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The energy trilemma: Balancing security, sustainability and affordability in a fragmented world

Mohammed Lawal Giwah [1, *], Ehizele Dean Okoduwa [1] and Abidemi Aina [2]

[1] *Yale School of Management, Yale University, New Haven, Connecticut, USA.*
[2] *School of Computer, Mathematical and Natural Sciences, Morgan State University, Baltimore, Maryland, USA.*

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Abstract

The global energy sector faces an unprecedented challenge in balancing the three competing demands of the Energy Trilemma viz; security, sustainability, and affordability within an increasingly fragmented geopolitical and economic landscape. As nations strive to ensure energy security amid supply chain disruptions, shifting alliances, and resource nationalism, the simultaneous urgency of transitioning to sustainable, low-carbon energy systems presents economic and technological challenges. The affordability of energy remains a pressing concern, particularly for developing economies and vulnerable populations, as rising costs and market volatility threaten equitable access. This research critically examines the winding trade-offs and interdependencies among these three pillars, assessing the impact of geopolitical fragmentation, regulatory uncertainties, and financial constraints on global energy governance. Through an analysis of regional strategies, the study evaluates how developed economies, emerging markets, and resource-rich nations are responding to the trilemma. Additionally, it explores the role of technological innovations such as smart grids, carbon capture, and hydrogen economies in mitigating conflicts between energy security and sustainability while maintaining economic viability. The study further investigates the policy instruments and market mechanisms that can drive an integrated and resilient energy transition. Drawing on global case studies and empirical data, the paper proposes strategic policy recommendations for governments, industry leaders, and multilateral institutions to navigate the evolving energy landscape.

Keywords: Energy Trilemma; Energy Security; Sustainability; Affordability; Fragmentation; Green House

1. Introduction

The global energy sector is at a crossroads, facing an involute challenge known as the Energy Trilemma, which is the need to balance energy security, environmental sustainability, and economic affordability [1]. This trilemma has become more pressing in an era marked by heightened geopolitical tensions, economic instability, and the urgent need for a transition to cleaner energy sources. Governments, industries, and international bodies are grappling with how to ensure a reliable and uninterrupted energy supply while minimizing environmental impact and maintaining economic viability. However, achieving this delicate balance is increasingly complicated by global fragmentation, where political divisions, economic disparities, and uneven technological advancements hinder cohesive action [2].

Energy security, a fundamental pillar of the trilemma, has come under strain due to supply chain disruptions, resource nationalism, and conflicts that threaten the stability of global energy markets. The 2022 Russia-Ukraine war, for example, exposed the vulnerabilities of energy-dependent economies and reinforced the risks of over-reliance on single-source energy supplies [3]. In response, many nations have sought to strengthen their energy security through diversification strategies, increased domestic production, and investments in alternative energy sources. However,

* Corresponding author: Mohammed Lawal Giwah

these efforts often come at the cost of environmental sustainability, as some countries revert to fossil fuels to mitigate immediate risks. Meanwhile, the urgency of climate change demands a shift to low-carbon and renewable energy sources, yet this transition is neither straightforward nor universally affordable [4]. Developing nations, in particular, face significant financial and infrastructural barriers in their quest for sustainable energy solutions.

Affordability remains a crucial concern, as energy price volatility and inflationary pressures threaten economic stability and social equity. The rising costs associated with clean energy investments, infrastructure overhauls, and carbon pricing policies have raised questions about how to balance long-term sustainability with short-term economic realities. In many parts of the world, the transition to cleaner energy is slowed by financial constraints, making energy access a privilege rather than a universal right [5]. Without targeted policies and financing mechanisms, the gap between energy-rich and energy-poor nations will continue to widen, exacerbating global energy inequality.

In this increasingly fragmented world, political, economic, and technological divisions complicate the resolution of the energy trilemma. Political fragmentation, characterized by growing nationalism, weakened multilateral cooperation, and shifting geopolitical alliances has impeded collective action on energy governance and climate policies. Economic fragmentation, fuelled by disparities in financial resources and development priorities, has led to uneven progress in clean energy transitions, with wealthier nations accelerating their decarbonization efforts while poorer regions struggle with outdated infrastructure. Technological fragmentation further deepens the divide, as some countries lead in energy innovation, while others lack the expertise and resources to deploy advanced energy solutions at scale [6, 7, 8].

Given these complexities, this research seeks to critically examine the energy trilemma within the context of a fragmented world, analyzing the challenges and trade-offs involved in balancing energy security, sustainability, and affordability. By exploring global case studies, policy responses, and technological innovations, the study aims to provide strategic insights into how nations can navigate these competing demands. The findings of this research will offer valuable recommendations for policymakers, industry leaders, and international organizations in their pursuit of a resilient, equitable, and sustainable energy future.

2. Conceptualizing the energy trilemma

The Energy Trilemma encapsulates the challenges of harmonizing three pivotal objectives: energy security, environmental sustainability, and economic affordability. These pillars are deeply interwoven, and efforts to enhance one often influence the others, necessitating a comprehensive approach to energy policy.

2.1. Energy Security

Energy security pertains to the assurance of a stable and reliable energy supply at prices that are accessible to consumers and industries. This concept encompasses the resilience of energy infrastructure, the diversification of energy sources, and the capacity to withstand disruptions, be they geopolitical conflicts, natural disasters, or market fluctuations [9]. For instance, the European Union has underscored the significance of interconnectivity and cross-border electricity trade to bolster energy security among member states [10]. However, during periods of high demand or supply constraints, national interests may supersede cooperative agreements, as observed in early 2017 when France, Germany, and the United Kingdom faced energy shortages [11]. This scenario highlighted that, despite integrated markets, countries might prioritize domestic energy needs, potentially limiting exports to neighbouring nations.

2.2. Environmental Sustainability

Environmental sustainability in the energy sector involves transitioning to energy systems that meet current demands without compromising the environment or the needs of future generations. This transition necessitates a shift from fossil fuels to low-carbon and renewable energy sources such as wind, solar, hydroelectric, and geothermal power. The global impetus for sustainability is driven by the pressing need to mitigate climate change, reduce greenhouse gas emissions, and minimize ecological degradation [12]. Policies and international agreements, like the Paris Agreement, aim to limit global temperature rise by advocating for substantial reductions in carbon emissions [13]. Achieving these targets requires not only the adoption of clean energy technologies but also enhancements in energy efficiency and the development of smart grids to manage variable renewable energy sources effectively.

2.3. Economic Affordability

Economic affordability ensures that energy remains financially accessible to all sectors of society, thereby supporting economic growth and social equity. Affordable energy is crucial for household budgets, industrial competitiveness, and

overall economic stability. However, the transition to sustainable energy systems often entails significant upfront investments in new technologies and infrastructure, which can lead to higher energy prices in the short term [14]. Balancing the need for these investments with the imperative to keep energy costs manageable is a complex policy challenge. Strategies to address this include implementing subsidies for renewable energy projects, designing tariff structures that protect low-income consumers, and fostering competitive energy markets to drive down prices. Moreover, energy efficiency measures can reduce overall consumption, thereby lowering costs for consumers and mitigating the impact of price increases associated with the energy transition [14, 15].

2.4. Interdependence and Trade-Offs

The three pillars of the Energy Trilemma are inherently interdependent, and actions to enhance one aspect can lead to trade-offs in the others. For example, prioritizing energy security by increasing domestic fossil fuel production may improve supply stability but can conflict with sustainability goals due to higher carbon emissions. Conversely, a rapid shift to renewable energy sources supports environmental objectives but may involve high initial costs, affecting affordability and potentially leading to energy insecurity if the renewable infrastructure is not yet reliable or widespread enough [16]. A study examining the European energy market highlighted these trade-offs. During periods of high demand, countries may prioritize national energy security and economic interests, sometimes at the expense of environmental sustainability [11, 17]. This situation highlights the challenge of balancing the Energy Trilemma, where actions in one aspect can profoundly impact the others.

Ultimately, achieving a balance between energy security, sustainability, and affordability requires collaborative efforts, cutting-edge technologies, and flexible policies that can adapt to evolving global conditions. Recognizing the interconnections and trade-offs among these elements enables stakeholders to develop an energy system that is dependable, environmentally sustainable, and financially viable.

3. Theoretical framework

Addressing the energy trilemma by balancing energy security, sustainability, and affordability requires a comprehensive understanding of the underlying theoretical frameworks that inform policies and practices. This section probes three pivotal theories: Energy Justice Theory, Sustainable Development Theory, and the Political Economy of Energy. Additionally, it examines existing models, notably the World Energy Council's Energy Trilemma Index, which track, measure, assess and compare national energy systems.

3.1. Energy Justice Theory

Energy Justice Theory centers on the equitable distribution of both the benefits and burdens associated with energy production and consumption. It emphasizes that all individuals and communities should have fair access to energy resources and services, and that the adverse impacts of energy systems should not disproportionately affect marginalized or vulnerable populations [18]. This theory is built upon three core tenets:

- **Distributive Justice:** Focuses on the allocation of energy resources and the associated environmental benefits and risks. It seeks to ensure that no group bears an undue share of negative impacts, such as pollution or health hazards, resulting from energy production and use [19].
- **Procedural Justice:** Concerns the inclusivity and fairness of decision-making processes in energy policy and project development. It advocates for the active participation of all stakeholders, especially those from historically marginalized communities, ensuring their voices are heard and considered in energy-related decisions [20].
- **Recognition Justice:** Addresses the need to acknowledge and respect the diverse identities, experiences, and cultural contexts of different communities. It calls for recognizing the unique challenges faced by various groups and tailoring energy solutions to meet their specific needs [21].

By integrating these principles, Energy Justice Theory provides a framework to evaluate and reform energy systems, aiming for outcomes that are equitable, inclusive, and respectful of all communities.

3.2. Sustainable Development Theory

Sustainable Development Theory advocates for meeting current energy demands without compromising the ability of future generations to meet theirs. It underscores the necessity of harmonizing economic growth, social inclusion, and environmental protection [22]. In the context of energy, this involves:

- **Economic Sustainability:** Promoting energy solutions that support long-term economic development and poverty alleviation. This includes investing in renewable energy industries that can create jobs and stimulate economic activity.
- **Social Sustainability:** Ensuring that energy systems are accessible and beneficial to all societal segments, thereby reducing inequalities and enhancing the quality of life.
- **Environmental Sustainability**: Implementing energy practices that minimize ecological footprints, reduce greenhouse gas emissions, and protect natural ecosystems [22, 23].

This theory serves as a guiding principle for policymakers and practitioners, encouraging the development of energy strategies that are viable in the long term and equitable for both present and future populations.

3.3. Political Economy of Energy

The Political Economy of Energy examines how political institutions, economic systems, and power dynamics influence energy policies and decisions. It examines the role of governments, markets, and key stakeholders in influencing energy production, distribution, and consumption [24]. Geopolitical factors play a significant role, as international relations and global power structures directly impact energy security, trade, and diplomacy. Countries often leverage energy resources to advance their political and economic interests, which in turn shapes global energy markets and influence supply chains [25]. Economic interests also drive energy policies, with corporations, financial institutions, and market dynamics play active role in determining energy investments and the adoption of new technologies. The pursuit of profitability and competitiveness affects decisions on energy infrastructure, resource allocation, and research into cleaner alternatives [24, 25].

Government policies and regulatory frameworks are equally vital in directing energy transitions and addressing market failures. Policy measures such as subsidies, carbon pricing, and emissions regulations influence the pace and direction of energy system transformation [26]. Effective governance is essential to balance national interests with international sustainability commitments, ensuring energy policies align with both economic growth and environmental goals. Understanding these political and economic dynamics is crucial for designing policies that address energy security, sustainability, and affordability in an increasingly fragmented global landscape.

3.4. World Energy Council's Energy Trilemma Index

The World Energy Council's Energy Trilemma Index is a critical tool designed to evaluate and rank countries based on their performance in three key dimensions: energy security, energy equity, and environmental sustainability. This index provides a comparative framework that helps assess how effectively nations manage the trade-offs and synergies among these dimensions [27]. One of the primary functions of the Energy Trilemma Index is benchmarking performance. Countries can use the index to compare their energy systems against global peers, identifying strengths and areas that require improvement. This comparative analysis enables nations to measure their progress and adapt strategies accordingly to enhance overall energy resilience.

The index also plays a crucial role in policy guidance. By providing data-driven insights into energy system performance, it helps policymakers design balanced and effective energy strategies [28]. These strategies must align with national energy priorities while addressing the interconnected challenges of security, equity, and sustainability. The ability to measure progress over time allows governments to refine policies that foster a stable, accessible, and environmentally responsible energy supply.

4. Global challenges and regional perspectives

Geopolitical fragmentation has become a defining factor in shaping global energy dynamics. Political conflicts, trade disputes, and resource nationalism contribute to supply disruptions and market volatility, making it increasingly difficult to balance energy security, sustainability, and affordability. The ongoing war in Ukraine has had significant implications for Europe's energy landscape, leading to supply shortages and rising prices. Many European nations have had to rethink their energy strategies, seeking alternative suppliers and accelerating investments in renewable energy [29]. Trade tensions between major economies, such as the United States and China, have also impacted the availability of critical materials needed for clean energy technologies, further complicating the transition to sustainable energy sources [30]. In response, energy diplomacy has gained renewed importance, as countries attempt to secure stable energy supplies through bilateral agreements and international cooperation.

Developed economies, including those in Europe and North America, are at the forefront of the energy transition, prioritizing policies that support renewable energy adoption. However, these efforts often come with significant cost

implications. The European Union, for example, has seen sharp increases in energy prices due to ambitious decarbonization targets and reduced reliance on Russian gas [31]. High electricity prices have posed challenges for both consumers and industries, raising concerns about economic competitiveness. In the United States, the Inflation Reduction Act [32] has introduced substantial subsidies for clean energy projects, but questions remain about long-term affordability and the resilience of power grids amid increasing reliance on intermittent renewable sources [33].

Emerging markets such as China, India, and Brazil are experiencing rapid industrialization, leading to a surge in energy demand. While these nations recognize the importance of sustainability, balancing economic growth with environmental commitments remains a challenge. China, as the world's largest energy consumer, has made massive investments in renewable energy, particularly in solar and wind power. However, it continues to rely heavily on coal to meet its growing electricity needs [34]. India faces similar challenges, with high dependence on coal but ambitious targets for solar expansion [35]. Brazil, blessed with abundant hydropower resources, is striving to diversify its energy mix by incorporating more wind and solar energy, although deforestation concerns in the Amazon pose additional environmental risks [36].

Energy-dependent economies, such as the Gulf States and Russia, face a different set of challenges. These nations rely heavily on fossil fuel exports, making them vulnerable to market fluctuations and the global shift toward cleaner energy. In response, countries like Saudi Arabia and the United Arab Emirates have launched diversification strategies, investing in renewable energy, hydrogen production, and economic sectors beyond oil and gas [37]. Russia, on the other hand, continues to leverage its vast energy reserves for geopolitical influence, using its natural gas exports as a bargaining tool in international relations. However, Western sanctions and declining European demand have forced Russia to seek new markets, particularly in Asia [38].

In Africa and other developing regions, energy access remains a pressing issue. More than 600 million people in sub-Saharan Africa lack reliable electricity, limiting economic development and quality of life [39]. The high cost of energy, coupled with insufficient infrastructure, exacerbates affordability challenges. Many countries still rely on expensive and polluting diesel generators, while efforts to expand grid access progress slowly. However, Africa holds immense renewable energy potential, particularly in solar and wind power. Investments in decentralized energy solutions, such as off-grid solar systems and mini-grids, are increasingly being seen as viable alternatives to traditional grid expansion. International financial support and technology transfers will be crucial in bridging Africa's energy gap and ensuring a just transition to sustainable energy.

Summarily, geopolitical fragmentation presents a complex and evolving challenge to the global energy trilemma. While developed economies struggle with the affordability of their energy transitions, emerging markets balance industrial growth with sustainability goals, and fossil fuel-reliant nations seek economic diversification. For developing regions, the focus remains on improving energy access and affordability. Addressing these challenges will require innovative policies, international cooperation, and significant investments in clean energy technologies to create a more secure, sustainable, and affordable global energy system.

5. Strategies for balancing the trilemma

5.1. Technological innovations

Technological innovations play a crucial role in addressing the energy trilemma by improving energy security, sustainability, and affordability. Advances in renewable energy technologies, particularly in solar, wind, hydro, and geothermal power, have significantly lowered the costs of clean energy production. Solar photovoltaic (PV) technology, for instance, has seen a dramatic reduction in costs over the past decade, making it one of the most affordable sources of electricity in many parts of the world [40]. Wind energy, both onshore and offshore, continues to expand, with improvements in turbine efficiency and grid integration. Hydropower remains a reliable renewable source, while geothermal energy offers a stable alternative, particularly in regions with high geothermal activity [41]. These advancements contribute to long-term sustainability while gradually enhancing affordability as economies of scale drive costs down.

Energy storage and smart grids are essential in ensuring the reliability and stability of modern energy systems. The intermittent nature of solar and wind energy necessitates efficient storage solutions, such as lithium-ion and solid-state batteries, to store excess energy for use during low-generation periods [42]. Pumped hydro storage and emerging technologies like flow batteries and sodium-ion batteries are also gaining traction. Smart grids, which use digital technologies to optimize energy distribution and consumption, improve efficiency and resilience. Through enabling

real-time monitoring and decentralized energy management, smart grids enhance security and sustainability while potentially lowering costs for consumers [43].

The hydrogen economy and carbon capture technologies offer additional pathways to balance the energy trilemma. Hydrogen, particularly green hydrogen produced through electrolysis using renewable energy, is emerging as a viable clean energy carrier [44]. It can be used for industrial applications, heavy transport, and even power generation, reducing reliance on fossil fuels [44, 45]. Meanwhile, carbon capture, utilization, and storage (CCUS) is another technology which aim to capture emissions from industrial processes and power plants, preventing carbon dioxide from entering the atmosphere [46]. While these technologies are still evolving, they hold significant potential for reducing emissions while maintaining energy security in sectors that are hard to decarbonize.

5.2. Policy and Regulatory Approaches

Carbon pricing and emissions trading schemes create economic incentives for reducing greenhouse gas emissions. By putting a price on carbon, governments encourage businesses and consumers to adopt cleaner energy alternatives. The European Union's Emissions Trading System (EU ETS) is a leading example of this mechanism, pushing industries to innovate and reduce their carbon footprint [47]. Similarly, carbon taxes implemented in countries like Canada and Sweden have driven emissions reductions while generating revenue for sustainability initiatives [48].

Government subsidies and incentives play a key role in accelerating clean energy adoption. Many countries offer tax credits, grants, and direct subsidies to promote renewable energy projects and energy-efficient technologies. The U.S. Inflation Reduction Act, for example, allocates significant funding to clean energy investments, making renewable technologies more accessible [49]. Subsidies also help lower the cost of electric vehicles, home solar installations, and grid-scale battery storage, ensuring affordability while advancing sustainability goals.

International agreements serve as a framework for global cooperation on energy issues. The Paris Agreement, signed by nearly 200 countries, sets ambitious targets for reducing greenhouse gas emissions and limiting global temperature rise [50]. Outcomes from COP summits continue to shape global energy policies, with commitments to phase out fossil fuel subsidies, increase renewable energy deployment, and enhance climate financing for developing nations [51]. These agreements foster collaboration and provide a structured approach to addressing the energy trilemma at an international scale.

5.3. Market Mechanisms and Private Sector Involvement

Market mechanisms and private sector involvement are also critical in driving energy transition efforts. Multinational corporations in the energy sector, such as BP, Shell, and TotalEnergies, are increasingly investing in renewable energy, signalling a shift from traditional fossil fuel dependence. Tech giants like Google and Microsoft are also leading the way in procuring 100% renewable energy for their operations, influencing broader market trends [52]. Financial institutions and investment funds are prioritizing projects with strong environmental, social, and governance (ESG) credentials. Green bonds, sustainability-linked loans, and climate-focused investment portfolios channel capital toward renewable energy, energy efficiency, and low-carbon infrastructure. The rise of sustainable finance ensures that clean energy projects receive the funding they need to scale, supporting both sustainability and affordability.

Public-private partnerships are instrumental in mobilizing resources for energy infrastructure development. Governments and private entities collaborate to build and expand energy projects, sharing risks and leveraging expertise. These partnerships have been successful in renewable energy deployment, smart grid implementation, and large-scale electrification projects in developing regions [53]. By combining public policy support with private sector innovation, these collaborations offer a pragmatic approach to balancing the energy trilemma.

6. Future projections and policy recommendations

The global energy landscape will undergo significant transformations in the coming decades. Renewable energy sources such as solar, wind, and hydrogen will expand rapidly, driven by technological advancements and falling costs. However, energy security concerns may persist due to supply chain vulnerabilities, geopolitical conflicts, and resource nationalism. While developed nations will focus on decarbonization, emerging markets and developing economies may struggle with affordability and infrastructure gaps, exacerbating global energy inequalities. A careful balance of policy, investment, and international cooperation will be required to navigate these challenges.

6.1. Policy Recommendations for Balancing the Trilemma

- **Enhancing Energy Security:** Governments must invest in diversified energy sources, upgrade grid infrastructure, and strengthen supply chains to reduce dependence on volatile energy markets. Expanding nuclear energy, energy storage, and smart grids can improve reliability.
- **Advancing Sustainability:** Carbon pricing, emissions trading, and stricter environmental regulations should accelerate the transition to clean energy. Research and development in hydrogen energy, carbon capture, and energy-efficient technologies must be prioritized.
- **Ensuring Affordability:** Subsidies for renewable energy, tax incentives, and investments in decentralized energy systems can lower costs for consumers. Public-private partnerships should be leveraged to finance large-scale projects in a cost-effective manner.

6.2. The Role of International Cooperation

Geopolitical fragmentation threatens energy stability, making international collaboration essential. Countries must strengthen multilateral agreements like the Paris Agreement and establish mechanisms for coordinated energy policies. Cross-border infrastructure projects, regional energy markets, and shared technology frameworks can reduce risks associated with unilateral energy policies. Additionally, financial aid and technology transfer should be directed toward developing nations to ensure an equitable transition.

6.3. Risks and Uncertainties in Global Energy Governance

Despite efforts to balance the trilemma, several risks remain. Political instability, trade disputes, and economic downturns could disrupt energy investments and cooperation. Technological advancements may not scale quickly enough to meet demand, while public opposition to high energy costs or land-intensive renewable projects could slow progress. To mitigate these uncertainties, policymakers must adopt flexible regulatory frameworks and build resilient energy systems that can adapt to future challenges.

The future of global energy stability depends on decisive action, strategic investments, and sustained cooperation. Without these, the risks of energy insecurity, economic disparity, and environmental degradation will only intensify.

7. Conclusion

The energy trilemma of balancing security, sustainability, and affordability remains a critical global challenge. Geopolitical conflicts, economic disparities, and the transition to cleaner energy sources complicate efforts to achieve this balance. While developed nations push for renewable energy adoption, emerging markets and energy-dependent economies face trade-offs between growth and sustainability, and many developing countries still struggle with energy access and affordability.

Addressing these challenges requires integrated solutions that combine technological advancements, strong policies, and financial investments. Renewable energy, energy storage, and grid modernization must be supported by regulatory frameworks, market mechanisms, and international cooperation. Agreements like the Paris Agreement are crucial, but their success depends on enforcement and collaboration. The future of global energy stability hinges on innovation, investment, and cooperation. While the transition to a low-carbon economy is inevitable, its success will depend on balancing the trade-offs effectively. Proactive policymaking and international partnerships will be essential in securing a stable, sustainable, and affordable energy future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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