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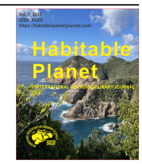

The Energy Trilemma: An overview of balancing security, sustainability, and affordability

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ABSTRACT

The global energy sector faces a complex challenge in balancing three critical dimensions: energy security, environmental sustainability, and economic affordability—commonly referred to as the energy trilemma. This paper provides a novel review of emerging trends, policies, and technological advancements that address this challenge. It particularly examines the role of top CO_2-emitting countries in navigating the energy trilemma, shedding light on their strategies and potential pathways for achieving a sustainable energy future. Findings demonstrate that these countries have achieved some success in their shift to cleaner energy systems, yet they maintain diverse approaches to policy frameworks, energy systems, and economic programs. Countries deal with specific obstacles because their economic systems combine with their energy reserves and climate agreement responsibilities. China and India remain the world's fastest-growing economies, but they must keep their economies expanding while reducing their coal dependence. The United States and Canada hold substantial fossil fuel reserves, yet they must establish a strategy that aligns their home energy security requirements with worldwide climate objectives. Renewable energy development remains vigorous in Germany and Japan, yet their progress is limited by high power costs, affecting their electrical grid stability. Countries with abundant resources, including Russia, Brazil, Indonesia, and Mexico, have not effectively incorporated sustainability into their plans for energy development. The findings underscore the need for integrated policies, increased investments in renewable energy, and international cooperation to achieve a balanced energy transition.

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Research Highlights

- Reviews global energy trilemma strategies.
- Analysis of top CO_2 emitters' energy policies.
- Highlights economic and resource challenges.
- Identifies barriers to renewable adoption.
- Calls for global cooperation in the energy transition.

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1 Introduction

One of the major focus of United Nations Sustainable Development Goals (SDGs) is on the role of energy transition, which is to encourage sustainability and resilience. SDG 7 (Affordable and Clean Energy) finds direct support through efforts that guarantee every person access to sustainable energy services and renewable energy dominance, combined with enhanced energy efficiency. The goal to fight climate change (SDG 13) requires the same urgency because moving past fossil fuels to low-carbon energy operations is crucial to reducing climate effects. The transition toward renewable energy stimulates the growth of green employment while generating new economic prospects within the renewable energy field, according to SDG 8 (Decent Work and Economic Growth). The advancement of SDG 9 (Industry, Innovation and Infrastructure) occurs through clean technology investments, which lead to the development of resilient energy infrastructure. Sustainable energy transition enables SDG 11 (Sustainable Cities and Communities) with its focus on efficient urban development that has reduced environmental pollution. Implementing sustainable energy goals leads to indirect advantages, such as better air quality under SDG 3 and SDG 12, which promote sustainable energy use practices. Total sustainable development gains can be maximized by recognizing interlocked connections between energy systems and various sustainable development goals.

The energy trilemma—the interdependent goals of energy security, environmental sustainability, and economic affordability—represents one of the most pressing challenges in contemporary energy policy (Zhao et al., 2024). The uninterrupted supply of affordable energy resources forms the basis of economic stability and national sovereignty (Shirazi, 2025). The urgent need for environmental sustainability requires swift changes away from pollutants in the power sector, which supports worldwide Paris Agreement goals (CarbonBrief, 2013). The performance of energy transitions depends on economic affordability to prevent the growth of social inequality and maintain industrial viability (Khan et al., 2022). The trade-offs and collaborative effects between sustainability and sovereignty goals become central issues for nations toward their mid-century net-zero emissions targets, which demand policy adjustments based on unique geopolitical situations and socioeconomic requirements.

Energy decision-making previously used the energy trilemma model, but is now a fundamental tool for evaluating worldwide energy transition intricacies (Song et al., 2023). Studies have shown that improving one energy system's benefit usually adversely affects other sector variables. Renewable energy excellence leads to power stability disruptions from intermittent supply, while fossil fuel price subsidies destroy pollution reduction results (Grigoryev and Medzhidova, 2020). New scientific discoveries reveal combined advantages between energy efficiency strategies that cut operating expenses and pollution levels. The four leading carbon dioxide polluting areas, led by China and the United States, together with India and the European Union, emit more than 60% of total planet-wide greenhouse gas emissions. China fights industrialization and is reliant on coal. At the same time, the U.S. battles political fragmentation and shale gas development. India must address both energy access needs and clean energy growth, and the European Union drives aggressive decarbonization through regulations (Khan et al., 2022).

This research examines strategies for leading carbon emitters to handle the energy trilemma challenges while transitioning toward net-zero objectives. This research examines energy trade-offs through national policy analysis and evaluation of technological progress and economic systems to describe synergy exploitation mechanisms. The Chinese state supports renewable energy investments while concurrently using coal, but the European Union's Green Deal demonstrates complete integration between sustainability and security goals. This study draws upon case studies to create new research about energy transitions, providing decision-making help for policymakers working with trade-offs. This research eliminates the current understanding gap between efforts for global decarbonization and the successful resolution of trilemma tensions to create sustainable energy systems.

Throughout the past twenty years, research has accumulated to study how changes in energy systems affect both environmental results and economic system equilibrium. Scientific investigations demonstrate how energy transition develops into a major force behind lowering greenhouse gas emissions while producing better air quality. Based on panel data investigations across different countries (IRENA, 2020; Ivanovski et al., 2020). The link between renewable energy consumption and CO_2 emissions shows a specific negative relation that proves climate change mitigation and long-term sustainability. The economic world now recognizes energy transition as a force that drives innovative activities while boosting employment opportunities and developing eco-friendly economic growth. Various scientific investigations (Aye and Edoja, 2017; Sarkodie and Strezov, 2019) have proven that renewable energy deployment builds economic stability by developing new sectors and job markets, particularly for countries prioritizing investments in clean technology systems. Nationwide energy markets become more stable because the energy transition delivers better energy efficiency and protects economies from erratic fossil fuel price fluctuations. The process of energy transition functions as both a necessary environmental solution and a key factor driving sustainable economic development.

Variable	Variable name	Unit of measurement	Definition	Data source
FM	Fuel Imports	% of merchandise imports	The share of fuel imports in total merchandise imports.	WDI
CO_2	CO_2 Emissions from Power Industry	Mt CO_2e	Carbon dioxide emissions from energy-related activities in the power industry.	WDI
REC	Renewable Energy Consumption	% of total final energy consumption	The proportion of renewable energy in total final energy consumption.	WDI
GDPE	GDP per Unit of Energy Use	PPP $ per kg of oil equivalent	Economic output generated per unit of energy used.	WDI
ENI	Energy Intensity Level of Primary Energy	MJ/$2017 PPP GDP	Energy use per unit of GDP, measured in megajoules per constant 2017 PPP dollars.	WDI
AE	Access to Electricity (Rural)	% of rural population	The percentage of the rural population with access to electricity.	WDI

Table 1. Summary of the key variables used.

Energy security, a closely related concept, is equally central to contemporary policy and academic discourse. Defined as the uninterrupted availability of energy sources at an affordable price, energy security has both short-term and long-term dimensions. Empirical research has emphasized its role in supporting economic performance and minimizing exposure to geopolitical risks and supply disruptions. For example, studies such as Behera et al. (2024), Payne et al. (2023) have developed quantitative indices to measure energy security and its economic implications, finding that countries with diversified energy portfolios and strong investments in domestic energy resources tend to exhibit greater macroeconomic stability and resilience. In addition, empirical evidence points to important synergies between energy security and environmental sustainability. Research shows that efforts to enhance energy security, such as increasing the share of renewables, improving energy storage capabilities, and modernizing grid infrastructure, often result in environmental co-benefits, including reduced emissions and improved resource efficiency (Amin et al., 2022; Karatayev and Hall, 2020). These dual benefits reinforce the notion that energy security and transition should not be treated as competing objectives but as mutually reinforcing goals vital for sustainable development. The alignment of these strategies with the United Nations Sustainable Development Goals (particularly SDGs 7, 8, 9, and 13) further underscores their significance.

This paper presents the first comprehensive review article focusing on the energy trilemma—the complex interplay between energy security, environmental sustainability, and energy equity—across diverse national contexts. This study's main breakthrough resides in examining strategies and policies with which leading global energy consumers and CO_2 producers mitigate the energy trilemma across various levels of technological implementation. The current research integrates an inclusive analytical method that surpasses prior studies focusing on individual energy aspects since it identifies operational connections and conflicts between trilemma elements. A new theoretical framework appears in this paper, which helps assess national energy plans concerning their ability to deal with conflicting policy demands. The study combines nation-specific transition pathways to demonstrate best practices while examining upcoming policy directions with the potential to direct sustainable and equitable energy transitions. The authors have added significant value to the literature through their cross-multinational study, which creates the basis for future policy research and empirical assessments in this field.

2 The energy trilemma dimensions

Key variables used in this study are summarized in Table 1, sourced from the World Development Indicators (WDI). These include indicators such as fuel imports (FM), CO_2 emissions from the power sector (CO_2), renewable energy consumption (REC), and GDP per unit of energy use (GDPE), which capture critical dimensions of the energy trilemma—security, sustainability, and affordability.

Energy security, environmental sustainability, and economic affordability are complex challenges for China, the United States, India, Russia, Japan, Brazil, Germany, Indonesia, Canada, and Mexico in their top CO_2-emitting categories. Analysis of the figures in this study unveils comprehensive knowledge regarding how countries handle the trade-off between their energy needs and economic development alongside environmental stewardship.

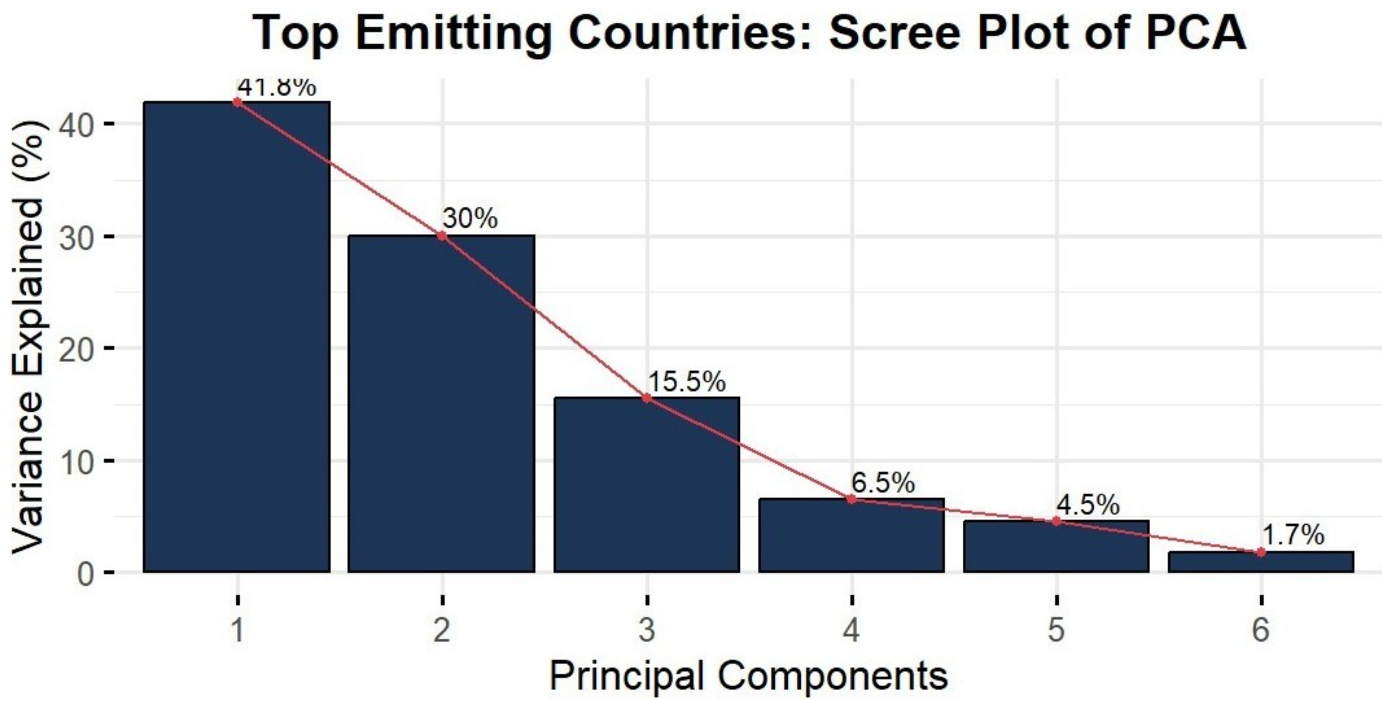

Fig. 1. Top Emitting Countries: Scree Plot of PCA.

The first principal component obtained from Principal Component Analysis (PCA) displays a 41.8% variance explanation in Fig. 1, demonstrating its capability to identify major energy-related determining factors in these countries. A significant part of the energy trilemma originates from several essential economic and energy indicators, including energy intensity, renewable energy consumption, and CO_2 emissions. The intense industrial activities of China and India cause these nations to display strong associations with the initial component because they rely heavily on coal power. Germany and Canada demonstrate a wide distribution of energy variances across various sectors because they maintain diverse power generation systems based on renewable sources.

The factor loadings in Fig. 2 demonstrate that fuel imports positively correlate with CO_2 emissions, renewable energy consumption, GDP per unit energy use, energy intensity, and electricity access levels. Renewable energy consumption shows a powerful negative link with CO_2 emissions because it works as an effective method to reduce environmental damage. Brazil and Canada lead the way with hydroelectric production since they derive substantial power from hydroelectric facilities, resulting in lower emissions rates. Despite their dependence on fossil fuels, Russia and Indonesia display strong relationships between energy intensity and CO_2 emissions. The variable for access to electricity shows a positive correlation with economic efficiency because countries that provide power to all citizens tend to maintain cheaper and more reliable power grid systems, such as those found in the United States and Germany, and Japan.

The top CO_2-emitting countries are shown in Fig. 3 through a ternary diagram displaying their relationships between fuel imports, CO_2 emissions, and renewable energy consumption. The graph illustrates the deciding factors that nations must manage when pursuing a balance between resources, sustainability standards, and economic costs. China and India maintain low positions regarding fuel imports but occupy elevated positions regarding CO_2 emissions because they depend heavily on carbon-intensive energy sources. Japan and Germany import considerable energy but excel at reducing their emissions through increased renewable energy use due to their energy security concerns. With its vast hydropower resources, Brazil stands out for its high renewable energy consumption and relatively low emissions. The different policies and resources indicate how nations handle their energy trilemma through frameworks matching resource availability.

The quantitative measure of energy-related variable relationships can be seen in Fig. 4, where correlation coefficients have been displayed. The data shows a direct negative relationship between renewable energy use and CO_2 emissions, thus proving clean power transitions are essential for reducing environmental impact. Countries that use renewables enjoy higher economic efficiencies, as indicated by their positive relationship with energy-use-based GDP. Energy intensity shows a negative relationship with GDP efficiency, which reveals that China and India, among

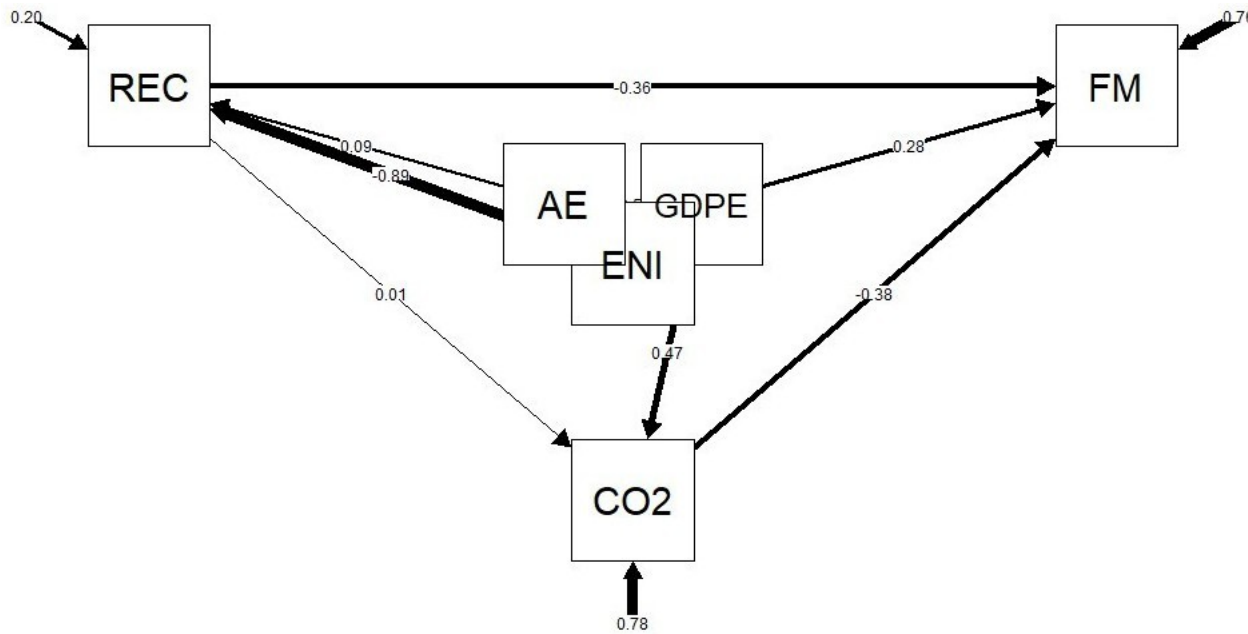

Fig. 2. Network Analysis Trilemma Triangle.

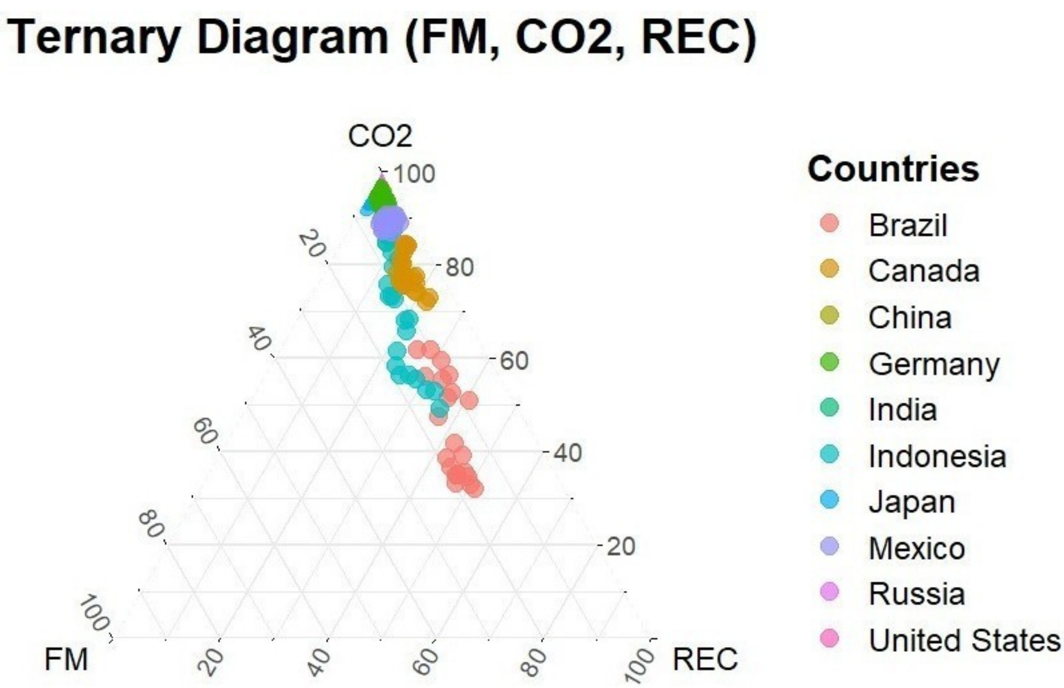

Fig. 3. Energy Ternay Diagram.

other nations, experience difficulties with energy efficiency because their output requires high energy usage. The availability of electricity positively affects various economic measures because it enables infrastructure developments that drive industrial progress and enhance the overall standard of living.

The extremely strong negative correlation value of -0.89 between GDP per unit of energy use (GDPE) and energy intensity shows that growing economies become more efficient in their energy use because of technological progress and structural changes in their economic makeup. A transition from fossil fuels seems likely to

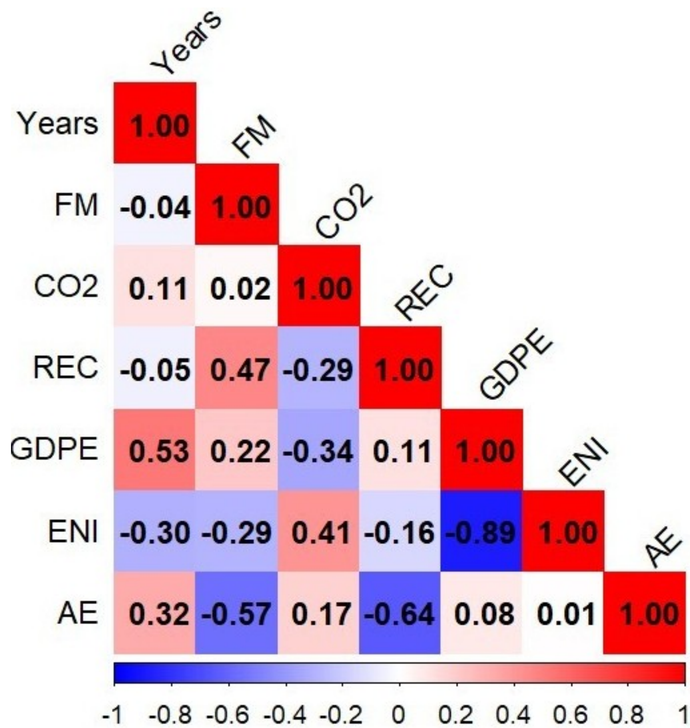

Fig. 4. Correlation Heatmap.

create widespread access to electricity alongside alternative energy sources since their relationship shows a negative correlation of −0.57. The data shows a somewhat negative association between renewable energy consumption, amounting to −0.64, which might indicate how well-developed countries' energy infrastructure has become. Results show an interesting trend where inefficient energy use leads to environmental degradation because the two factors display a similar 0.41 correlation level. Energy transitions are directly related to sustainable development since economic growth rose 0.53 while alternative energy access climbed 0.32 throughout this period. The research confirms the necessity for adapted energy policies to enhance efficiency measures while building new renewable energy facilities and simultaneously protecting the environment.

The Fig. 5 radar chart analyzes CO_2 emission levels of leading countries through their representation across various energy trilemma aspects. The chart delivers an overall evaluation of nation-to-nation performance for these nations. The United States and Germany balance energy security needs through renewable installation and affordable energy management systems. China and India overcome their affordable energy prices by confronting major environmental sustainability issues because of their ongoing coal utilization. The position of Russia as a top fossil fuel producer supports its secure energy situation, yet its insufficient development of renewable energy persists. Hydropower strengthens the energy sustainability of Brazil and Canada, yet they need to increase their energy security through diversified power sources. Sustainable solutions require nations to choose between affordability and environmental sustainability when developing their energy combinations.

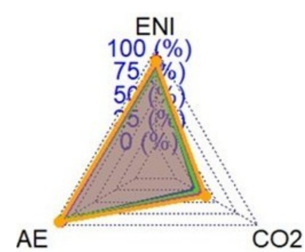

Fig. 5. Energy Trilemma Radar Chart in Top Emitting Countries.

Fig. 6 creates a ternary plot to visualize nation-state positions regarding the energy trilemma, which combines energy security with environmental sustainability and economic affordability. The analysis shows Russia, India, and China form a group that emphasizes economic affordability in their energy policies. At the same time, Germany, Japan, and the United States strive for secure sustainable energy solutions, and Brazil and Canada demonstrate a strong commitment to renewable energy development.

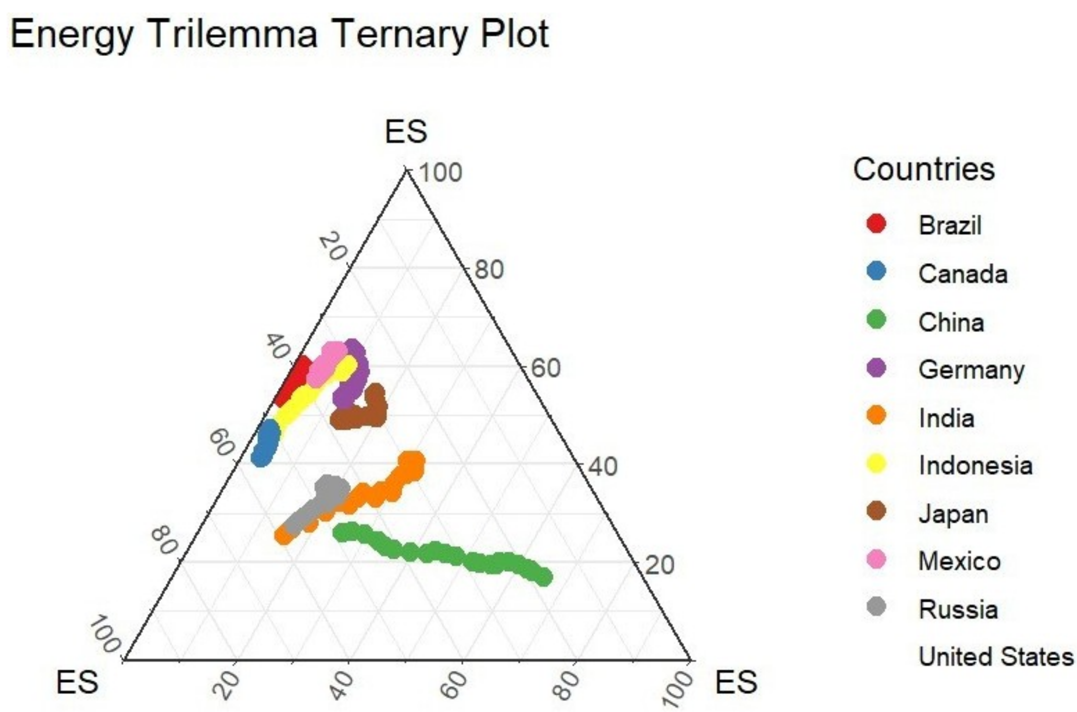

Fig. 6. Individual Cross-sections Energy Trilemma Ternary Plots.

The positioning of nations in the ternary plot requires separate policy strategies for each sector. China and India must speed up their shift toward ecological power generation methods while keeping costs reasonable. In contrast, Japan and Germany must improve their energy defense by combining imported resources with new power sources. Brazil and Canada should utilize renewable resources to create dual benefits of sustainable leadership and economic stability from energy exports.

3 Top CO_2-emitting countries and their energy strategies

Global energy patterns derive from operating the largest carbon dioxide-emitting facilities worldwide. This section examines major nations' energy policies and strategies for achieving equilibrium between the three components of the energy dilemma. Fig. 7 displays how top-emitting nations show differences in emissions patterns and cluster groupings of primary factors affecting their energy policies.

The massive CO_2 emissions from China stem from its fast industrial growth and its heavy use of coal. Although it retains the title of coal's global production leader and consumer, China continues to pursue multipurpose energy transformation through diverse power generation methods. Solar and wind power represent significant investments from the country, and its renewable energy installations rank as the highest in the world. The Chinese government aims to achieve complete carbon neutrality by 2060 and decrease dependence on coal by implementing the emissions trading scheme and renewable energy subsidy policies (World Energy Council, 2020a). Efficient integration of renewable energy sectors into distribution systems has to overcome existing barriers to provide reliable power to an expanding economy.

The United States depends on multiple energy sources, including natural gas, renewable-based, and nuclear power resources. Natural gas and renewable energy sources have replaced coal as primary energy sources, while coal consumption has decreased in recent years in the United States. Through the Inflation Reduction Act, authorities have quickened funding allocations for clean energy and electric transportation systems. The society faces ongoing difficulties in achieving sustainable targets while trying to maintain its previous dependence on fossil fuels. State-level policy variations, market dynamics, and political changes make the shift to clean energy more difficult since they both increase energy costs and reduce long-term security (World Energy Council, 2019).

The Indian energy strategy adopts renewable energy growth parallel to resolving power system deficiency issues. The country established the National Solar Mission to pursue leadership in global solar energy generation through its set targets. India still depends heavily on coal power generation because it supplies more than 70% of its electricity needs, even while making energy development

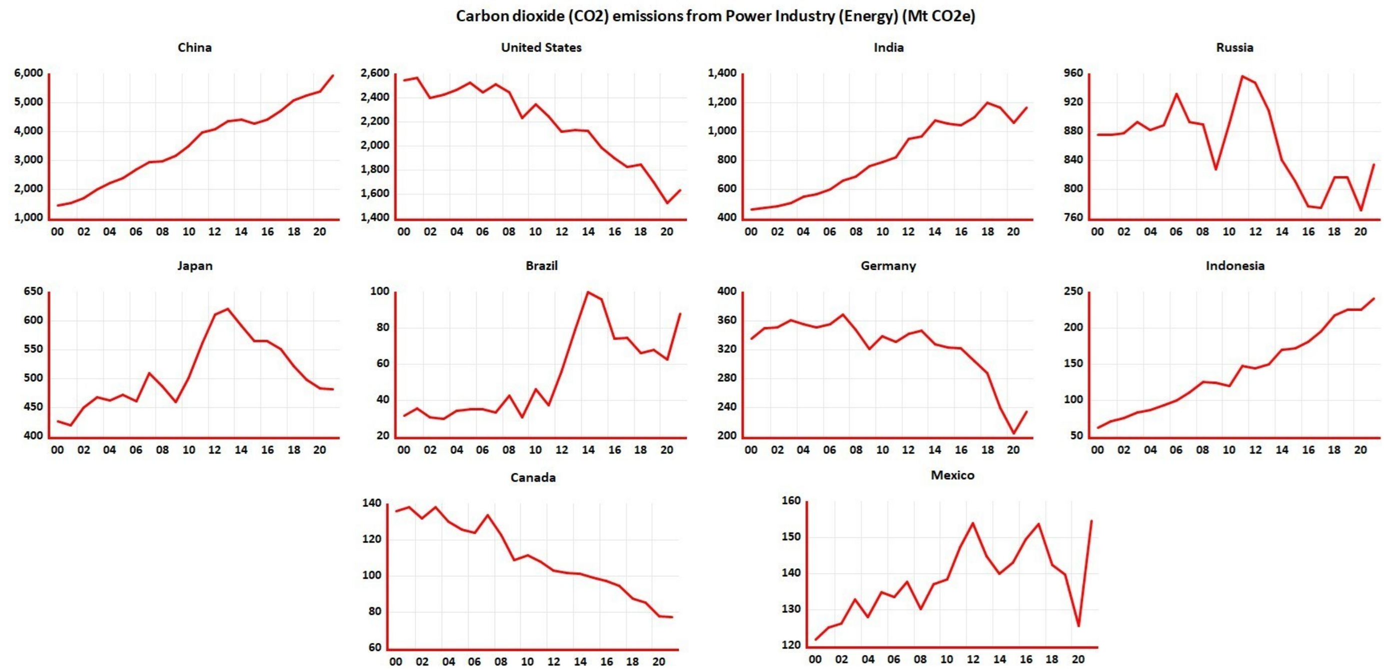

Fig. 7. CO_2 emissions from Power Industry (Energy) (Mt CO_2e).

efforts. Balancing economic progress, energy safety, and environmental responsibilities is the main difficulty. Energy demand increases dramatically as India experiences rapid urbanization, requiring policymakers to strike the proper balance between sustainable practices and affordable energy delivery (Rej and Nag, 2021).

Due to Russia's firm reliance on exporting fossil fuels, the nation places energy security at the forefront of its key policies. Local renewable energy adoption remains sluggish while the nation invests funds into nuclear power and carbon capture technologies to reduce greenhouse gas emissions. Russia's energy policy receives guidance from geopolitical elements because it maintains robust market positions worldwide in petroleum and natural gas business operations. Russia faces barriers to energy transformation because its economy depends on fossil fuels, and there are few economic advantages to implementing expansive renewable energy projects (Grigoryev and Medzhidova, 2020).

The Fukushima disaster triggered Japan to choose energy efficiency and technological advancement as key elements for its energy policy framework. Hydrogen energy and offshore wind power have received national investment from the country alongside the continued importance of nuclear power for long-term strategic goals. The Japanese energy policy aims to lower dependency on foreign fossil fuel imports by providing sustainable power provision at competitive rates. The transition to sustainable energy systems meets two main obstacles because it must counter the support against nuclear power while managing the price tag associated with changing energy sources (World Energy Council, 2020b).

Brazil has achieved a world-leading position in electricity sector cleanliness because the nation primarily generates power through hydropower and biofuel technologies. The massive use of hydroelectric power generation in Brazil has reached more than 60% of its power production capacity, thus minimizing Brazil's need for fossil-based energy. The sustainability initiatives of Brazil face ongoing resistance because of environmental problems, including ecosystem destruction and greenhouse gas production from agricultural sources. The country demonstrates expanded interest in broadening its power sources through new investments in wind and solar power generation (Baloch et al., 2020).

The world acknowledges Germany as an industry leader in renewable energy, specializing in wind power and solar technology. Energiewende policy enables the country to increase investments in clean energy and eliminate nuclear power capabilities. Germany's energy transition has produced enhanced coal and natural gas imports because of geopolitical conflicts threatening energy stability. Germany must balance its renewable energy leadership with affordable electricity costs and secure electricity supply despite supply-demand fluctuations (Oliver, 2015).

Indonesia's power production heavily relies on coal, and domestic coal reserves maintain fundamental positions for energy protection. Indonesia faces delays in its transition to renewable energy sources even though the government approved the Energy Transition Roadmap and signed international climate agreements. Developing an environmentally friendly energy mix faces strong resistance from fossil fuel subsidies from the government and the limited availability of renewable energy funding (Chi et al., 2023).

Hydroelectric resources stretch across Canada, which results in its electricity sector being one of the least carbon-dense power grids in leading countries. The power generation across Quebec and British Columbia primarily depends on hydroelectric power, which helps the provinces decrease their dependence on fossil fuels. Current debates exist between determining enough oil and gas supply while preserving climate commitments because Canada is an active producer of these resources. The nation's energy direction toward the future depends heavily on adopting policies with carbon prices and emission reduction goals while investing in clean technologies (Shirazi, 2025).

Mexican governments have implemented policies for expanding fossil fuels and supporting renewable energy development as political changes happen in administrative positions. The drive for cleaner sources of energy becomes evident through recent investments in solar and wind technology, but grid infrastructure integration and policy stability present obstacles to full implementation. The extent of state control over energy firms and private sector participation in the energy market defines the current energy rules in Mexico (Oliver, 2021).

4 Policy innovations and technology trends

Modern policies and upcoming technologies shape the future of the energy sector in countries that produce the highest levels of CO_2 emissions globally. The sustainability goals rely heavily on three major initiatives: carbon pricing schemes, energy storage systems, and technological advancements in renewable energy infrastructure.

The Chinese government established Emissions Trading Systems (ETS) while introducing the world's biggest carbon market in 2021 (China_Power, 2020). The country directs substantial financial resources toward solar photovoltaics (PV), wind energy, and other renewable energy technologies (China_Power, 2020). The integration of modern power grids and battery storage systems, together with advancing hydrogen technologies, helps industrial facilities reduce their carbon footprint (Dong et al., 2018).

Through the Inflation Reduction Act (IRA), the United States offers financial benefits for the adoption of renewable electric vehicle (EV) systems and the deployment of carbon capture technology (Bai et al., 2021). Emission reduction happens through carbon pricing systems established by individual states, with the California Cap-and-Trade Program being one example (Södersten et al., 2018). Smart grids, energy-efficient buildings, and direct air capture (DAC) are leading technology drivers advancing sustainability.

India has established Renewable Energy Targets that mandate developing 500 GW worth of non-fossil fuel capacity during the 2030 period (Chopra et al., 2022). The National Hydrogen Mission works to create green hydrogen methods simultaneously with policies to speed up renewable energy expansion by installing solar parks and wind farms and building battery storage facilities (Cai et al., 2022). The Perform Achieve Trade (PAT) scheme established by India is an industrial energy efficiency program.

Russia has chosen carbon capture utilization storage (CCUS) technologies to reduce carbon emissions from its heavy industrial sectors (International Energy Agency, 2021). The energy sector mainly relies on fossil fuels, but the government is advancing initiatives to boost nuclear energy capability alongside developing hydrogen production installations. Forest carbon capture projects are one of the government's strategies to reduce carbon emissions.

Japan has implemented green innovation approaches by selecting power plants and co-firing hydrogen and ammonia as its main focus (Ohta and Barrett, 2023). Hassan et al. (2024) identify the country as a technology leader for renewable grid systems and energy storage infrastructure. The Green Growth Strategy includes the development of future batteries and floating offshore wind generation alongside advanced nuclear reactor technologies.

According to BioEnergyConsult (2019), bioenergy operations in Brazil, including ethanol production and biodiesel manufacturing, demonstrate substantial capabilities to decrease emissions. Through the RenovaBio Program, Brazil promotes decarbonization by establishing a trading system for biofuel credits, as described by Tiburcio et al. (2023). Sustainable energy development receives support from hydrogen power generation, wind power production, and improved battery storage systems (Meng et al., 2021).

Germany's Energiewende (Energy Transition) policy strives to eliminate coal usage while increasing the size of renewable energy generation (World, 2019). Solar and wind power projects gain investment support through feed-in tariffs and carbon pricing (Bompard et al., 2022). The national initiative includes advanced research projects on hydrogen energy and VPPs that enhance power grid flexibility.

The Indonesian government invests in its Geothermal Energy Development Plan by developing plentiful geothermal resources (Unwin, 2019). The power sector decarbonization strategy includes the carbon tax policy, which parallels solar PV expansion initiatives. The development of palm oil biodiesel represents one strategy that helps reduce fossil fuel consumption (Yaqoob et al., 2021).

Canada's main initiatives include nationwide carbon pricing policies and hydrogen fuel investments. The country is developing its clean energy transition through investments in small modular nuclear reactors (SMRs), carbon capture, and energy storage technology (Zhao et al., 2024). The Clean Fuel Standard is another policy instrument that strengthens emissions reduction.

According to Mejía-Montero et al. (2020), Mexico is developing its renewable energy capabilities by focusing on solar and wind power systems. Through the Energy Transition Law, the country promotes energy efficiency and upgrades its power distribution networks (Stefano, 2000). Presently, the government extends support to reduce natural gas emissions and expand geothermal capabilities.

These leading carbon emitter nations are implementing modernizing changes in their energy policies through technological innovations that modify the worldwide energy platforms. The run-up of carbon pricing methods combines energy storage development, renewable power sources, and hydrogen technologies to reduce emissions while sustaining energy safety and economic growth. The global path toward sustainability advances thanks to technological breakthroughs and regulatory instruments because these nations remain dedicated to innovative solutions (World Energy Council, 2021).

5 Challenges and future directions

Challenging conditions persist for reaching an ideal energy trilemma outcome that combines maximum security with environmental protection while promoting equal access to power. Many nations face difficulties when they try to integrate renewable power generation with established power infrastructure systems while managing renewable energy supply uncertainties, which affect affordability for general customers. Emerging economies face two obstacles to the large-scale adoption of clean technologies: financial limitations and inconsistent policy implementation practices. The supply chains that transport critical energy components like lithium, rare earth elements, and hydrogen infrastructure face significant uncertainty due to geopolitical risks, trade barriers, and raw material shortages.

International energy initiatives should unite forces while businesses must commit more resources to clean energy development and strategic policy formation to boost the renewable transition. The IEA (2023) stresses that bridging the energy divide needs international carbon market frameworks to become more substantial and new agreements for energy trade between countries and advanced climate financing systems. The development of next-generation battery technologies and artificial intelligence and breakthroughs in nuclear fusion research point toward solutions that can overcome existing technical barriers. Global nations must build innovation and collaboration to develop a low-carbon energy structure that overcomes economic and social obstacles in worldwide energy progress.

6 Conclusion

Worldwide energy management handles three essential challenges: safeguarding energy supplies, maintaining environmental stewardship, and managing affordable market costs. Research has studied how top carbon dioxide polluters in China, the U.S., India, Russia, Japan, Brazil, Germany, Indonesia, Canada, and Mexico cope with the energy trilemma. Research demonstrates that countries have achieved some success in their shift to cleaner energy systems, yet they maintain diverse approaches to policy frameworks, energy systems, and economic programs. Countries deal with specific obstacles because their economic systems combine with their energy reserves and climate agreement responsibilities. China and India remain the world's biggest growing economies, but they must keep their economies expanding while reducing their coal dependence. The United States and Canada hold substantial fossil fuel reserves, yet they must establish a strategy that aligns their home energy security requirements with worldwide climate objectives. Renewable energy development remains vigorous in Germany and Japan, yet their progress is limited by high power costs, affecting their electrical grid stability. Countries with abundant resources, including Russia, Brazil, Indonesia, and Mexico, have not effectively incorporated sustainability into their plans for energy development.

Several unified energy development patterns have emerged despite varying governmental energy approaches. The rapid growth of renewable energy occurs everywhere within major economies, yet these countries predominantly rely on fossil fuels for their energy supply. Energy efficiency improvements have become more prevalent, yet industrial and transport sector demands remain elevated, especially among countries such as India and Indonesia, which are experiencing rapid economic development. Deploying carbon capture, smart grids, and hydrogen energy systems faces substantial barriers due to their expensive development costs. Progressive policy structures emerge while regulatory ambiguities and geopolitical threats maintain influence over energy cost and safety standards. The absence of enhanced global cooperation and dedicated pledges will maintain risks toward enduring energy equilibrium because of trade-offs between energy safety, sustainability, and affordability.

Research results demonstrate that energy trilemma equilibrium needs customized national approaches that align with national targets, resource availability, and developmental points. Energy policy in China and India needs to move beyond basic energy demand fulfillment because these nations face growing energy needs. Hence, they require the swift implementation of renewable infrastructure because this reduces carbon intensity and assures steady power supplies. America should advance energy equity through clean energy expansion in underprivileged areas and invest in carbon capture technology development and new-generation nuclear resource exploration. Advanced renewable sectors in Germany and Japan need to work on combining grids and establish hydrogen programs while coordinating energy exchange across borders to retain electricity security through decarbonization. Resource-rich nations such as Russia and Indonesia must adapt their energy policies through two primary measures, which include developing alternative energy sources while reducing fossil-based consumption patterns and financing research and development for clean technologies. At a pan-national level, all countries must fuel sustainable energy transformations by funding eco-friendly technologies, rigorous regulation enforcement, and multinational partnerships.

Top-emitting countries should establish complete policies to unite economic progress with environmental safeguards in their energy management. India, China, and Indonesia require immediate investments to build solar power facilities, wind power plants, and hydroelectric power sources to reduce their reliance on coal power. During this period, the U.S. and Canada must use natural gas as an intelligent transition fuel to create clean energy infrastructure. Enhanced carbon pricing regulations should become a priority in Germany and Japan since they need to improve their carbon taxation strategies to achieve efficiency goals without causing financial hardship for consumers. Russia, Brazil, and Mexico's governments need to develop more severe emissions control measures to drive their industrial operations and transportation systems toward cleaner operations. The deployment of energy storage systems, hydrogen technologies, and carbon capture operations should receive top funding from China and the U.S. as emerging economies need to collaborate for green technologies through financing and technology-sharing programs.

The successful development of power distribution systems through grid modernization and improvements in energy efficiency drives balanced progress in energy transformation. Japan, Germany, and Canada need better systems for stabilizing their power grids and improved storage capabilities to effectively handle variable renewable energy sources. At the same time, India and Brazil must expand their smart grid infrastructure to optimize their energy availability and efficiency. The solution to the energy trilemma requires significant international partnerships to achieve successful results. Clean energy adoption will speed up through enhanced research partnerships and energy trade relationships, and developed countries must offer financial aid to build economies and establish sustainable infrastructure.

A sustainable energy future, security requirements, and affordable costs require wise policy decisions, advanced technologies, and worldwide partnership efforts. Achieving an energy trilemma balance requires combined action from countries and extended planning, although countries maintain their unique challenges. Leading CO_2-emitting countries are responsible for developing policies that will promote sustainable development while protecting energy systems' economic stability and reliability.

Hydrogen energy is becoming pivotal to worldwide energy transformation, yet it remains essential to study future energy routes. Green hydrogen produced through the electrolysis of renewable electricity brings an attractive opportunity to replace fossil fuels within hard-to-decarbonize industrial operations and transportation sectors. To achieve their net-zero objectives, multiple countries now understand hydrogen to function as an adaptable energy carrier, strengthening intermittent renewable tools and providing grid flexibility alongside extensive storage capability. Multiple countries understand hydrogen's strategic role, so they have included it in national energy transition strategies while directing funds for building hydrogen projects and advancing production systems and international trade frameworks. The development of hydrogen energy will focus on minimizing costs through technological breakthroughs and the development of international hydrogen markets. Green hydrogen will gain pricing competitiveness in future decades due to improved electrolyze performance while utilizing greater production capabilities and reduced renewable energy rates. Several international alliances currently pursue standardizing hydrogen certification systems to enable the creation of international hydrogen supply chains, particularly in resource-rich areas. The European Union, Japan, Australia, and multiple Middle Eastern countries engage in green hydrogen project investments toward their future decarbonization plans.

The usage of hydrogen serves two critical purposes in securing energy resources because it creates different energy sources and minimises reliance on foreign fossil fuel imports. The generation, storage, and transportation of hydrogen takes place at local levels, which boosts energy infrastructure flexibility and resilience. The integration of hydrogen technologies into present energy systems enables the quick advancement of sector coupling mechanisms, which unite the power system with transport and heating networks. Hydrogen supports emission reduction efforts, sustainable energy transformation strategies, and the implementation of diverse energy sources. The increasing importance of hydrogen energy makes its addition to energy transition discussions yield essential guidelines about future policy decisions and potential directions. The study demonstrates that new technologies should merge with current energy planning techniques to support creating a sustainable and resilient low-carbon energy system.

Declaration of competing interest

The author states that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The author is an Associate Editor of this journal and was not involved in the editorial review or the decision to publish this article.

Credit author statement

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