial vehicles.

Sustainable Development Policies Based on Data

The expanding influence of big data and artificial intelligence (AI) in the realms of energy, economic, and environmental management necessitates the development of data-driven policies. These policies are essential for refining decision-making processes and facilitating more accurate forecasting and monitoring of energy consumption, emissions, and economic growth. The exploration of future research avenues may involve the integration of artificial intelligence and machine learning algorithms aimed at optimising energy distribution, enhancing efficiency, and forecasting demand patterns. Artificial intelligence possesses the capability to discern patterns in energy consumption, enhance grid management, and identify inefficiencies in real-time scenarios. By the year 2030, the implementation of artificial intelligence within the energy sector has the potential to decrease energy consumption by as much as 15% and diminish carbon emissions by 10% on a global scale.

The application of blockchain technology in energy trading has the potential to fundamentally transform energy markets. It facilitates peer-to-peer energy trading, thereby empowering consumers to engage in direct transactions for the buying and selling of energy among themselves. This has the potential to enhance market efficiency, lower expenses, and promote the generation of renewable energy. The exploration of blockchain's applications within energy markets is poised for significant expansion, particularly in areas such as carbon trading, grid management, and the

certification of renewable energy sources. For effective policy formulation, it is imperative that governments establish robust infrastructure capable of collecting and analysing real-time data pertaining to energy consumption, CO2 emissions, and economic performance. Through the application of data-driven insights, policymakers are equipped to formulate interventions that effectively reconcile the imperatives of energy security with the necessity of environmental protection. India's National Smart Grid Mission, for instance, seeks to deploy more than 200 million smart meters by the year 2030 to effectively monitor and manage energy consumption. The data collection initiatives undertaken can significantly inform future energy policy frameworks and facilitate the establishment of more precise emission reduction objectives.

Global Cooperation and Exchange of Knowledge

In light of the worldwide implications of the climate crisis, it is imperative that nations engage in collaborative efforts to foster the development and dissemination of sustainable technologies and exemplary practices. The prospective trajectory of international collaboration is fundamentally anchored in the augmentation of knowledge dissemination, the facilitation of technology transfer, and the provision of financial assistance for sustainable development initiatives, especially within the context of developing countries.

The Green Climate Fund (GCF) is designed to allocate \$100 billion annually to assist developing nations in their shift towards low-carbon economies. A greater number of nations must engage in contributing to this fund to guarantee equitable access to clean technologies and energy infrastructure for countries such as India. The transference of clean technologies from developed nations to developing countries is imperative for the attainment of global climate objectives. India, being a significant contributor to greenhouse gas emissions, stands to gain from the exchange of knowledge and technologies pertaining to renewable energy, carbon capture, utilisation and

storage (CCUS), and energy efficiency from advanced nations such as the United States, Germany, and Japan.

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Appendices

List of Publications

RO	Title	Status	Index
RO1	Singh, A. & Kumar, N. "Assessing the relationship among energy, economy, and environment with special reference to India"	Published	Scopus
RO2	Singh, A. & Kumar, N. "Analysing the long run relationship between CO2emissions and Energy use of United Kingdom", Published ISSN 0971–765X 2024; pp.	Published	Web of Science
RO3	Singh, A. & Kumar, N. "Analysis of renewable energy and economic growth of Germany, Published (2024) Vol. 15 (2): 2349-2355"	Published	Web of Science
RO4	Is CCUS technology be a better choice for India's net zero carbon emission mission by 2050: Evidence from Fuzzy Analytical Hierarchy Process	Communic ated	SCIE

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- ➤ Role of nuclear energy in carbon mitigation to achieve United Nations net zero carbon emission: evidence from Fourier bootstrap Toda-Yamamoto
- Assessing the Relationship among Energy, Economy and Environment with a special reference to India.
- ➤ Analysing the long run relationship between CO2 emission and energy use of United Kingdom
- ➤ Investigating the Economic and Environmental sustainability of logistics operation in India using ARDL procedure
- ➤ Reviewing the role of coal in India's Energy Transition
- Analyzing and prioritizing risks including circular economy initiatives in supply chains

International Conference

- ➤ International Conference on Advances in Power generation, Renewable Energy and Sustainable Development (APGRES-2023)
- ➤ International Conference on Trends and Recent Advances in Civil Engineering, Department of Civil Engineering (TRACE-2022)
- ➤ International Conference on Advance Production and Industrial Engineering (ICAPIE-2022)
- ➤ International Conference of Advance Research and Innovation (ICARI-2021)

Books Chapters

- ➤ Chapter in Recent Development in Energy and Environment.
- ➤ Chapter in Advance production and Industrial Engineering

Seminars and Webinars

- ➤ Organized a workshop on Panel data in Stata at Humanities, Delhi Technological University, New Delhi
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- ➤ Participated in UNEP/OCHA Joint Environment Unit on Environment and Emergencies in the face of COVID-19 Crisis Waste Management
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Delegations

- ➤ RAISINA Dialogue 2024
- Young Leader- Participation of Youth of Our Country 2023, Parliament of India

Speaker, Chair and Judge

- > Special Guest at Sri Guru Govind Singh College of Commerce, DU 2024
- > Special Guest and Judge in Optima Society Debate Competition at Satyawati College, 2024
- > Judge in National Debate Competition at ARSD College, Delhi University 2024

Administrative Assignments

- ➤ NIRF committee , ARSD College, University of Delhi (2023-24)
- ➤ Discipline committee, ARSD College, University of Delhi (2023-24)
- Admission Committee, ARSD College, University of Delhi (2023-24)
- > Annual Day, Organizing Committee, SGGSCC, University of Delhi (2022-23)
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Technical Skills

- > R software
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- > Engineering Economics
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- ➤ Indian Economy

Assessing the Relationship Among Energy, Economy, and Environment with a Special Reference to India



Akanksha Singh and Nand Kumar

Abstract There exists a complex relationship between energy, economy, and environment. The coupling and coordination development of energy, economy and environment would help to analyze their relationship and it would further provide the basis of rational use. In this paper coupling and coordination are developed for India's energy, economy, and environment from 2006–2019. The results revealed four patterns such as: (1) The coordination between energy and economy improved with the passing year, it started with mild disorder category in 2006 and reached intermediate coordination in 2018; (2) The coordination between economy and environment showed a frequently unbalanced category only once, in 2016 it improved and reached to primary coordinated category; (3) The coupling and coordination development between energy and economy started with a mild disorder in 2006 and improved in 2008 to barely coordinated, it was stable until 2016 when it further improved to primary coordinated development; (4) The coordination between energy, economy, and environment repeated barely coordinated category most often, although there was an improvement in 2016 to primary coordinated but again in 2018 it deteriorated to barely coordinated. There exists a complex relation between the energy, economy, and environment in which they interact, promote and limit each other. The world at present is in the energy transition phase hence it's very important to know the relationship between the 3Es for the policy makers so that they can take decision in the right direction.

Keywords Energy · Economy · And environment (3Es); Coupling coordination and development

1 Introduction

Energy, economy and environment (3Es) are the wheels to reach the goal for development of any country. Achieving a sustainable development agenda while maintaining the right balance between environmental preservation, energy security, and economic growth has proven to be one of the greatest challenges of the modern period. We all need energy and its consumption increments to ensure a better quality of social life and to support the economic development, especially in developing countries. However, we need to generate more energy to fulfill the modern energy demand and ensure that the environment remains protected at the same time; hence the 3Es analysis is important. Therefore, 3Es have an important role in all past, present and future era, and also plays an important role in sustainable development. It is important to know the relationship of the 3Es to reach the desired equilibrium. The SDG7 affordable and clean energy, SDG12 responsible consumption and production, and SDG13 climate action can only be reached when all the 3Es are balanced. (Zhang et al. 2020) presented the assessment of the 3Es based on LCA and remanufacturing.

Kılkış and Kılkış (2017) studied the New exergy metrics for the 3Es for nearlyzero exergy airport (nZEXAP) systems. It applied the second law of thermodynamics to analyze the relationship between energy, environment, and economy. Pao et al. (2015) Used Lotkae Volterra model to examine the competitive interactions among the 3E in the U.S. The study was an emphasis on the existence of the environment Kuznets curve. Raza et al. (2019) applied wavelet analysis to analyze the impact of energy and economics on environmental degradation in the USA by Wang et al. (2019) analyzed the relationship between the 3Es economy by using the coupling coordinates and panel data approach and observed that the status has improved. Li et al. (2015) evaluated the decoupling of economic growth and CO₂ emissions in China. Cao et al. (2020) developed a Ternary coupling model to show the relationship between the 3Es. The observations were drawn based on the panel data of Hebei province. Yan et al. (2019) analyzed the rational use of the 3Es for the protection of ecological environment. Zile (2019) analyzed the coupling relationship by establishing a coupling model of energy-economy-environment. Shen and Mo (2014), and Sun and Sun (2016) calculated the average coupling coordination degree of the 3Es in China and claimed that it is lower as compared to the international standard. China (n.d.) studied and rationally contributed to the situation and development trend of the 3Es in China. Jin et al. (2016), Wang et al. (2020) drew a coupling and coordination model analysis of the complex relationship between urbanization, economy and environment. Mederly et al. (2003) considered the development of an integrated environmental sustainability index in Czech Republic. Singh et al. (2022) examined the effect of environment and economic variables on logistic performance in India using ARDL model on a time series data from 2007 to 2018. It showed a complex relation between the energy, economy and environment where they interacted, promoted and restricted each other.

Yan et al. (2019) studied the primary issues faced by the world today major which is climate change mainly because of increasing population, energy consumption and

economic development. The author examines the relationship between economic growth, food, biomass, and greenhouse gas emission. The results revealed the existence of Kuznets curve hypothesis. Wang et al. (2019) studied clean energy and renewable energy remains a major concern for most of the countries, the author suggests how biogas can be purified through combined UV irradiations and thermal annealing treatments. As there is an increase in the pace of developmental work around the world increased the petroleum consumption majorly for transportation, industrial application and electrification that has increased the air pollution, which in turn degraded the environment. Kusworo et al. (2020), the author suggests ways to reduce NO_X emission by adding hydrogen-rich synthesis gas generated by plasma-assisted fuel reformer. By using the technique, it was observed that approximately 50% of harmful pollution was reduced.

Alharbi et al. (2020), even renewable energy has some disadvantages like voltage instability in wind and solar energy. The author reviews the importance of optimal location and sizing distributed generation units for voltage stability. Rawat and Vadhera (2019), the challenges in renewable energies of instability in solar and wind energy were addressed by designing a new hybrid power plant. The energy obtained from solar and wind was stored in accumulators and as soon the accumulators were full the energies were transferred to plateau houses or to the network for production. Alhaddad et al. (2015), the AERMOD program and the Industrial Source Complex Short-Term Model are used by the author to analyze the air pollution emission patterns from Kuwaiti oil refineries. The studies also indicated that oilfields and oil refineries were the biggest contributors, with all pollutants being higher than anticipated.

This paper contributes to the literature in several ways firstly to the best of my knowledge no literature has stated the relationship among the 3Es using coupling coordination in the Indian context secondly the world at present is in the energy transition phase hence it's very important to know the relationship between the 3Es for the policy makers so that they can take decision in the right direction. The author examines the coupling and coordination of development between the 3Es of India between the years 2006 to 2019. The level of coupling and coordination development of the three E's exhibited an increasing trend.

2 Material and Methods

2.1 Index Selection

The selection of indicators was such that they can mostly represent and reflect the development degree of energy, economy, and environment.

2.1.1 Energy

The energy use per \$1000 GDP is the commercial energy use measured in units of oil equivalent per \$1000 GDP converted from national currencies using the purchasing power parity. Energy use refers to using primary energy before transformation to other end-use fuels, equal to native manufacture plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. The energy data have been taken from World Bank data as shown in Table 1. Energy production: It refers to the value of how much primary energy the country obtains from nature. It does not include any exports or imports and is just the total of what is extracted from nature. Total primary energy supply: The total amount of primary energy that a country has at its disposal. The total primary energy supply includes the imported energy minus the exported energy. It also consists of the energy obtained from natural resources. Electricity final consumption: Electricity consumption serves as an essential measure for a country's electric power development. Electric consumption usually grows faster during the development and industrialization phase.

Table 1 Energy data

Unit	Million tons of oil equivalent	Million tons of oil equivalent	Terawatt-hour
Year	Energy production	Total primary energy supply	Electricity final consumption
2006	405.77	532.99	584.45
2007	424.73	568.1	632.18
2008	445.26	603.83	670.79
2009	483.6	663.17	720.47
2010	503.78	700.76	785.81
2011	521.46	733.66	856.44
2012	524.18	766.26	907.19
2013	522.04	778.81	965.45
2014	532.76	822.05	1059.21
2015	537.3	834.53	1116.86
2016	550.84	852.22	1199
2017	551.62	882.88	1258.19
2018	573.56	919.44	1309.44
2019	593.5	973.7	1345.41

Source World Bank Database

2.1.2 Economy

Table 2 represents the economic data referenced from World Bank database. Gross Domestic Product It is a standard measure for measuring the value-added of the total goods and services produced in a nation during a specific period. Although GDP is the single most crucial indicator of economic growth, it does not indicate anything about the material well-being in a country. The GDP growth rate: It tells us about the percentage growth of a country's GDP. It is calculated by finding the percentage increase in the GDP year on year. GDP per capita is the value obtained by dividing the country's population from its total GDP. The GDP output approach: It is occasionally referred to as GDP (O), is the amount of output or production in the economy. It covers the entire economy and uses the same data that make up the index of production, output in the construction industry, retail sales index, and services index. The output approach to calculate GDP sums the gross value added of various sectors, plus taxes and less subsidies on products. The final consumption expenditure: It is the residential units' expenditure, including households, enterprises, and other consumers whose economic interests lie in the particular economic region. The goods and services used are for the direct satisfaction of individual wants and needs and the community.

 Table 2
 Economy data

Unit	US \$ trillion	US \$ trillion	Percentage	Percentage	INR billion
Year	GDP	Final consumption expenditure	GDP growth rate	GDP per capita growth	GDP output approach
2006	0.94	0.619	8.061	6.403	40,486
2007	1.217	0.798	7.661	6.048	47,142
2008	1.199	0.805	3.087	1.588	54,562
2009	1.342	0.904	7.862	6.351	59,895
2010	1.676	1.101	8.498	7.042	72,938
2011	1.823	1.227	5.241	3.894	84,871
2012	1.828	1.227	5.456	4.165	96,370
2013	1.857	1.261	6.386	5.135	108,981
2014	2.039	1.398	7.41	6.187	122,142
2015	2.104	1.461	7.996	6.797	133,907
2016	2.295	1.597	8.256	7.083	149,452
2017	2.653	1.851	7.044	5.912	166,226
2018	2.713	1.91	6.12	5.024	185,792
2019	2.901	1.97	6.34	5.891	189,275

Source World Bank Database

2.1.3 Environment

The environment plays a fundamental role in healthy living and existence of life. Over the years we have been witnessing an increased number of abnormal situations related to the environment. The weather is becoming extreme, increase in the number of tropical storms, the sea level rising and deterioration in air and water quality. The environmental factors that are important to track and the critical indicators are Air quality, waste management, country's green cover, and deforestation rate. The environmental performance Index (EPI) uses 32 performance indicators in 11 different categories which help countries to identify problems and set targets for best policy practices. The overall EPI rankings indicate which countries are the best in addressing environmental issues in various categories like waste management, sanitization and drinking water, air quality, and biodiversity.

2.2 Model Construction and Index Normalization

Indicators can be positive or negative indicators. A positive indicator correlates with increasing values, while a negative indicator correlates with decreasing values. A typical example of an indicator used to measure economic direction is the GDP per capita or nominal growth rate. Indicators have units associated with them and are thus prone to all the biases that come with non-standardized variable calculus and are therefore difficult to group with other indicators, to effectively compound different indicators, these variables need to be converted into a normalized standard index.

The given indicators are used to construct indices between 0 and 1 as lower and upper boundary values respectively, but in some cases, these bounds can be increased (or decreased) with the original minimum (or maximum) values in order to diminish the influence of extreme outliers. The natural logarithmic values of these bounds are used in some cases this takes care of probable deviations brought on by non-linear and exceptionally skewed indicator values' distribution. We first convert an indicator value (V) into an index score (I) by:

$$I = \frac{V - \min}{\max - \min} \tag{1}$$

To avoid linearization, we can use the lognormal transform and standardize the transform

$$I = \sqrt{\frac{V - \min}{\max - \min}} \tag{2}$$

Standardization to check for outliers

$$I' = \frac{I - \mu}{\sigma} \tag{3}$$

2.3 Coupling Development

Coupling is a concept in which interaction between two or more elements affects each other where Coordination and development are the two critical levels. Coupling is a probabilistic tool used in the joint construction of two or more random variables usually to deduce the individual elements' properties. Coordination is the degree of close interaction between systems, and development is the process of continuous improvement of the level of interaction between systems.

2.3.1 Binary Coupling (Coordination Coefficient)

For a statistic X & Y, the coupling or coordination coefficient C is given by

$$C = \frac{xy}{\left(\frac{x+y}{2}\right)^2} \tag{4}$$

The corresponding development is given by

$$D = CT (5)$$

where C stands for coordination and T is a weighted index of X &

$$T = \alpha X + \beta Y \tag{6}$$

With α , β being the appropriate weights.

2.3.2 Tertiary Coupling (Coordination)

Here coordination C' for statistics X, Y & Z is equal to

$$C' = \frac{3(XY + YZ + ZX)}{(X + Y + Z)^2} \tag{7}$$

The development D' is equal to

$$D' = C'T' \tag{8}$$

where

$$T' = \alpha X + \beta Y + \gamma Z \tag{9}$$

And $\alpha = \beta = \gamma = \frac{1}{3}$.

3 Results and Discussions

Table 3 represents the comprehensive index of the 3Es where the value of energy and economy was formulated by using Eqs. 1, 2 and 3 whereby environment index was obtained from epi.yale.edu. Table 4 represents the judgment criteria table based on which the results were formulated for the 3Es. Table 5 represents the results of the 3Es using Eqs. 4–9, where D is the development index and T is a weighted index of X & Y.

Figure 1 shows the trends of comprehensive index of the 3Es from 2006 to 2018 whereby the environment index shows a downward trend until 2014 and after that there exists an improvement in the trend between energy economy and environment. Figure 2 represents the coupling coordination between energy and economy (XY) and shows the rising trend. Similarly, Fig. 3 shows the coupling coordination between energy and environment (XZ), it is observed that in 2014 it reached the level of 0.83 value and put to the barely coordinated. In 2016 the relationship was improved. Figure 4 represents the trends of coupling coordination between economy and environment (YZ) and observed that a dip was observed in 2014. Figure 5 shows the trends of coupling coordination among energy, economy and environment (XYZ) and it is presented that after 2014 the riding trends were observed in relation and after 2016 it started to decline the coordination. Figure 6 explained the combined trend of coupling coordination between energy, economy (XY), energy environment (XZ), economy environment (YZ) and energy, economy environment (XYZ). Figure 7 represents the trend of 3Es development in India from 2006 to 2018.

Table 3 Comprehensive index of the 3Es

Year	Energy (X)	Economy (Y)	Environment (Z)
2006	0.277189136	0.468615693	0.477
2007	0.367030754	0.508199605	0.54
2008	0.437007993	0.348110576	0.603
2009	0.532282842	0.54625564	0.543
2010	0.591973325	0.608634013	0.483
2011	0.643224312	0.543528903	0.42265
2012	0.672915897	0.560308965	0.3623
2013	0.690717768	0.601823314	0.3373
2014	0.737801927	0.655672615	0.3123
2015	0.758341222	0.684423193	0.42405
2016	0.791876136	0.715503978	0.5358
2017	0.814440162	0.721088501	0.42075
2018	0.852549672	0.709972969	0.3057
2019	0.885482712	0.719756213	0.4057

Source Authors 'estimation energy and economy index', environment index from (epi.yale.edu)

Table 4 Comprehensive index of the 3Es

Coordination level	Criterion	Types
1	0-0.09	Extremely imbalanced
2	0.10-0.19	Sever disorders
3	0.20-0.29	Moderate disorder
4	0.30-0.39	Mild disorder
5	0.40-0.49	Frequent imbalanced
6	0.50-0.59	Barely coordinated
7	0.60-0.69	Primary coordinated
8	0.70-0.79	Intermediate coordinated
9	0.80-0.89	Good coordinated
10	0.90-1.00	Highly coordinated

Source Authors' estimation-energy and economy index, environment index from (epi.yale.edu)

Table 5 Coupling and coordination development degree of the 3Es of India

Year	XY	YZ	ZX	XYZ	Т	D	Types
2006	0.9337	0.999928	0.92964	0.974284	0.407	0.397	Mild disordered
2007	0.974	0.99906	0.96361	0.987306	0.471	0.465	Frequent imbalanced
2008	0.9871	0.928102	0.97452	0.973917	0.462	0.45	Frequent imbalanced
2009	0.9998	0.999992	0.99989	0.999938	0.539	0.54	Barely coordinated
2010	0.9998	0.986686	0.98971	0.995055	0.56	0.558	Barely coordinated
2011	0.993	0.984343	0.9574	0.985949	0.536	0.529	Barely coordinated
2012	0.9916	0.953882	0.90971	0.970776	0.531	0.516	Barely coordinated
2013	0.9952	0.920355	0.88141	0.961711	0.542	0.522	Barely coordinated
2014	0.9965	0.87371	0.83539	0.947338	0.568	0.538	Barely coordinated
2015	0.9973	0.944936	0.92015	0.973487	0.621	0.605	Primary coordinated
2016	0.9974	0.97933	0.96283	0.987588	0.68	0.672	Primary coordinated
2017	0.9963	0.93099	0.89873	0.966923	0.651	0.63	Primary coordinated
2018	0.9916	0.84188	0.77725	0.930883	0.622	0.579	Barely coordinated
2019	0.9934	0.85623	0.77564	0.948543	0.634	0.586	Barely coordinated

Source Authors' estimation coupling coordination of (XY), (XZ), (YZ), and (XYZ)

There was a mild disorder in the coordination of economy and energy in the year 2006, India has a huge population and to provide energy to all citizens demanded huge investments in the energy sector is required. The National Grid system was yet not established in 2006 that could facilitate electricity to all. As the National Grid or Central Grid system was established in 2013 and since then India's energy supply has increased unfold by 18% from 2013 to 2018. Whereas, the overall energy supply from 2006 to 2018 has increased by 55%. The coordination between energy economies

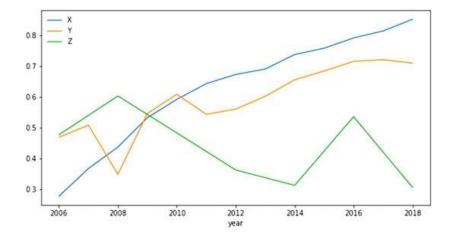


Fig. 1 The trend of the comprehensive index of 3Es in India

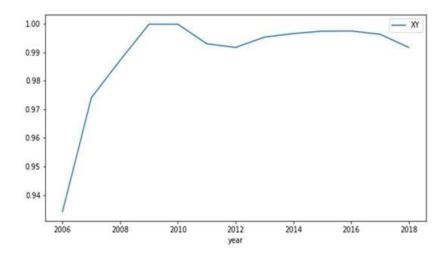


Fig. 2 Trends of coupling of energy-economy (XY)

also improved from barely coordinated to primarily coordinated in 2012. Whereas, it moved to intermediately coordinated in 2015 and showed stability by maintaining the coordination degree. The coordination between economy and environment has been very unstable and has majorly had frequent imbalanced coordination only once in 2016 it improved to primary coordinated. The reason for this was India's strong average economic growth rate and the ever-rising population of the country, created pressure on the biosphere, which has led to environmental degradation.

The Indian energy sector has steadily increased its production. The domestic energy production is dominated by coal and bio-energy. If we go back to 1973 the domestic energy production was largely dominated by bio-energy and waste around three fourth share of the total energy production. But the exploration of coal mines in the last three decades has made coal a prime material for the production of energy and its share has increased ever since. Therefore, the coordination between energy and environment was in a mild disorder in 2006. In 2008 at the conference of the parties 15,

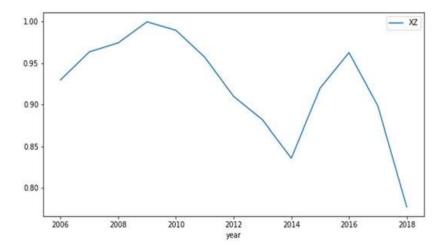


Fig. 3 Trends of coupling of energy-environment (XZ)

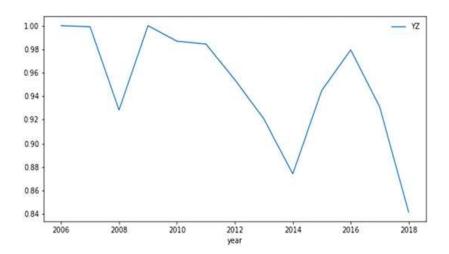


Fig. 4 Trends of coupling of economy-environment (YZ)

India announced to reduce the emission intensity by 20–25% of its GDP against 2005 levels by 2020. Therefore we can see an improvement in the coordination between energy and environment from mild disordered to barely coordinate and for seven consisting years it maintained the same coordination. In 2016 after Paris Agreement, India focused on achieving the NDC's built target of reducing emissions by 33–35% of GDP against 2005 emissions by 2030, to increase the cumulative electric power by 40% from non-fossil fuel based energy and to increase the forest and tree cover to increase carbon sink by 2030 (IEA 2020). Therefore, there is an improvement in the coordination between energy and environment from barely coordinated to primary coordinated. In 2018 as electrification work in the country was going on due to which there was a huge gap between demand and supply of energy and the coordination again deteriorated to barely coordinate.

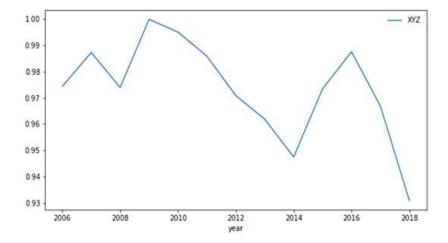


Fig. 5 Trends of coupling of energy-economy-environment (XYZ)

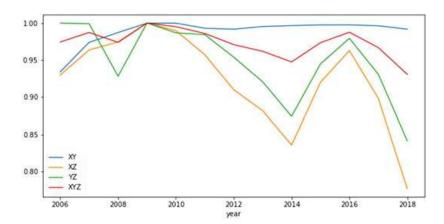


Fig. 6 Combine trends of coupling of (XY), (XZ), (YZ), and (XYZ)

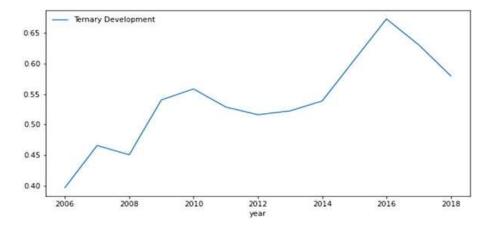


Fig. 7 The trends of development of India from 2006–2018

4 Conclusion

Energy, Economy and Environment are the components of a complex system that interact, promote and restrict one another. The three Es' were systematically evaluated by constructing a coupling coordination and development model of India from 2006 to 2018. In the years from 2006 to 2018, the development trends between the 3Es have been in recession or mild disorder category in 2006 but in 2009 it improved and moved up to barely coordinated and maintained the same for six years. This was mainly due to the Indian government being driven to reduce the energy's intensity, also to provide electricity to all the citizens while the growth rate of the economy was also maintained. Hence, there was further improvement in the coordination with 0.6049 to primary coordinated in 2015 and was stable till 2017. Again in 2018, it dipped back to barely coordinated with 0.579 score. This was due to the humongous pressure on the environment due to the ambitious targets of the government to provide electricity to all, which was mostly met by coal that was the reason for the increase in the emission of greenhouse gases.

The coupling coordination between economy and environment has mostly been unstable. It has shown a declining trend since 2010 till 2014, mainly due to the increase in demand of energy that was majorly met by coal. The use of unclean energy degraded the environment. In 2015, we see an improvement in the coordination but it was short lived and again declined after 2016. It was due to an increase in the pace of developmental work. Barely coordinated category has been observed in case of energy and environment. It started with mild disorder in 2006 and in 2018 it was still in frequent imbalanced category only once in 2016 it was in primary coordinated category due to growing environmental concerns internationally. The EPI was at its worse in 2018 with score of 0.306. The energy, economy, and environment are interlinked with each other to an extent that changes in one E affect both the Es'. In India, the coupling coordination and development between the 3Es have been very unstable. There is a need for efficient policies and research & development and deployment for positive coupling coordination between the 3Es in India.

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RESEARCH ARTICLE

Analysis of renewable energy and economic growth of Germany

Akanksha Singh, Nand Kumar*

Abstract

The study aims to investigate the effect of energy use, renewable energy consumption, nuclear energy consumption and air transport freight on CO_2 emissions in Germany. Auto-regressive distributed lag (ARDL) technique was used to establish the short and long-term correlations between the dependent (CO_2) and independent variables (Energy use, nuclear consumption, renewable consumption, air transport freight) on a time series data from 1970 to 2021. The results demonstrated the dependence of energy use on non-renewable energy sources by revealing a significant and positive relationship between short and long-term energy use and CO_2 emissions. Similar to energy use, nuclear energy use and air transport freight was also found to be positively correlated with CO_2 emissions. On the other hand, despite the fact that there is a strong negative connection between carbon dioxide emissions and renewable energy, the results reveal that the correlation between the two is not statistically significant. The study aims to investigate the effect of important economic factors on Germany's CO_2 emissions in order to move further in a sustainable manner. The data reveals an astonishing increase in the usage of nuclear energy for power generation between 1965 and 1985, which was followed by a fall in 2012 as a result of the Fukushima tragedy and growing social unease in Germany, which ultimately led to the phase-out of nuclear power. Nonetheless, BAU projections revealed that even with 200 nuclear power plants, CO_2 emissions would still be reduced to 278 by 2070, in part because of the additional power produced by other energy sources.

Keywords: CO, emissions, ARDL, Renewable energy consumption, Nuclear consumption, Air transport.

Introduction

One of the most important concerns of mankind today is perhaps climate change. This is clear from the fact that the world is no longer wasting time on theoretical debates and has turned its attention to concrete regulations and environmental laws. Therefore, it has become a matter of tremendous interest to spot and solve the challenges pertaining to reduction in carbon dioxide emission levels. Environmental degradation brought on by human activities that release CO₂ includes ecological problems, global warming, climate change and environmental pollution.

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According to BP statistics, the G7 nations contributed approximately 25% of global CO₂ emissions in 2019 and slightly less in 2020 to 23.2%. The world's most industrialized economies play a crucial role and their policies and practices are frequently imitated by other nations (B. Li and N. Haneklaus. 2022). We will examine the impact of macroeconomic variables on Germany's CO₂ emissions because it is one of the greatest energy consumers in the world and ranks third in the G-7 countries for overall CO₂ emissions, after the United States and Japan (M. Blesl. *et al.* 2006).

Environmental issues are having a growing impact on German energy policy. The government has set the objective of lowering greenhouse gas (GHG) emissions by at least 55% by 2030 and by 85% by 2050 compared to 1990 emission levels as part of the German Climate Action Plan 2050 (P. Markewitz., et al. 2019). The government has promoted initiatives for energy efficiency and renewable energy. The eco-tax was created in 1999 with the intention of promoting energy efficiency, renewable energy use, and conservation. The German Renewable Energy Act (EEG), which went into effect in 2000, established a feed-in tariff (FIT) system for all renewable technologies, which led to an astonishing increase in renewable energy capacity (C. Eui,

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C. Marcantonini, and A. D. Ellerman, 2013). However, only an energy shift is not sufficient to reduce GHG emissions significantly. In order to meet the ambitious ideals set by the German government, all sectors, including energy, industry, transport, agriculture and homes, will need to drastically reduce their GHG emissions. For a more comprehensive analysis, we have taken into account a number of sectors, including consumption of renewable energy, nuclear energy and air transportation along with energy use.

As per popular belief, clean energy fuels have a direct impact on the reduction of carbon dioxide levels through production as well as consumption. In this paper, we have emphasized on consumption, so renewable energy consumption is a significant regressor in our analysis. Renewable energy must be able to supply the necessary energy for economic activity and lessen environmental issues brought on by the use of fossil fuels (Y. Fang, 2011). It is worthwhile to mention that clean fuels not only require energy innovation at its pinnacle but also political and social commitment. Therefore, renewable energy consumption's impact may not be as direct and immediate as it seems. Trade is a crucial component of economic growth, which in turn implies that air travel is a crucial component as well. Despite its significance for the advancement of the nation and the creation of jobs, its unfavorable impact on GHG emissions is a serious concern. In fact, 915 million tonnes of CO₂ were created by flights globally in 2019, accounting for 12% of all transport-related CO₂ emissions. This leads us to the inclusion of air transport freight as an essential variable in the study. In an effort to build alternative sources of energy and to avoid the price fluctuations associated with oil import, nuclear power plants have been set up in several countries. Nuclear energy is proposed to offer a significant advantage in terms of reducing CO₂ emissions and curbing the effects of global warming (Y. Wolde-Rufael and K. Menyah, 2010). Hence, the nuclear consumption of Germany has also been taken into account in this study. The use of recent statistics, such as the BP statistics on G7 nation's CO₂ emissions, adds credibility and relevance to the discussion. The mention of Germany's position in global CO₂ emission provides a focused context for the study.

Review of Literature

Chang explored the relationships between energy use, carbon dioxide emissions and economic growth in China. The results of the study indicated that rising economic activity increases energy use and CO₂ emissions (C.C. Chang., 2010). A similar study on Russia's CO₂ emissions, energy use, and economic growth was analyzed by (H.T. Pao., et al. 2011). They used the causality test and the co-integration technique to analyze the data between the period of 1990 and 2007. Empirical findings indicated that emissions appear to be elastic in terms of energy use but inelastic in

terms of output in the long run (A. Singh., et al. 2022) used ARDL analysis on data from 2007 to 2018. The study looks at how economic and environmental factors affect logistic performance in India. The logistics performance index (LPI) is found to be positively impacted by foreign direct investment (FDI) and negatively impacted by the use of fossil fuels, both in the short and long term. While greenhouse gas emissions show a positive correlation with LPI, GDP per capita has a negative correlation, raising worries about the environment. The global economy suffered as India's logistic performance rating fell from 35th to 44th in the world. The report makes suggestions for how to enhance logistics and explains why India

Some of the other studies focussed on factors different from energy use. Apart from energy consumption, Baek also investigated the effects of nuclear energy and income on CO_2 emissions in 12 major nuclear-generating countries. The research demonstrated that nuclear energy typically reduces CO_2 emissions (J. Baek, 2015). Related research by Al-mulai examined the impact of nuclear energy use on GDP growth and CO_2 emissions in 30 nations worldwide. But unlike the previous research, the study's results revealed that nuclear energy use has no long-term impact on CO_2 emissions, but it has a positive long-term impact on GDP growth (U. Al-mulali, 2014)

Some research also studied the relationships of renewable energy use (K. Menyah and Y. Wolde-Rufael, 2010) investigated the relationship between nuclear and renewable energy use and carbon dioxide emissions in the US from 1960 to 2007. The research showed no correlation connecting renewable energy to CO₂ emissions, but it discovered a unidirectional causality between the consumption of nuclear energy and CO, emissions. (S. Kumari and N. Kumar., 2023) concludes that while renewable energy boosts the green economy, helps agriculture, and lowers CO₂ emissions, it also highlights the need for better nuclear waste management to avoid environmental risks (A. Singh., et al. 2023). The study assesses GDP, nuclear energy consumption, and CO₂ emissions in the United States, France, and Japan from 1965 and 2020 in order to validate the environmental Kuznets curve (EKC) theory. It is demonstrated that nuclear energy greatly lowers CO₂, SO₂, and NOx emissions using the Fourier ARDL and FBTY causality tests. The report recommends boosting the generation of nuclear and tidal energy and making sure that radioactive waste is disposed of safely in order to reach the UN's 2050 net-zero carbon targets.

Similar research was conducted, which studied the causal association between renewable energy use and economic growth in Turkey from 1990 to 2010. The result revealed that there is a unidirectional causal relationship linking economic growth to renewable energy use (O. Ocal and A. Aslan, 2013). Sebri investigated related research for the BRICS countries

between 1971 and 2010 using a multivariate approach. The research showcased that based on the ARDL estimations, empirical data demonstrates that there are long-run equilibrium relationships between the variables (M. Sebri and O. Ben-Salha, 2014). Similar techniques like ARDL and VAR methodology was used to examine the relationship between CO₂ emissions, economic growth, energy consumption and renewable energy consumption in Germany for the years 1975 to 2014 and suggested that the government should create and implement appropriate support programmes to encourage investment in new renewable energy technology by (S. khoshnevis Yazdi and B. Shakouri, 2018).

Different factors from energy use, nuclear energy use, and renewable energy use were analysed in some of the other research. (R. Waheed., et al. 2017) Studied the impact of Pakistan's agricultural and forest production on carbon dioxide emissions in addition to renewable energy use. The research showcased that the use of renewable energy and forests have negative and significant effects on CO2 emissions, whereas agricultural production has a positive impact on CO₂ emissions. (Y.Cai., et al. 2018) Examined the nexus between clean energy usage, economic growth and CO₂ emissions. The result revealed that in Canada, France, Italy, the US, and the UK there was no correlation between real GDP per capita, clean energy consumption and CO₃ emissions. However, when real GDP per capita and CO₂ emissions are the dependent variables, co-integration occurs in Germany and when CO₂ emissions are the dependent variable, co-integration occurs in Japan.

Methodology

The study establishes a relationship between CO₂ emissions and energy use, renewable energy consumption, nuclear energy consumption and air transport freight over the period 1970–2021 in Germany.

For the purpose of this study, we have used secondary data that was acquired from the World Bank Development Indicators (WDI). Equation 1 establishes the relationship of CO_2 emission with energy use, nuclear consumption, renewable consumption and air transport freight in the context of Germany during the period 1970-2021.

 $InCO_2 = f$ (In Energy, InNuclear, InRenew, InAir)(1) The variables are described in Table 1 and in, the natural log, is used in the equation above.

$$\Delta \ln CO_2 = \alpha_0 + \sum_{i=1}^n \alpha_{i:} \Delta \ln ENERGY_{t-i} + \sum_{i=1}^n \alpha_{i:} \Delta \ln NUCLEAR_{t-i} + \sum_{i=1}^n \alpha_{i:} \Delta \ln RENEW_{t-i} + \sum_{i=1}^n \alpha_{i:} \Delta \ln AIR_{t-i} + \beta_1 \ln ENERGY_{t-1} + \beta_2 \ln NUCLEAR_{t-1} + \beta_2 \ln RENEW_{t-1} + \beta_4 \ln AIR_{t-1} + \mu_t$$

In equation 2 the short-run relationship is represented by α_1 to α_4 whereas the long-run relationship is represented by β_1 to β_4 where α_0 is the drift component and μ_t is the error term and n_t is the optimal lag.

$$\Delta \ln CO_{2_t} = \beta_0 + \sum_{i=1}^{n_1} \beta_{i,i} \Delta \ln ENERGY_{t-i} + \sum_{i=1}^{n_2} \beta_{2i} \Delta \ln NUCLEAR_{t-i} + \sum_{i=1}^{n_3} \beta_{3i} \Delta \ln RENEW_{t-i} + \sum_{i=1}^{n_4} \beta_{4i} \Delta \ln AIR_{t-i} + \theta ECM_{t-1} + \mu_t$$

In order to create an error correction model, the co-integration of the variables was first tested, whereas θ is the speed of adjustment of the long-run equilibrium.

The description of the variable is shown in Table 1 where ENERGY, NUCLEAR, RENEW and AIR are the independent variables affecting CO₂ emission. We discovered that the ARDL technique was best suited for our research since some variables were stationary at the first difference and some at a level.

Results and Discussion

A popular statistical test to determine whether a particular time series is stationary or not is the augmented Dickey-Fuller test (ADF test). In time series analysis, the unit root test is used to determine if a time series is stationary or not. The null hypothesis states that time series have a unit root, whereas the alternative hypothesis states that time series are stationary. Therefore, we require the probability values to be smaller than 0.05 in order to reject the null hypothesis. The outcome of the unit root test is shown in Table 2. The results proved the stationarity of the dependent variable CO₂ at a level as well as 1st difference, whereas the independent variables were stationary at 1st difference.

For the purpose of examining co-integration, Pesaran, Shin and Smith (PSS) created the ARDL bounds test. (A. Montenegro., 2019) The ARDL model is the most suitable for our study since it permits having a mixture of variables at a level and first difference. Another advantage that ARDL test offers is that it is relatively more efficient in the case of small and finite sample data sizes (M. Belloumi, 2014). The ARDL bound test is used to evaluate the long-term connection between the dependent and independent variables prior to performing ARDL co-integration. The upper bound and lower bound are the two essential values that the bound test

Table 1: List of variables

Variables	Description
CO ₂	Carbon dioxide emissions (Million Tonnes)
Energy	Energy use (kg of oil equivalent per capita)
Nuclear	Nuclear consumption (EJ)
Renew	Renewable consumption (EJ)
Air	Air transport, freight (million ton-km)

Source: [WorldBank Database, 2020]

Table 2: ADF unit root test

Variables	Level t-statistics	Level probability	1st difference t-statistics	1st difference probability
CO ₂	-4.278871	0.0070	-8.039970	0.0000
Energy	-3.318208	0.0748	-7.844101	0.0000
Nuclear	-2.700536	0.2408	-4.932591	0.0011
Renew	-1.581440	0.7860	-1.615187	0.0995
Air	-1.279795	0.8816	-9.082132	0.0000

Table 3: Auto-regressive distributed lag bond test for co-integration

Variable	F statistics	Co-integration	
F (CO ₂ , energy, nuclear, renew, air)	4.445385***		
Critical value (%)	1	5	10
Lower bound	3.29	2.56	2.20
Upper bound	4.37	3.49	3.09

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

Table 4: Auto-regressive distributed lag short-run estimates

Variables	Probability	t-statistic	Co-efficient
Energy	0.0000***	7.733957	0.892228
Nuclear	0.1056*	1.655687	0.038417
Renew	0.1581	1.438348	0.039372
Air	0.0002***	4.112279	0.135124

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

characterizes. The lower limit assumes that all variables are at level, while the upper bound presumes that all variables are at first different. The null hypothesis is rejected and co-integration is shown to exist if the upper bound value is less than the F statistic.

Table 3 displays the results of the ARDL bound test; the findings reveal that the dependent and independent variables exhibit considerable co-integration because the F statistic is significantly higher than both the upper bound and lower bound statistic.

The findings of the ARDL short-run test are shown in Table 4. Energy use (0<0.05) and air transport (freight) (0.002<0.05) are significant and have a positive correlation with CO_2 emission, whereas nuclear consumption also has a positive relation with CO_2 emission and is significant at 10% (0.10>0.05). On the other hand, renewable energy has no significant correlation with CO_3 emission in the short run.

Table 5 describes the results of the long-run ARDL test. Energy use, is statistically significant and is positively correlated with carbon dioxide emission. Similarly, nuclear energy is positively correlated with $\rm CO_2$ emissions and is significant at 10%. Moreover, air transport (freight) is again significant and has a positive correlation with $\rm CO_2$ emission. On the other hand, renewable energy, an important variable of our study, is not statistically significant and has a negative correlation with carbon dioxide emissions.

Table 6 illustrates the results of the diagnostics tests that were performed to validate our findings. The Jarque-Bera test, which has achieved widespread acceptability among econometricians, is one of the most well-known tests for determining the normality of regressors. (T. Thadewald and H. Büning., 2007) Since normality is the most common presumption when using statistical procedures, we applied the Jarque-Bera test, and the findings indicate that variables are normally distributed.

Table 5: Auto-regressive distributed lag long-run estimates

Variables	Probability	t-statistic	Coefficient
Energy	0.0046**	3.000507	0.639761
Nuclear	0.1056*	1.655687	0.038417
Renew	0.3594	0.927247	0.028450
Air	0.0002***	4.112279	0.135124

^{*}Significant at 10% level, **significant at 5%, ***significant at 1%

Table 6: Diagnostic tests

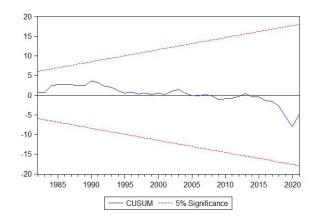
Jarque-Bera normality test JB stat	0.2346	0.8893
Ramsey RESET test, Log likelihood ratio	1.0537	0.2985
Breusch-Godfrey serial correlation, LM test	2.2290	0.3281
Heteroskedasticity Breusch-Pagan-		
Godfery test, Obs R-squared	15.3637	0.0814

Table 7: Granger causality test

Direction of causality	F-statistics	Probability
Energy - CO ₂	1.76577	0.1827
CO ₂ - Energy	6.13381	0.0044**
Nuclear - CO ₂	0.61963	0.5427
CO ₂ - Nuclear	4.48486	0.0167**
Renew - CO ₂	1.76303	0.1832
CO ₂ - Renew	2.27442	0.1146
Air - CO ₂	2.59037	0.0861*
CO ₂ - air	0.18345	0.8330
Nuclear - energy	4.08311	0.0235**
Energy - nuclear	2.11688	0.1322
Renew - energy	5.07704	0.0103**
Energy - renew	0.28825	0.7509
Air - energy	6.70181	0.0028***
Energy - air	0.96116	0.3902
Renew - nuclear	2.2363	0.1186
Nuclear - renew	2.90893	0.0649*
Air - nuclear	5.03021	0.0107**
Nuclear - air	1.21720	0.3056
Air - renew	5.13433	0.0098***
Renew - air	0.81349	0.4497

Homoscedasticity is a crucial presumption in statistical analysis. In order to determine if the data are homoscedastic or heteroscedastic, the heteroskedasticity Breusch-Pagan Godfrey test has been used; the results show that the dataset is homoscedastic.

Further Ramsey RESET test was used, and the outcome demonstrates that the model is free from specification error. Specification error means that at least one of the model's fundamental characteristics or presumption is erroneous.



*Significant at 10% level, **significant at 5%, ***significant at 1%

Figure 1: CUSUM test

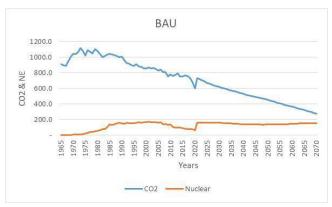


Figure 2: The business usual estimates

As a result, model estimation could produce inaccurate or deceptive results. Lastly, the Breusch-Godfrey Serial Correlation LM test demonstrated that our model's error component is not serially correlated.

Table 7 shows the results of the Granger causality test, the test is applied to time series data to determine whether there is any pronounced predictive power from one variable to the other. In essence, it aids in determining if a variable is helpful or not and whether it is capable of predicting other factors or not. It describes a one-to-one relationship between variables. As per our results, CO_2 - energy use, CO_2 - nuclear consumption, CO_2 - air, energy use - nuclear consumption, energy use - renewable energy consumption, energy use - air transport (Freight), renewable energy - nuclear consumption, nuclear consumption - air transport (Freight), renewable energy - energy use have unidirectional causal relationships.

Figure 1 demonstrates the result of the cumulative sum of the recursive residual stability test (CUSUM). Brown *et al.* invented the CUSUM test in 1975. It is a common statistical tool for analyzing and tracking structural changes in time series models (S. Otto and J. Breitung., 2022). The Figure 1

implies that the model is stable because our graph is within the bounds of 5% significance level.

BAU Estimates

The analysis a trend of sharp increase in the use of nuclear energy for power generation between the years 1965 to 1985. However, the trend started declining from the year 2012 mainly because of the 2012 Fukushima accident and the concerns in German society regarding nuclear accidents were deep, so the government had to completely phase out nuclear power generation. However, the BAU estimates from 2022 to 2070 show that even if the nuclear power generation would have maintained the 200 mark then also the ${\rm CO_2}$ emission would have dropped to the mark of 278 by the year 2070. It's also because of the increase in power generation through other sources of renewable energy (Figure 2).

Conclusion

CO₂ emission is a major contributor to climate change and global warming. Substantial increase in CO₂ emission over the years has altered the proportions of our atmosphere and has given rise to global temperatures. The negative effects of this are currently being felt throughout the planet in the form of abrupt changes in weather patterns, extremely high temperatures, rising sea levels and melting ice caps. In this era of widespread recognition of the current issue, countries all over the world are issuing laws and taking precautions, but before one can be sure that these actions are effective, one must first determine whether or not they are even addressing the proper cause. In this paper, we analyzed whether or not the theoretically stated variables had an impact on Germany's CO₃ emissions. One can make some inferences from the empirical testing carried out in this paper.

The focus of the study is to find out whether CO_2 emissions are affected by energy use, renewable energy consumption, nuclear consumption, and air transport (freight) in Germany from the period 1970 to 2021. The results show a substantial and positive correlation between short and long-term energy use and CO_2 emissions, demonstrating the dependence of energy use on non-clean energy sources. The amount of energy used nationwide directly affects carbon dioxide emissions. Similarly there is a positive association between air transport (freight) and CO_2 emissions, indicating that the expansion of the aviation industry has contributed to increased emissions.

Consumption of nuclear energy is positively correlated with CO_2 emissions. It is obvious that Germany's CO_2 emissions will not decrease by switching to nuclear energy. As a result, the country's policy of using nuclear energy as a clean fuel has not been successful. On the contrary, we observe a rise in CO_2 emissions due to other factors such as energy use, industry, population, etc. Although there is a negative correlation between carbon dioxide emissions

and renewable energy, which is a significant variable in our analysis, the test findings show that this correlation is not statistically significant. This suggests that just implementing policies to increase the use of renewable energy has little effect on carbon dioxide emissions. The aforementioned two findings are guite important since they show that, in the case of Germany, the energy industry has no impact at all on CO₂ emissions. Significant CO₂ emissions are not being caused by energy generation or consumption. Other economic sectors like transportation, industrialization, etc, instead influence CO2 emissions. As a result, the nation needs to change its focus on the source of CO₂ emissions. In a complicated economic system, it is exceedingly difficult to comprehend the underlying causes of CO₂ emissions. We can never be certain that our efforts to conserve the environment will be successful if we don't understand the true cause. As a result, ongoing efforts are made in this area, and our work has been essential in understanding some of the real variables influencing Germany's CO, emissions. The data demonstrates a strong rise in the usage of nuclear energy for power generation between 1965 and 1985, which was followed by a fall in 2012 as a result of the Fukushima tragedy and growing social unease in Germany, which ultimately led to the phase-out of nuclear power. Due in part to enhanced power generation from other renewable energy sources, BAU projections show that even with 200 units of nuclear power generation, CO₂ emissions will still be reduced to 278 by 2070. Further research can be done on managing the waste disposable generated by nuclear energy.

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Analysing the long run relationship between CO₂ emissions and Energy use of United Kingdom

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ABSTRACT

In this study, the time series data of the United Kingdom from 1965 to 2021 for energy usage, total reserves, manufacturing, GDP and total carbon emission have been examined using autoregressive distribution lag (ARDL) model. The results revealed that energy usage, manufacturing and GDP have a positive relation with $\rm CO_2$ emission both in the short run and long run raising environmental concerns on the contrary only total reserves have a negative relation in the short and long run. United Kingdom increasing energy efficiency have been a top priority in the recent era, in order to achieve the target of net zero carbon emission by 2050, government need to promote policies for energy mix which would increase the usage of other renewable energy as the challenges remain for manufacturing and transportation industry because the overall emission from these sector remains largely unchanged despite advancements in fuel efficiency because the results indicates that a percentage increase in energy usage increase the $\rm CO_2$ emission by 0.23% whereas 1% increase in manufacturing leads to 0.25% increase in the $\rm CO_2$ emission.

Key words: ARDL, CO2 emission, GDP, Energy mix, SDGs

Introduction

Over time, the UK has significantly reduced its carbon dioxide (CO₂) emissions as shown in Fig. 1. Between the early 1990s and 2019, emissions had decreased by about 43%, largely as a result of a move away from coal-based energy production, improved energy efficiency, and the expansion of renewable energy sources. The energy industry has significantly reduced its emissions. This reduction was greatly aided by the closure of coal-fired power stations and their replacement with natural gas and renewable energy sources like wind and solar. A challenge has been the transportation industry. The overall emissions from this sector remained largely unchanged because of a rise in road traffic, despite advancements in fuel efficiency and the use of electric vehicles. The United Kingdom government has established challenging goals for emissions reduction. The goal is to achieve net-zero emissions by 2050, which is legally required. The UK has introduced a number of policies, including carbon pricing and subsidies for renewable energy, to achieve this.

The United Kingdom's energy mix has evolved over time, Fig. 2 shows the total energy usage of UK.

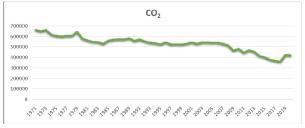


Fig. 1 CO₂ emission

While natural gas, nuclear power, and renewable energy sources have gained popularity, the amount of coal used to generate electricity has significantly decreased. The UK is now a global leader in offshore wind energy because to the significant increase of wind power in particular. In the UK, increasing energy efficiency has been a top goal. This covers metrics for building, appliance, and industrial process energy efficiency. To promote more energy-efficient housing, initiatives like the Energy Performance Certificate (EPC) have been introduced. Energy production has become more decentralized in the UK, where more homes and businesses are using solar energy and small-scale wind power to generate their own electricity. This trend to decentralized energy production has helped to cut down on transmission losses. Although there have been oscillations in energy use in the household and industrial sectors, there has been an overall trend towards increased energy efficiency. Government incentives and policies have contributed to the promotion of sustainable practices and energy efficiency.

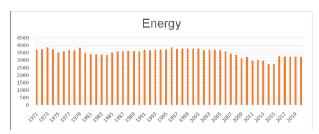


Fig. 2. Energy Usage

Emissions reduction in the transport industry is still a difficult task. It will take significant infrastructural investments to make the switch to electric vehicles and lessen reliance on fossil fuels. It will take time and effort to increase the housing stock's energy efficiency in the UK, particularly renovating older structures. In this study, we looked at the connections between CO₂ emissions, economic expansion (GDP, manufacturing value), total reserves and energy use. A multivariate model is used to investigate the causation, short and long sighted interdependence between CO₂ emission, economic growth (GDP, Manufacturing), total reserves and energy usage. The goal of the study is to identify the factors that are beneficial to environment sustainability so that we can advance in a more sustainable way.

Literature Review

A significant number of studies show that, despite the fact that economic growth does result in an increase in energy consumption, carbon emissions are not permanently reduced as a result. Some scholars use econometric models to look at the short- and long-term dynamic interactions between factors like carbon emissions, financial growth, suburbanization, and international trade in order to offer direction for the sustainable development of a region or a nation. According to the environmental Kuznets curve (EKC) theory, there is an inverse Ushaped relationship between environmental pollutants like CO, and GDP (Jebli et al., 2016; Leal and Marques, 2020; Rafiq et al., 2016; Dong et al., 2017; Shahbaz et al., 2019).

Time series data for the three major nations of the USA, France, and Japan were studied from 1965 to 2020 using the Fourier ARDL, Fourier bootstrap Toda-Yamamoto, and wavelet coherence methods. According to this analysis, France crossed the breakeven threshold in 1978, demonstrating that CO₂ levels decreased as nuclear energy use increased (Singh *et al.*, 2023). The South Asian EKC hypothesis was also confirmed, demonstrating the beneficial effects of LPG use on the environment (Murshed, 2021).

GDP and CO2 emissions are inversely correlated, according to research on 31 developing countries with subpar clean energy development Aye et al. (2017). While few studies (Teng et al., 2021; Ahmed et al., 2019; Ahmed et al., 2020; Odugbesan and Adebayo, 2020; Pablo et al., 2016; Wasti et al., 2020) found a positive link between GDP and CO2 emissions. The most modern econometric approaches, like as ARDL, Wavelet coherence, and Fourier analysis, have been used in several research to analyse the causal relationship and unidirectional connectivity between energy, GDP, and CO, emissions. Yang and Zhao (2014), Adebayo et al., 2020; Adebayo et al., 2021; Khobai and Roux (2017), Wu et al., 2022, Adebayo, 2020; Gao and Zhang, 2021; Faisa et al., 2016, Jafari et al., 2015, Wang et al., 2019; Aydoan and Vardar, 2020; Kirikkaleli et al., 2020; Kirikkaleli and Adebayo. 2021.

The study found that using biofuels instead of fossil fuels reduces greenhouse gas emissions by 70%. The economic potential of biofuels was studied between 2001 and 2022 using bibliometric analysis. The research revealed that while the US, China, In-

SINGH AND KUMAR S257

dia, and Europe have the largest biofuel markets, many other developed and developing countries still have smaller and less developed markets for sustainable biofuels (Hasan and Coworkers, 2023).

Methodology

To test our hypothesis and accomplish our objective, we used secondary time series data that we obtained from the World Bank Development Indicators (WDI). Equation 1 was created to analyse the relationship between CO₂ emissions, GDP, energy use (EU), manufacturing value (MV), and total reserves (TR) in the context of the United Kingdom from 1965 to 2021.

$$ln CO_2 = f(lnGDP, lnEU, lnMV, lnTR) ... (1)$$

Here, In is the natural log in the equation above, and Table 1 defines the variable description has definitions of the variables.

$$\Delta \ln CO2_{\tau} = a_0 + \sum_{i=1}^{n} a_{i,i} \Delta \ln GDP_{t-i}^2 + \sum_{i=1}^{n} a_{2,i} \Delta \ln EU_{t-i} + \sum_{i=1}^{n^2} a_{3,i} \Delta MV_{t-i} + \sum_{i=1}^{n^3} a_{4,i} \Delta \ln TR_{t-i} + \beta_1 \ln GDP_{t-i} + \beta_2 \ln EU_{t-1} + \beta_4 \ln MV_{t-i} + \beta_4 \ln TR_{t-i} + \mu, \dots$$
(2)

The letters a1 to a3 in the equation above reflect the short-run relationship, b1 to b3 represent the long-run relationship, and a0 the drift component. While ni is the optimal lag and t is the error term.

Variables	I(0)	I(0)	I(1)	I(1)
	t-stats	p-value	t-stats	p-value

$$\Delta \ln CO2_{t} = \beta_{0} + \sum_{i=1}^{n_{t}} \beta_{1i} \Delta \ln GDP_{t-i} + \sum_{i=1}^{n_{2}} \beta_{2i} \Delta \ln EU_{t-i} + \sum_{i=1}^{n_{3}} \beta_{3i} \Delta \ln MV_{t-i} + \sum_{i=1}^{n_{3}} \beta_{4i} \Delta \ln TR_{t-i} + \theta ECM_{t-1} + \mu_{t}......(3)$$

In the equation above, the letters all to a 4 stand for the short-run relationship, bl to b4 for the long-run connection, and a0 for the drift element. While t is the error term and ni is the ideal lag.

Results and Discussion

The study is conducted on time series data for 57 years so ADF unit root test was applied to check the stationarity of the variables, the results indicated that the variables were stationary at first difference, ARDL model is applicable if variables are stationary at level or first difference or a mixture of both and as the variables were stationary at first difference ARDL model was well suitable for this study. The table below illustrates the results of ADF unit root test.

Table 1. ADF unit root test

CO2	-2.897	0.1713	-8.379	0.0018***
GDP	-1.591	0.78	-7.015	0.002***
EU	-2.703	0.239	-7.567	0.018***
MV	-1.488	0.822	-7.525	0.003***
TR	-2.830	0.1931	-8.618	0.0098***

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level.

The long-term relationship between the dependent and independent variables is assessed using the Auto Regressive Distributed Lag bond (ARDL) bound test. The upper bound and lower bound are two critical variables that the test displays. The lower bound assumes that all the variables are equal, while the upper limit assumes that there is a first difference for all of them in this situation.

The null hypothesis is rejected and co-integration is shown to exist if the upper limit value is less than the F statistic. ARDL bound test is used to check the cointegration between the variables, the finding reveals that the dependent variable CO_2 and the independent variables GDP, manufacturing, energy usage and total reserves are cointegrated as the F statistic is 4.26 which is greater than 3.49 the upper bound and 2.56 the lower bound at 5% significance level. Table 2 illustrates the results of the ARDL bound test.

Table 2. ARDL bound test

Variables	F-Statistics		
F (CO ₂ , GDP, EU, MV, TR)	4.264781**		
Critical Value	1%	5%	10%
Lower Bound	3.26	2.56	2.2
Upper Bound	4.47	3.49	3.09

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level.

Table 3 The results of the ARDL short run estimates are indicated in Table 4 indicating that energy usage and GDP is significant at 1% and is positively correlated with $\rm CO_2$ emission, a 1% increase in the GDP will increase $\rm CO_2$ by 1.12% whereas one percentage increase in energy usage will increase the $\rm CO_2$ emission by 0.23% on the other hand manufacturing also has a positive relation and is significant at 10%, in all the independent variable only total reserves is negatively correlated with $\rm CO_2$ emission indicating that a percentage increase in the reserves leads to 0.04 reduction in the $\rm CO_2$ emission.

Table 4 displays the results of ARDL long run estimates where the results of ARDL long run esti-

Table 3. ARDL short run

Variables	Probability	t-Statistics	Coefficients
GDP	0.0001***	4.5845	1.1222
MV	0.0701*	1.8598	0.2589
EU	0.0049***	2.9732	0.2321
TR	0.0239**	-2.3450	-0.0483

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level

mates where the results indicates that GDP, manufacturing and energy usage are significant at 1%, 10%, and 1% respectively and has a positive relationship with CO_2 emission hence it would be advisable to use more of green energy both for manufacturing process and energy use which would also impact the GDP on the other hand total reserves is significant at 5% and has a negative relation with the CO_2 emission.

Table 5 displays the results of diagnostic test Jarque-Bera normality test was employed to check whether the residual are normally distributed or not and the result reveal that the residuals are normally distributed (0.20 > 0.05). Ramsey Reset test was used to check the specification error and the result revealed that there was no specification error in the model (0.40 & gt; 0.05). Breusch-Godferyserial correlation, LM test revealed that there exist no serial correlation among the error components in the model (0.38 & gt; 0.05). Lastly the outcomes of heteroscedasticity Breusch-Pagan-Godfery test demonstrates that the data is homoscedastic.

Table 4. ARDL long run

GDP	0.0000***	4.5845	1.1222
MANUFACTURING	0.0701*	1.8598	0.2589
ENERGY	0.0049***	2.9732	0.2321
RESERVES	0.0216**	-2.3880	-0.0589

^{***, ** &}amp;*denotes 1%, 5% & 10% significance level

Granger causality test is used for the time series data to predict whether one variable has potential prediction impact on the other variable. The results reveals that there exist unidirectional causation between CO₂ emission-GDP, total reserves- manufac-

turing and $\rm CO_2$ emission-reserves at 10% significance level whereas manufacturing- $\rm CO_2$ and GDP-reserves have a unidirectional causuallinkage at 1% and 5% respectively. The Granger causality test results are shown in Table 6.

Table 6. Granger causality test

Direction of Causality	F-statistics	Probability
CO ₂ -GDP	3.16670	0.0507*
Manufacturing-CO,	5.07605	0.0098***
GDP-reserves	3.22392	0.0482**
Reserves-manufacturing	2.89367	0.0647*
CO ₂ -reserves	3.02068	0.0577*

^{***,**&}amp;*denotes 1%, 5% & 10% significance level

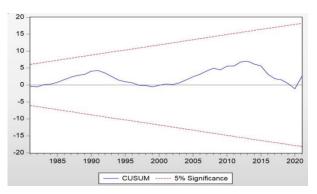


Fig. 3 CUSUM test

The stability of the model was checked by the cumulative sum of the recursive residuals stability test (CUSUM) and as the statistics were found to be between the critical bounds the model was found stable as shown in Fig. 3.

Conclusion

This study uses data from 1965 to 2021 to examine the relationships between carbon emissions, economic growth (GDP, Manufacturing, Reserves), and energy consumption of the United Kingdom. The findings reveal that energy use, GDP and manufacturing are positively related whereas total reserves have a negative relation with CO₂ emission both in the short run and long run respectively. The short

Table 5. Diagnostic tests

JB Normality Test	2.02	0.66
Ramsey RESET test	10.25	0.318
Breusch-Godfery serial Correlation	16.68	0.122
Heteroskedasticity B.P.G. test, Observed R-squared	5.46	0.325

SINGH AND KUMAR S259

and long run impact of GDP, energy usage and manufacturing on CO₂ emission is unfavourable that is a concern for the environment. Estimates of the linkages between economic expansion, CO₃ emissions, and energy consumption reveal that the United Kingdom has a wide range of options for establishing its energy policy toward alternative and renewable energy sources in anenvironmentally friendly and long-term manner. They could diversify their energy strategies in this direction, reducing environmental pollution while steadily and reliably increasing the energy supply over time. By supporting the development and widespread use of alternative and renewable energy technologies, it may also play a leading role in ensuring that future generations inherit a more habitable and cleaner environment.

Conflict of Interest- None

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Investigating the Economic and Environmental Sustainability of Logistic Operations in India Using ARDL Procedure

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Abstract. The study aims to examine the effect of environment and economic variables on logistic performance in India. In order to study the long run and short run association between the variables the study employed auto regressive distribution lag (ARDL) approach on a time series data from 2007 to 2018. The result revealed that foreign direct investment (FDI) has a positive relation with LPI whereas fossil fuel consumption in both the short and long run has a negative relation. On the other hand, GDP per capita has a negative relation with LPI while total greenhouse gas emissions has a positive relation, which is a sign of concern for environment sustainability. In the recent report published by the World Bank India's rank has slipped down from 35th to 44thposition worldwide whereby all the six dimensions have shown a downward trend. India being one of the largest customer oriented market would negatively affect the world economy if its logistics operation are poorly driven. This study highlights few reason why India lacks behind in its logistics performance and provide suggestion how India can improve its logistic operation at global level.

Keywords: Logistic performance index, ARDL, total greenhouse gas emission, foreign direct investment, GDP per capital

1. Introduction

In the 21st century, logistics assumes an indispensable part in associating urban communities, nations, and landmasses all around the world [Khan et al., 2018]. As of late, logistic industry has pulled in much consideration in academic studies because of its focal points and inconveniences on nations' monetary development and ecological execution. Firms around the world have begun to implement green practices in their logistics tasks to accomplish social, economic and environmental sustainability, while in many countries green practices have a negative impact on the firm's profit. In an

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examination to discover the influence of green supply chain network on firms' financial and natural exhibition, it was establish that green experiments including an environmental plan of items, participation with clients, green buying of crude materials and segments, green transportation, and dispersion have a critical positive relationship with nature. It was also analyzed that green practices particularly green buying, adversely affects a company's productivity because of weighty charges and import obligations on material and segments [Khan et al 2017]. Undeniably, worldwide logistics tasks intensely rely upon energy, particularly petroleum derivative, bringing about natural crumbling and grave repercussion on general wellbeing. An investigation on European nations to examine the connection between logistics and energy request, the outcomes indicated that logistical tasks have a solid relationship with energy interest [Zaman et al., 2017]. Logistics industry plays a critical role in the monetary advancement of a nation yet nations do not invest the required time and energy on the other hand green practices in logistical tasks are the lone answer to bring about control in air contamination, environmental change and a worldwide temperature alteration issue[Li et al., 2018] and [Khan et al., 2017]. The BRICS nations should develop a model for green practices and business through appropriation green practices in logistics activities, [Aldakhil et al., 2018].

1.1 Research motivation and objective

Logistic operation play's a critical role in the economic development of the country but its percentage contribution in the GDP is comparatively less, the government need to focus on measures which promotes logistic performance as countries like Germany, Sweden and Belgium are leading the list of logistic performance index whereas India far lack behind. The motive behind the study is to highlight the parameter, which are good for logistics operation so that logistic operation can move forward in a sustainable manner.

2. Review of Literature

[Khan et al., 2019; Zhang et al., 2019; Khan et al., 2017; Mensah et al., 2020] studied the relationship among GLP and social, environmental and economic factors and suggested that constructive policy that promotes the logistic industry without compromising the Environment sustainability should be encouraged. [Yadav et al., 2016] examined the intension of the young consumer towards buying a green product. The research carried out in India using Theory of Planned Behavior (TPB) to check environmental concern and environmental knowledge. [Chhabra et al., 2017;Pishvaee et al., 2012] used MDCM to analyze the alternatives for green practices in the assembly and packaging processes, to obtain best alternative solution for the logistic company particularly in India. They concluded the best packing alternative is carbon positive material whereas the best alternative for assembly operation is clinch joint.[Karaman et al., 2020] investigates the relation between GLP and sustainability drawing from the signaling theory and tested the link with the corporate governance. [Zhang et al., 2020; Oliverira et al., 2016] used LCA for a better understanding of remanufacturing and assessment of 3Es. [Kilkis et al., 2017] introduced the nearly zero exergy airport and used the law of thermodynamics to analyze the relationship between the 3 Es. [Pao et al., 2015] employed Lotkae Volterra model to examine the competitive interaction among the three Es and laid emphasis on EKC hypothesis. [Sarkodie et al., 2019; Wang

et al., 2019] revealed the existence of inverse U-shaped relationship between the increasing population's increasing demand for energy consumption, food production and economic development that has triggered climate change. [Menash et al., 2020, Kwak et al., 2020] employed partial least square structural equation modeling to check the relationship among green logistics management practices, social-environmental sustainability and business performance (BP). [Karaman et al., 2020] employed the signaling theory to analyze the relationship between GLP and sustainability reporting, it was discovered there is positive and relevant relationship between them. [Mensah et al., 2020] used Heterotrait- Monotrait ratio and Fornell-Larcker criteria to analyze the relationship among GLMP on social, environmental, market and financial performance and it was noted that environmental performance was positively impacted by GLMP whereas, social, market and financial performance has insignificant impact on EP. [Baah et al., 2019] employed partial least square structural equation modeling to analyze the effects of regulatory stakeholder pressure and organizational stakeholder pressure on financial performances and GLP. The results revealed GLP was influenced by organizational stakeholders and regulatory stakeholder's pressure. [Gupta et al., 2020] applied graph theory matrix approach to analyze the sustainability index of the logistics service provider and concluded that green procurement, renewable energy sources, recyclable packaging, carbon emission reduction, rainwater harvesting, use of CNG fleets, reduction in fuel consumption and resources optimization plays a major role in sustainable practices. [Zhang et al., 2020] conducted interviews based on the grounded theory method and concluded that the development level of logistics industry, the level of social supervision, the perfect of GLP system, the level of perception of logistics enterprises on GLP and the green governance capacity of government have a great influence on GLP.[Menash et al., 2020] employed partial least square structural equation model software to study the impact of green warehousing logistics optimization and social values and ethics on economic performances and supply chain sustainability. [Abdullahi et al., 2020] proposed a weighted sum model and an opsilion-constraint model that combines three dimensions of the 3Es. [Paul D.larson., 2021] employedHayes Process macro to analyze the indirect effects of LPI on economic and environment. [Richnak et al., 2021] used Pearson chi-square test to test the hypothesis. A total of 165 enterprises were surveyed and the result indicated that environmental policy were used by large enterprises in Slovakia. [Chawla et al., 2021] deployed fuzzy AHP to analyze green operations management practices and operation management. It laid emphasis that through GOM both nature and man-made world can coexist.[Stekelorum etal., 2020] used fuzzy set comparative analysis to survey 232 third party logistic provider to analyze the internal and external green supply chain management practices that influences TPLs operational and financial performances.[Nair et al., 2021] reviewed papers from 2000 to 2020 and collected data through survey and found that very few literature exist on social sustainability and also identified twenty six social issues in supply chain exist in two different economy USA and India.[Zhanget al., 2021;Guirong et al 2012; Alexandrova et al., 2021] used Grey relation analysis method GRA to predict urban logistic demand and concluded that subway can promote sustainability in urban logistic they highlighted the importance of government in order to achieve a circular economy. [Li et al., 2021] employed two stages least square and generalized method to analyze the environment and economic effects of green logistics and the results indicated that green logistics positively impact the economies of MENA, Asian and OBRI countries but promote environmental pollution. [Caggiani et al., 2021] proposed a two-echelon electric vehicle routing problem (2E-EVRPTW-PR) model for last-mile urban deliveries where e-vans and ecargo bikes can be used for customers' deliveries in the urban zone and second restricted traffic zone, respectively. [Adams et al., 2021] Concludes that firms cannot expertise in supply chain and sustainability at the same time and managers should have qualification and background of both. [Zheng et al., 2021] employed fuzzy AHP and analyzed that the growth of different logistic models has negative affect on agricultural product cold chain. [Managi et al., 2021] viewed that science, technology and innovation plays an important role in achieving the SDGs. [Naqvi et al., 2010] correlated renewable energy consumption, financial development and real income to ecological footprint by augmented panel algorithm method and concluded that financial development is positively related however per capita income for real income and highincome group have a negative outcome. [Majid, M. A., 2020] [Harjanne et al., 2019] objective was to present challenges, investment and employment opportunities in the field of renewable energy in India. [Zhang et al., 2019] examined the relationship between tourism, environment degradation and logistics in a time series data in Thailand using ARDL model.

3. Methodology

Logistic performance index was first calculated in 2007 by the world Bank based on the six key indicator i.e. speed of custom clearance process, quality of infrastructure related to trade and transport, ease of competitive price shipment, quality of logistic service, ability to track and trace consignments and expected delivery time of goods and services to destination. This study draws the relationship between India's logistic operations with economic (GDPPC, FDI) and environmental factor (TGHGE, Fossil). Undoubtedly logistic operation are very important for a country's economic growth but due to their high dependence on fossil fuel they enhances carbon emission and global warming, a sustainable policies in the field of logistics operation is needed to solve the various environmental and social problems[Khan et al.,2018]. In this study, we have used secondary data downloaded from the World Bank development indicators (WDI) for testing hypothesis and achieving research objective. Equation: 1 is formulated to check the relationship of overall logistic operation with environment and economic factors in the context of India during the period 2007-2018.

$$\ln LPI = f(\ln GDPPC, \ln FDI, \ln TGHGE, \ln FOSSIL)....(1)$$

In the above equation, ln is the natural log and the descriptions of the variables are in table 1.

$$\begin{split} &\Delta \ln LPI_{t} = a_{0} + \sum\nolimits_{i=1}^{n_{1}} a_{1i} \Delta \ln GDPPC_{t-i} + \sum\nolimits_{i=1}^{n_{2}} a_{2i} \Delta FDI_{t-i} + \sum\nolimits_{i=1}^{n_{3}} a_{3i} \Delta \ln TGHGE_{t-i} \\ &+ \sum\nolimits_{i=1}^{n_{4}} a_{4i} \Delta \ln FOSSIL_{t-i} + \beta_{1} \ln GDPPC_{t-1} + \beta_{2} \ln FDI_{t-1} + \beta_{3} \ln TGHGE_{t-1} + \beta_{4} \ln FOSSIL_{t-1} + \mu_{t}......(2) \end{split}$$

In equation 2 the short run relationship is represented by α_1 to α_4 whereas the long run relationship is presented by β_1 to β_4 and the drift component is α_0 . While n_i is the optimal lag and μ_t is the error term.

$$\Delta \ln LPI_{t} = \beta_{0} + \sum_{i=1}^{n_{1}} \beta_{1i} \Delta \ln GDPPC_{t-i} + \sum_{i=1}^{n_{2}} \beta_{2i} \Delta \ln FDI_{t-i} + \sum_{i=1}^{n_{3}} \beta_{3i} \Delta \ln TGHGE_{t-i} + \sum_{i=1}^{n_{4}} \beta_{4i} \Delta \ln FOSSIL_{t-i} + \theta ECM_{t-1} + \mu_{t}$$
 (3)

Co- integration among the variables was tested and then the error correction model was developed whereas θ is the speed of adjustment of the long run equilibrium.

Table 1: List of variables

Variables	Description
LPI	Logistics performance index(1=low to 5=high)
GDPPC	GDP per capita, PPP (constant 2017 international \$)
TGHGE	Total greenhouse gas emissions (kt of CO ₂)
FDI	Foreign direct investment, net inflows (% of GDP)
FOSSIL	Fossil fuel energy consumption (% of total)

Source: [World Bank Database, 2020]

As some variables were stationary at level and some at first difference, we found ARDL (autoregressive distribution lag) technique to be most appropriate for our research. Table 1 indicates the variable description where GDPPC, FDI represents the economic factor affecting LPI on the other hand TGHGE and FOSSIL are the factors affecting environment sustainability.

4. Results and discussion

Table 2: Illustrates the result of unit root test. Augmented Dickey Fuller (ADF) test was employed to check the stationarity at level and 1st difference. The results proved the stationarity of the dependent variable LPI at level whereas the independent variables were stationary at 1st difference. ARDL model allows having a mixture of variables at level and first difference, therefore, ARDL model is most appropriate for our study. Before applying ARDL co-integration, ARDL bound test is used to check the long run association between the dependent and independent variables. The bound test shows two critical values the upper bound and the lower bound where upper bound assumes all variables are at first difference and lower bound assumes that all variables are at level. If the value of upper bound is less than F statistic the null hypothesis is rejected showing the presence of co-integration vice-versa.

Table 2: ADF Unit Root test

Variables	level	level	1 st diff	1st diff
	t-statistics	Prob.	t-statistics	Prob.
LPI	-3.937927	0.0169	-4.092602	0.0156
GDPPC	-2.736086	0.2449	-4.064610	0.0531
TGHT	-2.555023	0.1324	-4.644740	0.0061
FOSSIL	-1.768203	0.3745	-3.162729	0.0539
FDI	-1.891757	0.3234	-4.761373	0.0052

Table 3:shows the results of ARDL bound test, the results indicates that there existence a significant co-integration between the dependent and the independent variables as F statistics is much greater than the upper bound statistic.

Table 3: Auto Regressive Distributed Lag bond test for co-integration

Variable	F statistics	Co-integration	
F(LPI,GDPPC,FDI,GHGE,FOSSIL)	23.16019***		
Critical value	1%	5%	10%
Lower bound	3.29	2.56	2.2
Upper bound	4.37	3.49	3.09

^{*}significant at 10% level, **significant at 5%, ***significant at 1%

Table 4: illustrates ARDL short run results where the findings indicates that total greenhouse gas emission (TGHGE) and FDI are significant and has positive correlation with LPI (0.07<0.1,0.25<0.05) whereas fossil fuel emission has a negative relation with the logistic performance and is significant at 5% (0.04<0.05). On the other hand GDP per capita is significant and have a negative relation with the LPI (0.02<0.05) indicating that government policies are not aligned with the logistic performance index in India.

Table 4: Auto Regressive Distributed Lag short-run estimates

Variables	Probability	t-statistic	Coefficient
GDPPC	0.0255*	-6.144854	-1.180468
FDI	0.0421**	4.720288	0.259092
TGHGE	0.0713*	3.540824	3.180970
FOSSIL	0.0650*	-3.727804	-2.924298

Note: Adjusted R² = 0.90 *significant at 10%, **significant at 5%, ***significant at 1%

Table 5: demonstrates long run result of ARDL, findings suggest that the value of F statistic is much greater than upper bound hence there exist a long run relationship at 5% level of significance between the dependent and independent variable. Total greenhouse gas emission (TGHGE) is statistically significant and is positively correlated with the logistic performance index which is a sign of concern for human health. On the other hand FDI is significant and have a positive impact on LPI performance in the long run. On the other hand Gross Domestic Product per capita (GDPPC) has a negative relation with the LPI performance and is significant in the long -run. This is mainly because government policies are notallied with logistic operations (World Bank, 2018). Lastly, in long-run Fossil fuel consumption has a negative relation with the logistic performance index, which has a positive sign for environmental sustainability.

Table 5: Auto Regressive Distributed Lag long-run estimates

Variables	Probability	t-statistic	Coefficient
GDPPC	0.0678*	-3.640979	-0.694821
FDI	0.0602*	3.888108	0.117010
TGHGE	0.0462**	4.488684	1.241758
FOSSIL	0.1064*	-2.422927	-1.096131

Note: Adjusted R² = 0.90 *significant at 10%, **significant at 5%, ***significant at 1%

Table 6: Illustrates the results of diagnostics test, we have used Jarque Bera test and results shows that residuals are normally distributed. In addition heteroscedasticity

Breusch – Pagan Godfrey test has been deployed to check where the data are homoscedastic or heteroskedastic the results indicates that the dataset is homoscedastic. Further Ramsey RESET test was employed and the result shows that the model is free from specification error. Lastly, Breush Godfrey serial correlation LM test revealed that there exists no serial correlation among the error terms in our model

Table 6: Daignostic tests

Jarque-Bera Normality Test, JB stat	0.6024	0.7399
Ramsey RESET test,Log likelihood ratio	61.2801	0.6646
Breusch-Godfery serial Correlation ,LM test	4.9906	0.5295
Heteroskedasticity Breusch-Pagan-Godfery	5.9676	0.6509
test, Obs R-squared		

Table 7 shows the results of Granger causality test. The test is used in time series data to assess whether there exits any potential predictability power from one variable to the other. The result indicates that there exists a unidirectional causality between LPI and FDI, FOSSIL and GDPPC, FDI and TGHDE and FOSSIL and FDI.

Table 7: Granger causality test

Direction of causality	F-statistics	probability
LPI-FDI	5.8833	0.0415*
FDI-TGHGE	4.3049	0.071**
FOSSIL-GDPPC	5.1398	0.053**
FOSSIL-FDI	4.6485	0.063**

Note: **significance at 10%,*significance at 5%

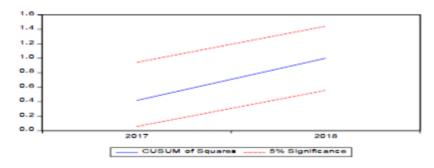


Figure 1: Cumulative sum of Square of recursive residuals

The model's stability was checked by cumulative sum of the recursive residuals stability test figure 1 suggest that model is stable. The findings reveal that foreign direct investment and total greenhouse emission are positively correlated with the logistic operation whereas fossil fuel consumption and GDP per capita have a negative relation.

5. Conclusion

The World Bank reports logistic performance index (LPI) at an interval of every two years. It is the weighted averages of six key dimensions i.e. speed of custom clearance process, quality of infrastructure related to trade and transport, ease of competitive price shipment, quality of logistic service, ability to track and trace consignments and expected delivery time of goods and services to destination. Logistic operation measures the relative ease and efficiency with which products can move inside a country, countries can compete globally by maintaining a good logistic as it would help to reduce the trade cost. The focus of this study is to find out is logistic performance index in India environmentally-economically sustainable during the period 2007-2018. To find the short run and long run relation among the dependent (LPI) and independent variables i.e. GDP per capita, FDI inflow (economic variable) and fossil fuel consumption, greenhouse gas emission (environmental variable) we employed ARDL technique. The findings confirmed that both in the short and long run foreign direct investments (FDI) are significant and are positively co-related with the LPI, which is a positive sign for the growth of an economy. Whereas Total greenhouse gas emission (TGHGE) is also significant and has a positive relation with the LPI, which is a sign of concern, as they are harmful for humanity and effect environment sustainability negatively, which is not the case in many other country like UK (Khan et al., 2017).GDP per capita being significant and having a negative relation highlights the ignorance from the government side. In the recent report India rank have slipped down from 35th to 44th position in the world LPI ranking were by all the six dimensions have fallen down (World Bank, 2018). This is mainly because of government policies are not primarily focus on logistic operations. With the ongoing expansion of the logistic industry government need to focus on efficient and effective policies in order to curb the pollution and waste generated by the logistic industries as countries like Germany, Sweden and Belgium are leading the list of logistic performance index whereby India lacks behind.

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