SYSTEMIC TRANSITIONS IN WORLD TRADE AND THEIR ENERGY MARKET REPERCUSSION

EDITOR
Luis Manuel Hernandez GOVEA

Liberty Publishing House
New York - 2025

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ISBN: 979-8-89695-115-5

DOI: https://doi.org/10.5281/zenodo.16317283

Edited By

Luis Manuel Hernandez GOVEA

July / 2025

New York / USA

Date: 22.07.2025

Liberty Publishing House
Water Street Corridor New York, NY 10038
www.libertyacademicbooks.com
+1 (314) 597-0372

adopted by Mariam Rasulan&Merve Küçük
ISBN: 979-8-89695-115-5

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PREFACE

The 21st century has been defined by a confluence of complex transformations—technological disruption, geopolitical realignment, environmental urgency, and systemic shifts in global trade and energy governance. These developments have fundamentally altered the way nations interact, markets operate, and strategies are formulated across the globe. This book, Systemic Transitions in World Trade and Their Energy Market Repercussions, emerges as a timely and indispensable contribution to our understanding of these intertwined transitions.

Gathering the insights of distinguished scholars and practitioners from diverse geopolitical and disciplinary backgrounds, this volume offers a comprehensive exploration of the evolving relationship between international trade systems and energy markets. Each chapter reflects a deep engagement with current theoretical frameworks and empirical realities, addressing pressing issues such as trade fragmentation, energy security, decarbonization, artificial intelligence in energy policy, and the role of emerging economies in shaping future dynamics.

Rather than viewing trade and energy in isolation, this collection embraces an integrated analytical lens—revealing how supply chains, digital platforms, regulatory mechanisms, and climate imperatives intersect in new and often unpredictable ways. The contributors challenge conventional paradigms, illuminating the strategic recalibrations underway in global institutions, national governments, and regional alliances.

We sincerely thank the editors and contributors for their rigorous work, and Liberty Academic Publishers for supporting the open access of this important volume. We believe it will be a valuable resource for academics, policymakers, business leaders, students, and all engaged in global transformation.

As the world continues to grapple with uncertainty and transition, may this volume inspire more informed dialogue, integrated solutions, and inclusive pathways toward sustainable and equitable global futures.

Editor
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July 28, 2025 New York, USA
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CHAPTER 1

TRANSFORMATION OF THE GLOBAL TRADE SYSTEM AND ITS IMPACT ON ENERGY MARKETS

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INTRODUCTION

The transformation of global trade systems has become one of the defining phenomena of the early 21st century, reshaping how energy is produced, distributed, and governed. While trade liberalization and globalization once promised increased efficiency and mutual gains, recent developments; including supply chain fragility, geopolitical fragmentation, digital trade acceleration, and climate imperatives have altered the assumptions underpinning global commerce. These structural shifts have profound implications for energy markets, whose governance structures, pricing mechanisms, and infrastructure are intimately tied to the rhythms of international trade (Bardazzi & Pazienza, 2023; Blondeel, 2021).

At the intersection of trade and energy lies a paradox: the forces driving integration and openness are increasingly in tension with those fostering fragmentation and protectionism. The COVID-19 pandemic, the war in Ukraine, and the intensifying US–China strategic rivalry have each exposed vulnerabilities in globally integrated energy systems, prompting a re-evaluation of the interdependencies that define modern trade (Gilpin & Gilpin, 2001; Bardazzi & Pazienza, 2023). As energy transitions accelerate and the demand for critical minerals, green technologies, and resilient supply chains grows, the global trade architecture is undergoing not just a series of shocks, but a deep structural realignment (Dincer & Yüksel, 2022; UNCTAD, 2023).

This chapter investigates how the reconfiguration of global trade affects energy markets — from pricing and logistics to infrastructure and digital platforms. It further explores how institutions, both multilateral and regional, are struggling to govern these overlapping transitions. Rather than treating trade and energy policy as discrete domains, this work conceptualizes them as interdependent systems whose mutual evolution demands new frameworks of analysis and governance.

By combining political economy, energy transition theory, and institutional analysis, the chapter aims to map the emerging contours of a world in flux. Special attention is given to peripheral economies - particularly in the Global South - whose capacity to shape and benefit from these transformations is often constrained. Understanding the co-evolution of trade and energy systems is not only analytically urgent, but politically essential for navigating a future characterized by complexity, contestation, and interdependence (Nyambuu & Semmler, 2023; Rafay, 2021).

CONCEPTUAL FRAMEWORK

Understanding the transformation of global trade and its impact on energy markets requires an integrated conceptual framework that brings together multiple strands of thought. This chapter draws on three intersecting domains: global political economy, energy systems transformation theory, and structural institutionalism. Together, these perspectives provide a multidimensional lens to examine how changes in trade regimes are altering energy flows, market behaviors, and governance structures.

At its core, global political economy (GPE) concerns itself with how power and wealth are distributed across states and how economic structures are embedded in political systems. Classical theories of comparative advantage emphasized the benefits of liberalized trade and specialization; however, contemporary GPE has shown that trade is often shaped by geopolitical rivalries, institutional asymmetries, and uneven development (Gilpin & Gilpin, 2001; Inshakova & Inshakov, 2017).

Strategic trade theory, in particular, posits that governments actively intervene in trade to protect nascent industries, secure critical resources, or assert influence over global value chains (Dincer & Yüksel, 2022). In the context of energy, this manifests in export controls, infrastructure diplomacy, subsidies for green technology, and regional trade blocs oriented around energy security.

Energy systems transformation refers to the long-term structural shifts in the generation, distribution, and consumption of energy, particularly toward low-carbon and renewable models. This transition is not only technical but also deeply political, involving contestation over land, labor, finance, and knowledge (IRENA, 2019; Schellnhuber, 2012). The energy transition intersects with trade through the movement of fuels and technologies, the embedded carbon in traded goods, and the demand for critical minerals and components used in renewable infrastructure (Rafay, 2021; Blondeel, 2021).

A useful conceptual distinction is between centralized energy regimes, characterized by vertically integrated fossil-fuel systems, and decentralized energy models, often enabled by renewables, digital platforms, and community ownership. Each has distinct implications for trade: while the former relied on pipeline diplomacy and bulk commodity trade, the latter leans toward modular, digitally-managed, and data-driven exchanges (del Río & Ragwitz, 2023).

Trade and energy systems are both governed by complex institutional arrangements, including international agreements (e.g., WTO, Paris Agreement), regional organizations (e.g., EU, AfCFTA), and national regulatory regimes. These institutions mediate access to markets, set technical standards, and arbitrate disputes. However, rapid transformation in both domains has created a governance gap; where existing institutions lag behind the realities of hybrid energy–trade linkages (UNCTAD, 2023; Nyambuu & Semmler, 2023).

This chapter adopts an institutionalist lens to explore how formal and informal rules, norms, and actors shape energy–trade interactions. It recognizes that governance is increasingly occurring through polycentric networks — involving states, firms, and civil society — rather than through centralized multilateral bodies alone (Bardazzi & Pazienza, 2023).

Finally, the framework acknowledges that interdependence in global trade and energy systems produces both resilience and vulnerability. While some countries benefit from diversified trade networks and technological capabilities, others — especially in the Global South — face structural dependencies and limited bargaining power. Yet, these peripheral actors are not passive; many are using tools such as strategic mineral policy, regional cooperation, and south–south trade to increase their agency (Nyambuu & Semmler, 2023; UNCTAD, 2022).

By combining these theoretical perspectives, the chapter provides a comprehensive lens for analyzing the co-evolution of global trade and energy systems under conditions of uncertainty, transition, and geopolitical contestation.

Historical Context of Global Trade and Energy Linkages

The relationship between global trade and energy systems has long been foundational to international economic order, though the nature of this relationship has evolved markedly over time. From the mercantilist empires of the early modern period to the neoliberal globalization of the late 20th century, energy has functioned not merely as a traded good but as a strategic pillar of geopolitical and developmental regimes (Gilpin & Gilpin, 2001; Buzan & Lawson, 2015).

Colonial Foundations and Industrialization

The early global trade system was heavily shaped by the needs of industrializing powers and their pursuit of extractive energy resources. Coal from Europe and later oil from colonies and protectorates underpinned imperial infrastructure, naval power, and early industrial trade (Buzan & Lawson, 2015). Energy flows were embedded in the coercive trade networks of empire, laying a path-dependent structure for the fossil-fuel-centered economies of the 20th century.

The Bretton Woods Order and Energy Security

After World War II, the establishment of the Bretton Woods institutions (IMF, World Bank) and the General Agreement on Tariffs and Trade (GATT) created a liberalized trade architecture that reinforced energy commodification. As global trade expanded under U.S. hegemony, energy security — particularly oil — became a central concern. This was made stark during the 1973 and 1979 oil shocks, which exposed the vulnerability of industrial economies to geopolitical supply disruptions (Gilpin & Gilpin, 2001; Bardazzi & Pazienza, 2023).

During this period, international trade institutions and energy governance bodies remained largely siloed. The WTO (and its predecessor, GATT) did not directly engage with energy pricing or regulation, and energy institutions like the IEA were formed in response to crises rather than as proactive, integrated trade bodies.

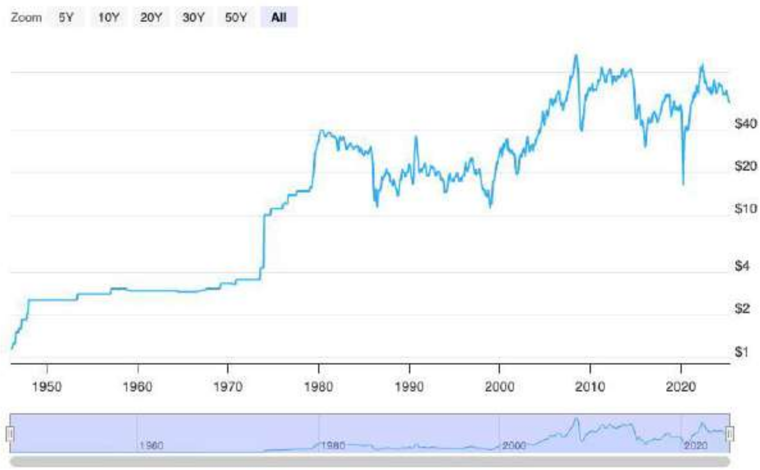

Figure 1*,Global crude oil prices,1946–2025, Source: Macrotrends*

Globalization and the Rise of Complex Energy Supply Chains

The post-1980s period of accelerated globalization brought with it deeply integrated global value chains, in which energy not only flowed as a traded good but also as an embedded input in virtually all traded products — from steel and aluminum to electronics and fertilizers (UNCTAD, 2023). Liberalized trade regimes encouraged the outsourcing of energy-intensive manufacturing to countries with cheaper labor and looser environmental standards.

This had two important consequences:

- **Geopolitical interdependence** increased, especially between the Global North and newly industrializing countries (e.g., China, India).
- **Carbon leakage** became a growing concern, as emissions were effectively outsourced along with manufacturing.

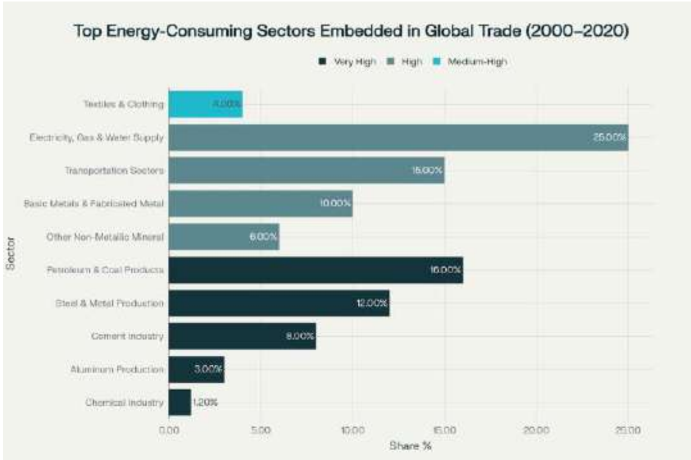

***Figure 2**, Top energy-consuming sectors embedded in global trade (2000–2020), Source: International Energy Agency (IEA)*

The 2008 global financial crisis exposed the fragility of over-leveraged financialized trade systems. For energy, it led to a dip in demand and forced major fossil-fuel firms to rethink investment strategies. Soon after, the shale revolution in the U.S. and the growth of China's Belt and Road Initiative began to rewire global energy logistics, reducing Atlantic-centric dependency while building Asia-centered corridors (Schellnhuber, 2012; Blondeel, 2021).

This phase also saw the institutional beginnings of trade–climate linkages, such as carbon border adjustments and sustainability clauses in trade agreements, foreshadowing the regime complexity now characterizing energy governance (Rafay, 2021).

THE SHIFT IN TRADE PARADIGMS: FROM GLOBALIZATION TO FRAGMENTATION

The last two decades have witnessed a paradigmatic shift in the global trade architecture, moving away from the expansionary ethos of globalization toward an era characterized by fragmentation, strategic competition, and technological sovereignty. This transformation is not merely a reversal of liberalization trends, but the emergence of new logics — geopolitical, digital, ecological — that are redrawing the rules of international trade and directly impacting global energy flows.

POST-2008 STRATEGIC REORIENTATION

The 2008 financial crisis signaled the limits of hyper-globalization. As global value chains were disrupted and consumer demand collapsed, states began rethinking the risks of excessive interdependence. A growing consensus emerged around the need for strategic trade policy; whereby nations actively shape trade to serve national interests in security, employment, and energy independence (Gilpin & Gilpin, 2001; Dincer & Yüksel, 2022). In particular, countries began to view energy not only as a tradable commodity but as a strategic asset, closely linked to industrial policy, geopolitical leverage, and technological competitiveness. This reorientation intensified in the aftermath of the COVID-19 pandemic and the Ukraine crisis, which exposed the fragility of global supply chains and the dangers of reliance on concentrated energy sources (Blondeel, 2021; UNCTAD, 2023).

Strategy	Efficiency Impact
Dual Sourcing	Increases costs, adds complexity
Increased Inventory Buffers	Ties up capital, raises costs
Regionalization/Nearshoring	Higher production costs
Advanced Planning Systems (APS)	Moderate investment needed
Digitalization/AI Tools	Upfront investment
Lean/Just-in-Time (legacy)	Maximizes efficiency

Table 1*, Resilience vs. efficiency trade-offs in global supply chains post-2020, Source: Authors*

Rise of Geo-economic Fragmentation

Fragmentation now takes several forms:

- Tariff wars and sanctions (e.g., U.S.–China rivalry)
- Digital sovereignty policies
- Green protectionism via carbon border adjustment mechanisms (CBAM)
- Export controls on critical minerals and clean tech components

These measures are justified as enhancing resilience or advancing sustainability but often function as tools of geo-economic power (Bardazzi & Pazienza, 2023; Rafay, 2021). For energy, this means the securitization of flows — where gas pipelines, rare earth metals, and electricity interconnectors are reclassified as national security assets rather than trade goods.

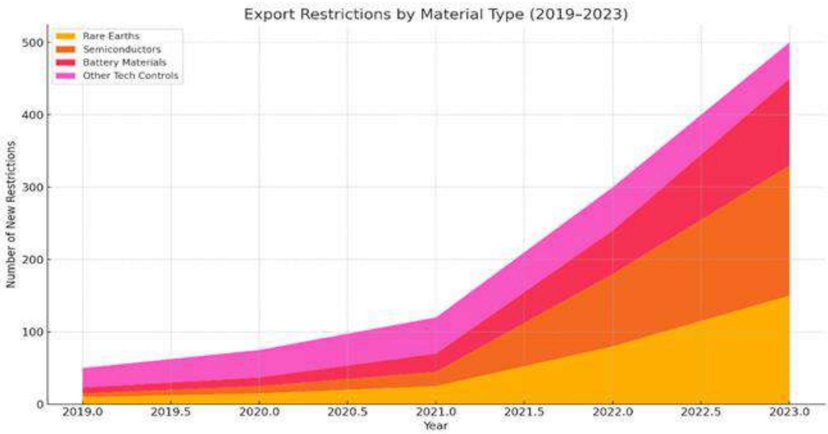

***Figure 3**, Export restrictions and trade controls on energy-related technologies (2019–2023), Source: OECD (2025)*

Rather than embracing a return to autarky, many states are pursuing regional trade alignments. These include:

- The African Continental Free Trade Area (AfCFTA)
- The EU's Green Deal diplomacy
- China's Belt and Road Energy Corridors
- U.S.-led Indo-Pacific Energy Cooperation frameworks

These alliances embed energy concerns directly into trade negotiations, including joint infrastructure investments, grid interconnection agreements, and synchronized decarbonization plans (IRENA, 2019; del Río & Ragwitz, 2023). This "geopolitical regionalism" reflects a new mode of governance; one that replaces multilateral consensus with strategic multilateralism, where blocs act collectively to secure energy futures on their own terms.

Another key shift is the platformization of trade. E-commerce, blockchain-enabled certification, and AI-managed logistics have accelerated the dematerialization and automation of trade systems. This affects energy in two ways:

- The digital infrastructure itself consumes and redistributes energy flows
- Digital governance platforms set private standards that shape energy trade (e.g., certification for green hydrogen or carbon-neutral goods)

Yet these private platforms often operate beyond public oversight, raising questions about data governance, transparency, and algorithmic bias (Nyambuu & Semmler, 2023; Yufriadi et al., 2024).

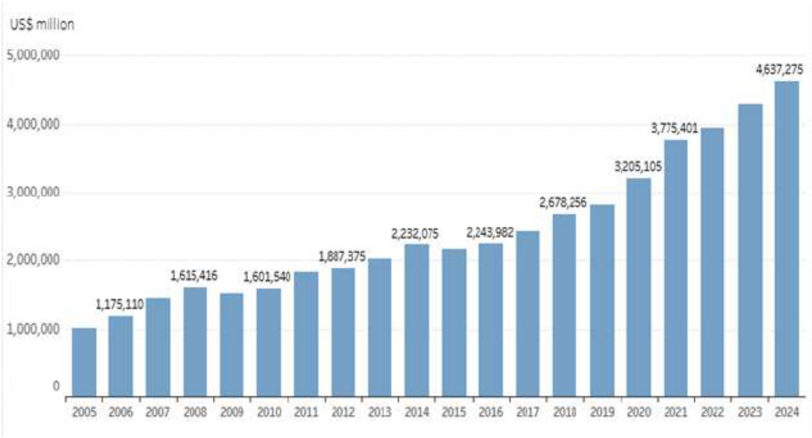

Figure 4, Digitally Delivered Services Exports (2005-2024), Source: WTO

Digitalisation has had a considerable impact on trade in services, as technological advances allow the remote delivery of many types of services. Digitally deliverable services, i.e. services that can be delivered remotely through computer networks, grew at an average annual rate of 7.4%, higher than the 4.7% recorded for non-digitally deliverable services. Indeed, digitally deliverable services accounted for about 55% of global services trade in 2023, up from 43% in 2005.

Energy Market Structures and Emerging Trends

Global energy markets are undergoing a structural transformation, shaped by decarbonization imperatives, shifting demand patterns, financial innovation, and new geopolitical configurations. These changes are not isolated; they are tightly interwoven with evolving trade paradigms and the reconfiguration of industrial strategies worldwide. This section examines the new logics governing energy production, distribution, and pricing, and how they interact with emerging trade dynamics.

From Fossil Fuel Dominance to Diversified Energy Portfolios

Historically, energy markets were dominated by fossil fuels — oil, coal, and natural gas — traded in bulk through long-established commodity exchanges and governed by a few key exporters and multilateral organizations. Today, that model is being challenged by the rapid rise of renewables, distributed energy systems, and critical mineral supply chains (IRENA, 2019; Bardazzi & Pazienza, 2023). The diversification of energy sources has produced a more fragmented but also more adaptable system.

The increasing role of solar, wind, and green hydrogen is transforming energy from a highly centralized system to a modular, geographically dispersed network. This transition alters not just infrastructure and investment flows, but also the geography of trade: countries that previously imported fossil fuels are now becoming exporters of renewable electricity or components (del Río & Ragwitz, 2023).

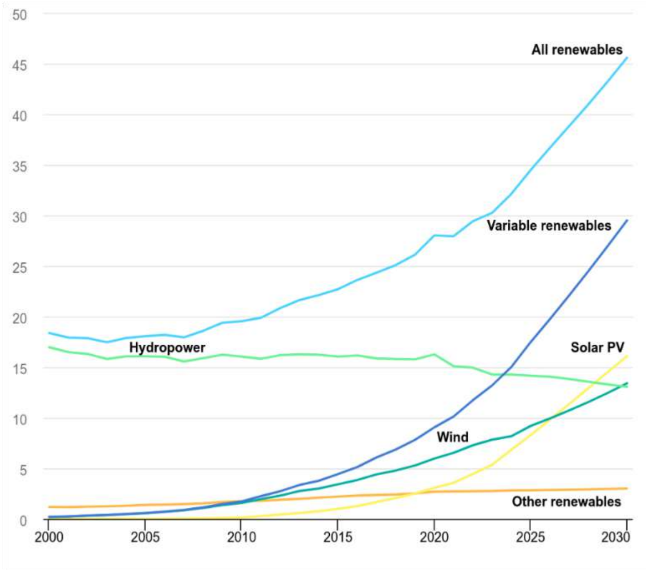

Figure 5, *Share of renewable electricity generation by technology (2000-2030), Source: IEA (2024)*

Energy Price Volatility and Market Power Shifts

Recent years have seen heightened volatility in energy prices, driven by geopolitical shocks (e.g., Ukraine war), OPEC+ production decisions, and financial speculation in carbon and energy futures. The traditional pricing mechanisms — such as oil-indexed long-term contracts — are giving way to more dynamic, spot-based and regionalized pricing systems (Schellnhuber, 2012; Dincer & Yüksel, 2022).

At the same time, market power is shifting. New exporters of liquefied natural gas (LNG), as well as critical mineral suppliers like Chile, Indonesia, and the Democratic Republic of Congo, are gaining strategic leverage in global trade. Their ability to influence prices and terms of access gives rise to a new geopolitical map of energy dependency.

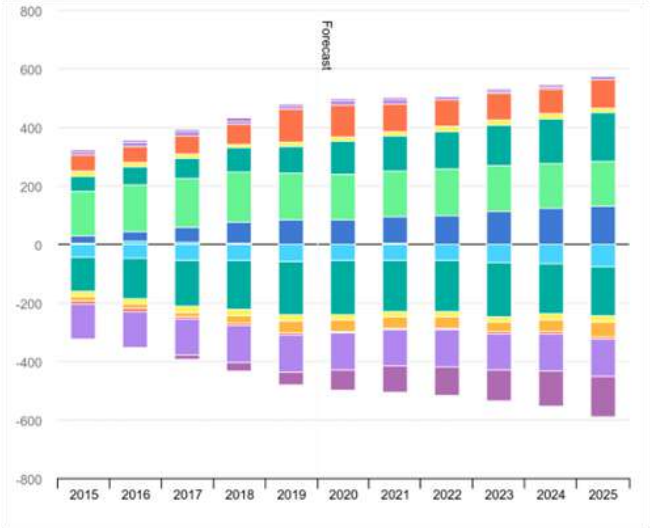

Figure 6*, World LNG imports and exports by region (2015-2025), Source: IEA (2020)*

Energy markets are also undergoing financialization, with new actors — hedge funds, green bonds, ESG investors — shaping investment patterns. Simultaneously, carbon pricing mechanisms, including Emissions Trading Schemes (ETS) and carbon taxes, are creating parallel markets that intersect with traditional energy commodity flows (Nyambuu & Semmler, 2023).

These financial tools affect trade competitiveness and raise important distributive questions: Who absorbs the cost of carbon pricing? How are these costs passed through supply chains? Countries with weaker institutional capacity often face challenges in monitoring, verifying, and enforcing such instruments. The energy transition relies heavily on critical raw materials such as lithium, cobalt, and rare earth elements — inputs essential to batteries, solar panels, and electric vehicles. Unlike oil, which has broad geographic distribution, the production and refining of these materials is highly concentrated, making the new energy economy vulnerable to supply disruptions and trade restrictions (Blondeel, 2021; Gilpin & Gilpin, 2001).

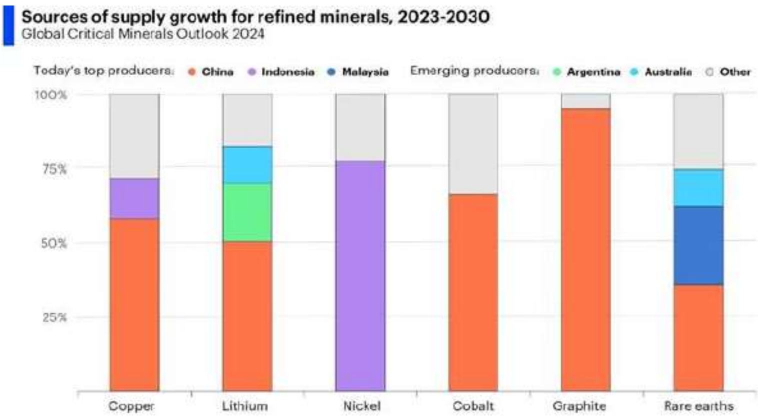

Figure 7, *Top producers and refiners of lithium, cobalt, and rare earths (2023-2030), Source: IEA (2024)*

Trade–Energy Nexus: Empirical and Theoretical Intersections

The complex interdependence between trade and energy has long been acknowledged in both academic literature and policy discourse, but recent global shocks have accelerated its transformation into a tightly coupled, co-evolving system. This section investigates the theoretical underpinnings and emerging empirical evidence on how energy transitions and trade reconfigurations are shaping one another; with implications for governance, equity, and resilience.

Embedded Energy in Global Trade Flows

One of the most critical mechanisms linking trade and energy is embodied energy — the total energy used in the production and transport of traded goods. The shift of manufacturing to developing economies has not only displaced carbon emissions geographically but has also entrenched energy-intensive trade patterns. Developed countries increasingly import energy embodied in intermediate goods, effectively outsourcing emissions and energy demand (UNCTAD, 2023; Blondeel, 2021).

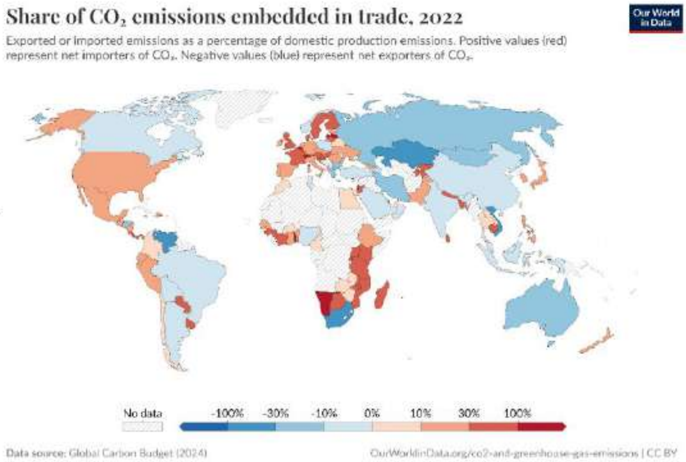

***Figure 8**, Share of CO_2 emissions embedded in trade, Source: Global Carbon Budget (2024)*

Exported or imported emissions as a percentage of domestic production emissions. Positive values (red) represent net importers of CO_2. Negative values (blue) represent net exporters of CO_2.

This phenomenon has raised calls for carbon border adjustment mechanisms (CBAMs), designed to equalize emissions responsibilities across borders and prevent "carbon leakage." However, such tools also risk functioning as disguised protectionism, disproportionately affecting exporters in the Global South.

Energy Intensity of Trade Infrastructure

Global trade is physically underpinned by infrastructure; ports, pipelines, freight corridors, and logistics networks, that are highly energy-intensive. The energy footprint of container shipping, aviation, and trucking continues to rise, especially with the growth of e-commerce and just-in-time delivery models (Schellnhuber, 2012; Rafay, 2021). Despite efficiency gains, the sector's dependence on fossil fuels remain stubbornly high.

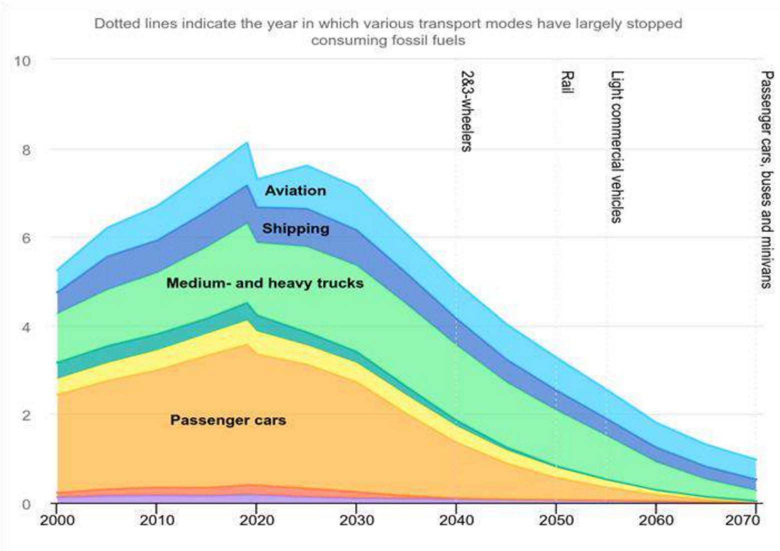

Figure 9*, Global CO2 emissions in transport by mode in the Sustainable Development Scenario (2000-2070), Source: IEA (2020)*

Decarbonizing this infrastructure through electrification, green hydrogen fuel, or digital optimization is increasingly a shared priority of trade and energy planners. Trade corridors like the EU's TEN-T or China's Belt and Road are beginning to incorporate clean energy standards into project design.

There is growing evidence that liberal trade regimes have facilitated the global diffusion of renewable energy technologies. The decline in tariffs for solar panels and wind turbines, alongside knowledge transfer and investment treaties, has allowed countries to leapfrog into new energy sectors (IRENA, 2019; del Río & Ragwitz, 2023). However, this openness has also created new dependencies — such as over-reliance on a single country for photovoltaic components — which can be strategically weaponized.

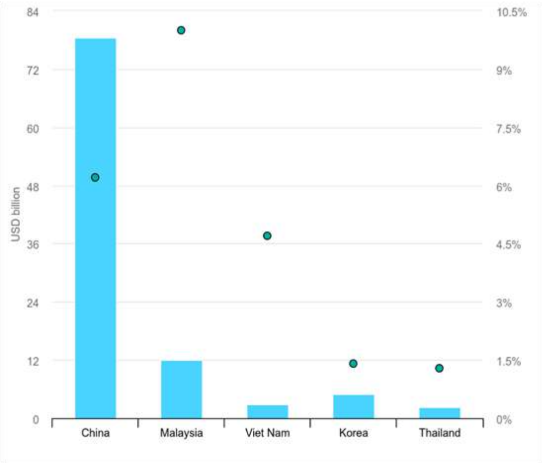

Figure 10*, Cumulative PV-grade polysilicon, wafer, cell and module trade balances (2017-2021), Source: IEA (2022)*

Trade has also enabled scaling and cost reduction. According to IRENA (2019), the global average cost of solar PV fell by 82% between 2010 and 2019; a trend made possible by international trade in components and assembly labor.

Policy Asymmetries and Regulatory Mismatch

One of the main theoretical challenges in the trade–energy nexus is the lack of regulatory synchronization. Trade rules — governed by WTO disciplines — often clash with national energy and climate policies. For example, renewable energy subsidies may violate WTO non-discrimination clauses, while trade tribunals rarely account for environmental externalities (Inshakova & Inshakov, 2017; Gilpin & Gilpin, 2001). Moreover, data asymmetry between energy regulators and trade authorities hampers joint planning. Policymakers lack integrated tools to model how a CBAM affects energy investment or how an export ban on rare earths reshapes global manufacturing.

For many developing countries, the intersection of trade and energy is marked by structural constraints. Limited access to clean energy, dependency on fuel imports, and exposure to volatile global prices make these economies highly vulnerable to external shocks.

Yet some are using trade to enhance energy security — for instance, through regional power pools, renewable energy zones, or preferential trade agreements in green goods (Nyambuu & Semmler, 2023; Dincer & Yüksel, 2022).

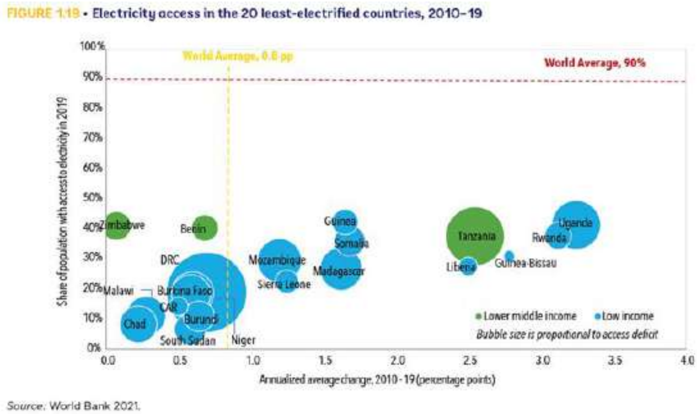

Figure 11, *Electricity access in the 20 least-electrified countries (2010–2019), Source: World bank (2021)*

According to the World bank report, the overall number of people without electricity access has steadily dropped worldwide, largely driven by the shrinking deficits in Central and Southern Asian countries. Notably, as seen in Figure 11, the 20 countries that comprise the smallest share of population with access to electricity in 2019 are all located in sub-Saharan Africa. At 7 percent, South Sudan had the lowest access to electricity in 2019, and countries like Chad, Burundi, and Malawi had slightly greater access. Figure 1 also shows improvements in access over 2010-2019 within this group of 20 countries. Uganda has the greatest access to electricity at 41 percent and experienced the greatest improvement in electrification, with an average annual growth of more than 3 percent. While all 20 countries are far below the world average of 90 percent for electricity access, half of them had much greater overall annual growth than the world average.

Future Outlook and Policy Recommendations

The transformation of global trade systems and their entanglement with evolving energy regimes present both unprecedented risks and opportunities. As the world moves toward decarbonization, digitalization, and geopolitical multipolarity, trade and energy must no longer be treated as parallel but as mutually constitutive systems. This section outlines key future trajectories and offers policy recommendations to strengthen the resilience, equity, and coherence of the trade–energy nexus.

Anticipated Trends in Energy-Trade Dynamics

The geographic map of energy is shifting away from fossil fuel monocultures and toward diversified, distributed systems. This will produce new energy corridors, trade patterns, and diplomatic alignments centered on green hydrogen, critical minerals, and cross-border electricity trade (IRENA, 2019; Blondeel, 2021).

Figure 12, *Projected global hydrogen trade corridors, Source: Globalhydrogenhub*

Trade Digitalization and Blockchain Verification

Trade governance is becoming increasingly digital. The rise of blockchain-certified clean energy, AI-managed carbon tracking, and smart contract-based logistics will reshape how energy commodities and sustainability credentials circulate globally (Nyambuu & Semmler, 2023; Yufriadi et al., 2024). This demands urgent attention to issues of data sovereignty, transparency, and digital equity.

The proliferation of carbon tariffs, sustainability clauses, and environmental trade barriers is likely to intensify. While these mechanisms aim to support decarbonization, they may also act as non-tariff barriers for Global South exporters, raising questions about fairness and historical responsibility (UNCTAD, 2023; Inshakova & Inshakov, 2017).

Policy Recommendations

Current institutional architectures treat trade (WTO) and energy (IEA, UNFCCC) as largely distinct. There is a pressing need for integrated governance platforms that align energy transition goals with trade disciplines. This could include joint task forces, treaty updates, or new cross-sectoral organizations (Gilpin & Gilpin, 2001; Rafay, 2021).

Encouraging regional energy-trade compacts, especially in Africa, Southeast Asia, and Latin America, could strengthen local supply chains and improve bargaining power. These compacts can coordinate investment in renewables, interconnect power grids, and establish shared standards for green exports (Bardazzi & Pazienza, 2023; Dincer & Yüksel, 2022).

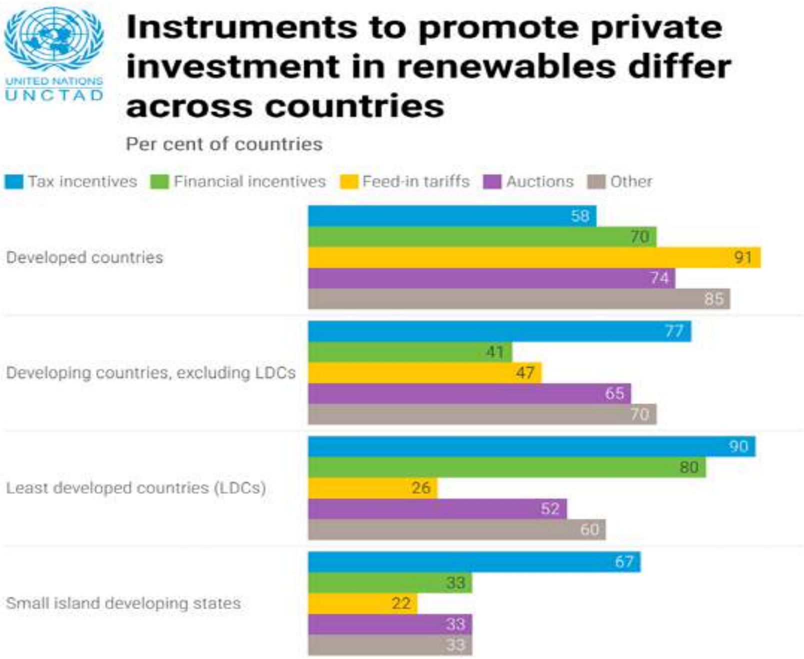

Figure 13, *The focus of renewable energy policies differs across countries, Source: UNCTAD*

CONCLUSION

The accelerating transformation of the global trade system is unfolding in lockstep with the reconfiguration of energy markets. Together, these dual transitions are reshaping the economic, political, and environmental architecture of the 21st century. This chapter has demonstrated that energy and trade are no longer discrete systems but deeply interdependent domains, where policy decisions in one increasingly reverberate through the other.

Historically, trade regimes and energy systems developed in parallel, often underpinned by fossil-fuel dependencies and governed by institutions that treated environmental concerns as peripheral. Today, climate imperatives, digital technologies, geopolitical tensions, and social justice demands are converging to produce a new paradigm — one that calls for integrated governance, regional resilience, and structural equity.

Through a combination of theoretical framing, empirical mapping, and policy analysis, this chapter has outlined how energy and trade are mutually reinforcing forces. It has shown how:

- Embedded energy and carbon in global trade challenge traditional measures of responsibility;
- Infrastructure and logistics are critical leverage points for both decarbonization and trade resilience;
- Trade liberalization can enable renewable diffusion, but also create new dependencies;
- And strategic interventions — from carbon border taxes to regional compacts — will shape the pathways of global energy justice and industrial realignment.

Going forward, it is imperative that policymakers, scholars, and international institutions recognize the co-evolutionary nature of energy and trade. Solutions will require not only technical coordination but also normative alignment: ensuring that trade supports, rather than undermines a just, green, and inclusive energy future.

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CHAPTER 2

TRANSFORMATION OF GLOBAL TRADE SYSTEMS AND ITS IMPACT ON ENERGY SYSTEMS

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INTRODUCTION

Global trade systems have undergone a significant transformation over the past few decades, driven by advances in technology, shifting geopolitical dynamics, and evolving economic policies (Awerbuch, 2006). These changes are not just reshaping the way goods and services are exchanged across borders but are also deeply impacting global energy systems. The rise of digital trade, the expansion of emerging economies, and the growing demand for sustainable products have altered the structure of international commerce. Simultaneously, energy systems around the world are undergoing a transformation, particularly with the shift toward renewable energy sources and the increasing importance of energy efficiency in supply chains. This dual evolution presents both challenges and opportunities for the future of global trade and energy sectors (Jaffe & Soligo, 2020).

Energy plays a central role in the functioning of global trade systems, from the production and transportation of goods to powering industries and facilitating digital transactions. The movement of energy resources, such as oil, gas, and electricity, is critical to global trade flows, and any disruption in energy markets can have widespread consequences for international trade patterns. At the same time, global trade systems are increasingly influenced by the need to transition to a more sustainable energy future, aligning with climate change goals and international agreements like the Paris Agreement. This intersection between trade and energy is reshaping global supply chains, introducing new opportunities for green technologies and renewable energy markets, while also challenging traditional energy trade dynamics (Gunningham & Sinclair, 2018). The transformation of global trade and its impact on energy systems are thus intricately linked, requiring new strategies for energy security, sustainability, and economic development. Understanding the evolving relationship between these two sectors is crucial for policymakers, businesses, and international organizations as they navigate the complexities of the 21st-century global economy.

1. EVOLUTION OF GLOBAL TRADE SYSTEMS

The evolution of global trade systems has been shaped by a series of historical milestones, from the early days of trade routes like the Silk Road to the establishment of multinational trade agreements in the 20th century. Initially, trade was limited to local regions, with countries relying on bartering and a few key commodities. However, the industrial revolution sparked a period of rapid globalization, marked by technological innovations like steamships and railroads, which made long-distance trade more feasible. The creation of major international institutions such as the World Trade Organization (WTO) and regional trade agreements like the European Union (EU) further accelerated global commerce by reducing trade barriers and promoting economic cooperation (Schrattenholzer & Haas, 2020).

In recent decades, the global trade system has experienced a dramatic shift, driven by the rise of digital technologies, globalization of supply chains, and the liberalization of markets. Innovations in logistics, communication, and the digital economy have expanded the scope of trade beyond traditional goods to include services, data, and intellectual property. The emergence of developing economies, particularly in Asia, has reshaped global trade flows, creating new hubs for manufacturing and consumption (Stern, 2018). The increasing importance of e-commerce, automation, and digital trade platforms has transformed the way goods and services are exchanged, making global trade faster and more integrated than ever before. However, these shifts also present new challenges related to cybersecurity, intellectual property protection, and unequal access to markets (Ottaviano & Perroni, 2021).

2. SHIFT TOWARD SUSTAINABLE TRADE PRACTICES

As global trade systems continue to evolve, there has been a growing emphasis on sustainability, driven by both environmental concerns and changing consumer preferences. The increasing awareness of climate change has led to the development of green trade policies and regulations, aiming to reduce the carbon footprint of international commerce. Many countries are adopting stricter environmental standards, promoting renewable energy, and incentivizing the use of sustainable materials in manufacturing. The integration of sustainability into trade practices is also reflected in the rise of green trade agreements, such as the European Union's Green Deal, which aims to create a carbon-neutral economy by 2050 (Kharrazi & Koo, 2018).

This shift toward sustainable trade is closely linked to the energy transition, as companies and governments seek to decarbonize global supply chains. The demand for clean energy, electric vehicles, and renewable technologies is reshaping trade patterns, with countries increasingly focused on securing resources for green technologies. Simultaneously, global trade is contributing to the global pursuit of climate goals, as countries work to align their economic growth with the broader sustainability objectives of the Paris Agreement. This transformation not only influences how goods are produced and traded but also introduces new opportunities for innovation in energy systems, such as smart grids and energy-efficient technologies, driving the convergence of trade and energy sustainability (Barbier, 2019).

3. ENERGY SYSTEMS IN GLOBAL TRADE

Energy systems are fundamental to the functioning of global trade, as energy is needed to produce, transport, and power industries that facilitate international commerce. The movement of energy resources, such as oil, natural gas, and electricity, is critical for the smooth operation of global trade flows. The global demand for energy affects trade routes and markets, as countries with abundant energy resources often become major exporters, while others rely on imports to meet their energy needs. The interdependence of energy and trade is evident in the significant role that energy security plays in global geopolitics, with energy-rich nations influencing trade policies and international relations (Lo, 2017).

In recent years, the transition to renewable energy has begun reshaping energy systems and, by extension, global trade dynamics. As countries increasingly focus on decarbonizing their economies, trade in renewable energy technologies, such as solar panels, wind turbines, and electric vehicles, has surged (Zhang & Zhang, 2020). At the same time, energy-intensive industries are being pressured to adopt cleaner production methods to comply with environmental regulations and meet consumer demand for sustainable products. This shift towards clean energy is driving new trade patterns, with renewable energy sources becoming key commodities in international markets.

Furthermore, innovations in energy storage, smart grids, and decentralized energy production are transforming the energy landscape, creating new opportunities for cross-border collaboration in the energy sector. These changes are fundamentally altering the way energy is produced, consumed, and traded globally (Hirschey & McClung, 2019).

Energy systems are at the heart of global trade, acting as both a facilitator and a major factor influencing international economic relationships. The production, distribution, and consumption of energy—whether in the form of fossil fuels, electricity, or renewable sources—directly impacts the flow of goods and services worldwide. Energy-intensive industries such as manufacturing, transportation, and agriculture depend heavily on reliable energy sources, making energy trade an essential aspect of global commerce. Oil, natural gas, and electricity have historically been some of the most traded commodities, and the distribution of these energy resources shapes not only trade routes but also global political dynamics. Energy-producing countries, particularly in regions rich in fossil fuels, exert substantial influence over global trade flows, often determining the terms of trade for importing and exporting nations (Mueller, 2021).

With the rise of renewable energy, the energy landscape of global trade is changing. The increasing adoption of wind, solar, and hydroelectric power is leading to a shift in how energy is produced and consumed, as well as how it is traded. Unlike fossil fuels, renewable energy sources are not as geographically constrained, allowing more countries to participate in the global energy market. This shift is also driving trade in renewable energy technologies, such as solar panels, wind turbines, and energy storage systems. As nations pursue energy independence and reduce their reliance on fossil fuels, energy trade patterns are evolving, with countries that can produce and export clean energy technologies becoming central players in the global economy. This transformation is also prompting changes in the geopolitical landscape, as nations work to secure access to critical resources like rare earth elements, necessary for the production of renewable energy technologies, while balancing the need for energy security and sustainability (Cherp & Jewell, 2011).

4. CHANGING ENERGY DEMAND AND ITS IMPACT ON TRADE

The global demand for energy is undergoing a profound shift, driven by factors such as population growth, urbanization, and the global transition to cleaner energy sources. Emerging economies, particularly in Asia and Africa, are experiencing rapid industrialization and urban development, leading to a surge in energy demand. This shift is reshaping global trade, as countries seek to secure energy resources, particularly fossil fuels, and renewable technologies, to support their growing economies. At the same time, the rise in demand for clean energy is prompting the expansion of renewable energy trade, with nations increasingly importing and exporting solar, wind, and hydropower technologies to meet sustainability goals (Barbier, 2019).

The energy transition, marked by the shift from fossil fuels to renewables, is significantly influencing trade patterns. Countries with abundant renewable energy resources, such as wind or solar power, are emerging as key players in global energy markets. Furthermore, the global push towards electric vehicles and energy storage technologies is driving trade in batteries, critical minerals, and electric mobility infrastructure. The increasing emphasis on energy efficiency is also reshaping supply chains, as industries adopt cleaner technologies to reduce their carbon footprints. As the world's energy needs evolve, the intersection between energy systems and global trade will continue to transform, creating new opportunities and challenges for international commerce.

As global energy demand continues to evolve, it is reshaping both international energy markets and trade systems. The rapid industrialization of emerging economies, especially in Asia and Africa, is driving a significant increase in energy demand, particularly for electricity, transportation, and industrial activities. This growing demand for energy is prompting countries to diversify their energy sources, shifting from traditional fossil fuels to renewable energy options like solar, wind, and hydropower. The need for clean energy technologies has sparked a new wave of international trade, with nations increasingly importing and exporting renewable energy technologies, such as solar panels, wind turbines, and battery storage solutions.

As a result, energy trade is becoming more dynamic and interconnected, with renewable energy systems fostering new trade routes and partnerships that did not exist in the fossil fuel-dominated past (Fattouh & El-Katiri, 2013).
At the same time, changing energy demand is influencing global supply chains, particularly as countries look to secure critical raw materials needed for the transition to clean energy. Minerals like lithium, cobalt, and nickel, which are essential for battery production and electric vehicle technologies, are now in high demand. This has led to shifts in trade patterns, with countries rich in these resources emerging as key players in global energy markets. Furthermore, the increasing adoption of electric vehicles (EVs) and energy-efficient technologies is driving demand for new infrastructure, such as charging stations and smart grids, which is spurring additional international trade. The demand for cleaner energy solutions is also placing pressure on traditional energy suppliers to adapt, leading to the growth of hybrid energy systems that incorporate both renewable and fossil fuel sources. These shifts in energy demand are fundamentally altering the landscape of global trade, creating new opportunities and challenges for nations seeking to meet the world's evolving energy needs (Nakamura, 2020).

5. THE ROLE OF TECHNOLOGICAL INNOVATIONS IN ENERGY AND TRADE

Technological innovations are playing a pivotal role in shaping the future of both global trade and energy systems. In the energy sector, advances in renewable energy technologies, such as more efficient solar panels, offshore wind turbines, and energy storage solutions, are transforming how energy is produced, stored, and consumed. These innovations are not only reducing the cost of clean energy but also opening up new opportunities for international trade in renewable energy technologies. Countries with strong capabilities in clean energy technology are positioning themselves as exporters in the global marketplace, while others seek to secure these technologies to meet their own sustainability targets (Jaffe & Soligo, 2020).

Simultaneously, the digitalization of trade is enhancing the efficiency and transparency of global commerce. The use of artificial intelligence, blockchain, and the Internet of Things (IoT) is revolutionizing how trade data is tracked, managed, and exchanged across borders. In the energy sector, smart grids, digital platforms for energy trading, and predictive analytics are enabling more efficient and decentralized energy distribution, improving grid management, and facilitating cross-border energy exchanges. These technological advances not only optimize energy systems but also enable new forms of collaboration and integration between global energy markets. As technology continues to evolve, it will further accelerate the integration of energy and trade systems, driving a more sustainable and efficient global economy (Schrattenholzer & Haas, 2020).

Technological innovations are transforming both energy systems and global trade, offering new opportunities for efficiency, sustainability, and cross-border collaboration. In the energy sector, advancements in renewable energy technologies, such as more efficient solar panels, wind turbines, and energy storage solutions, are reducing costs and making clean energy more accessible worldwide. These innovations not only facilitate the global transition to renewable energy but also create new markets for energy technologies, boosting international trade in green solutions. Additionally, digital technologies like blockchain, artificial intelligence, and IoT are enhancing trade processes, enabling more transparent, efficient, and secure exchanges of goods and services across borders. In the energy sector, smart grids and decentralized energy systems are optimizing energy distribution and enabling countries to more easily engage in cross-border energy exchanges, further integrating global energy markets. As technological advancements continue to evolve, they will play an increasingly vital role in shaping the future of energy trade, helping to meet the growing demand for sustainable solutions while fostering international economic growth (Ottaviano & Perroni, 2021).

6. GEOPOLITICS AND GLOBAL TRADE IN ENERGY

Energy resources have long been at the heart of global geopolitics, with countries that control significant energy supplies wielding considerable influence over global trade. The geopolitical landscape of energy is shifting as new energy producers emerge, and traditional power dynamics evolve. Nations rich in fossil fuels, such as oil and natural gas, continue to shape global trade flows, but the growing emphasis on renewable energy is altering these power structures. Renewable energy sources, such as solar, wind, and hydropower, are less geographically constrained and allow for more diverse energy production, reducing dependence on a few key regions. As such, energy trade is increasingly influenced by factors beyond just resource availability, including technological innovation, infrastructure development, and policy decisions related to climate change (Hirschey & McClung, 2019).

Trade relations between energy-producing and energy-consuming nations are also evolving, with energy security becoming a central concern in international relations. Countries are increasingly seeking to diversify their energy sources, investing in renewable energy technologies, and participating in international energy markets to reduce their reliance on volatile fossil fuel markets. The rise of energy nationalism, where countries prioritize energy self-sufficiency, is becoming a key factor in energy trade policies. Moreover, energy-related trade disputes, such as those between major oil-producing nations or the imposition of tariffs on renewable technologies, can disrupt international trade. As energy systems transition to cleaner, more sustainable sources, geopolitical factors will continue to play a crucial role in shaping global trade and international cooperation on energy issues (Foster, 2020).

7. THE IMPACT OF GLOBAL TRADE SYSTEMS ON ENERGY SUSTAINABILITY

Global trade systems play a critical role in advancing or hindering energy sustainability. As countries and companies prioritize sustainable practices, trade has become a vehicle for promoting green technologies and solutions. International trade in renewable energy resources, such as solar panels, wind turbines, and batteries, is expanding, facilitating the global transition to a low-carbon economy. By enabling countries to access the technologies and resources necessary for the energy transition, trade can drive innovation in clean energy and support global sustainability goals. However, the sustainability of trade itself is increasingly under scrutiny, with calls for greener supply chains, reduced carbon emissions from transportation, and the use of sustainable materials in manufacturing (Cazcarro & Duarte, 2014).

At the same time, the growth of energy-efficient technologies in global trade is shaping industries to reduce their environmental impact. Companies are increasingly adopting energy-efficient solutions to align with both consumer demand for sustainable products and stricter environmental regulations. The integration of sustainability into global supply chains is also driving the demand for cleaner energy in production processes. However, challenges remain, such as addressing the carbon emissions from international shipping and air freight, which are significant contributors to global greenhouse gas emissions. To ensure that trade contributes positively to energy sustainability, policies that promote green trade practices, support innovation in clean energy technologies, and incentivize the reduction of environmental impacts across global supply chains will be essential (Gunningham & Sinclair, 2018).

8. CASE STUDIES OF ENERGY SYSTEM IMPACT

Several real-world case studies illustrate the growing impact of global trade systems on energy systems, highlighting both opportunities and challenges in the transition to a more sustainable energy future. In the European Union (EU), the integration of renewable energy into the energy mix has been accelerated through cross-border energy trading and regulatory frameworks like the EU Green Deal. This has not only promoted the adoption of cleaner energy sources but also fostered cooperation between member states to achieve energy security while reducing emissions. Trade in renewable energy technologies, such as wind turbines and solar panels, has become central to the EU's energy transition, helping to set a global example of how trade and energy systems can align for sustainability (Schrattenholzer & Haas, 2020).

In the U.S. and China, energy trade relations have been deeply impacted by both economic and geopolitical factors. The U.S. has become a major exporter of natural gas, while China is investing heavily in renewable energy technologies and rare earth metals required for the production of green energy solutions like electric vehicles and solar panels. These two global superpowers have shaped energy trade flows and pricing, with shifts in their energy policies having significant ripple effects on the global market.

However, trade tensions and tariff policies, particularly between the U.S. and China, have also affected the global supply of energy-related technologies, presenting challenges for both nations in meeting their renewable energy targets (Lo, 2017).

In Latin America and Africa, emerging markets are seeing increasing trade in renewable energy technologies, with countries like Brazil and South Africa becoming key players in the renewable energy market. Both regions are rich in natural resources and are leveraging these assets to build local green energy industries. As demand for renewable energy grows, Latin American and African nations are positioning themselves as critical suppliers of clean energy and technologies to global markets, transforming local economies while contributing to global sustainability goals. These case studies demonstrate how global trade systems are influencing energy production, consumption, and sustainability in diverse regions, driving the global transition toward cleaner energy (Mueller, 2021).

Several case studies highlight the transformative effects of global trade on energy systems, demonstrating how energy and trade dynamics are evolving in different regions. In Germany, the country's "Energiewende" (energy transition) initiative is a key example of how trade in renewable energy technologies has reshaped national energy systems. Through strong investments in wind and solar energy, Germany has become a global leader in renewable energy exports, while also driving energy trade across Europe (Foster, 2020). This shift has been facilitated by trade agreements and regional integration within the European Union, allowing Germany to export renewable technologies and share surplus energy with neighboring countries. In contrast, the energy landscape in India presents a case where rapid industrialization and population growth have led to a dramatic rise in energy demand. To meet this demand, India has turned to both renewable energy imports, such as solar panels, and the development of domestic renewable energy projects, positioning itself as a major player in the global renewable energy market. These case studies show how global trade systems are not only influencing the production and distribution of energy resources but also enabling countries to transition to cleaner, more sustainable energy systems while boosting their economies through innovation and international partnerships.

9. FUTURE OUTLOOK OF GLOBAL TRADE AND ENERGY SYSTEMS

The future of global trade and energy systems is poised for dramatic transformation as countries continue to adjust to the realities of climate change, technological innovation, and shifting economic dynamics. In the coming decades, we can expect a deeper integration of renewable energy in global trade, with an increasing emphasis on clean technologies, energy efficiency, and sustainable production practices (IEA, 2021). The continued growth of renewable energy markets will likely foster new trade routes, as countries with abundant renewable resources like solar, wind, and hydropower will become major exporters of clean energy and associated technologies. At the same time, the push for decarbonization will lead to a reduction in the trade of fossil fuels, reshaping energy geopolitics and supply chains (Barbier, 2019).

Technological advancements in energy storage, grid modernization, and digitalization of trade will further transform the landscape, enabling more efficient energy distribution and trade. The widespread adoption of electric vehicles, smart grids, and digital platforms will accelerate the convergence of energy systems and global trade networks, optimizing energy use across borders and facilitating cross-border energy exchanges. Innovations like blockchain and artificial intelligence will streamline trade processes, ensuring greater transparency and efficiency in energy markets. As trade becomes more digitized, the role of data will also increase, driving the exchange of information vital for managing global energy systems (Ghosh, 2021).

The future of global trade and energy will also be influenced by international collaborations and agreements focused on achieving global sustainability goals. Trade policies will likely be shaped by environmental considerations, with countries enacting policies that promote green trade and support the global energy transition. In this context, global trade will become not only a driver of economic growth but also a critical mechanism for achieving a sustainable, low-carbon future. The coming decades will see a reshaped energy trade system, with cleaner, more efficient energy at its core, fostering a new era of sustainable economic development (O'Neill & Wood, 2019).

CONCLUSION

The transformation of global trade systems and their profound impact on energy systems is creating a new paradigm for the 21st century. As the world faces the urgent challenges of climate change, geopolitical shifts, and the need for sustainable economic growth, the intersection of trade and energy will continue to evolve. The integration of renewable energy, digital technologies, and innovative trade policies is driving a global transition toward cleaner energy systems, reshaping how goods, services, and energy are exchanged across borders. This evolution presents significant opportunities, but also challenges, as countries work to balance energy security, sustainability, and economic development.

To navigate these changes effectively, it will be crucial for governments, businesses, and international organizations to collaborate on innovative solutions, promote green trade policies, and ensure that energy systems are resilient to future demands. As global trade and energy systems become increasingly interconnected, the ability to adapt to new technologies, foster international cooperation, and address environmental concerns will determine the success of the transition toward a sustainable energy future. The continued evolution of global trade will be critical in shaping a world where energy is both abundant and sustainable, enabling long-term global prosperity.

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CHAPTER 3

ARTIFICIAL INTELLIGENCE AT THE SERVICE OF MOROCCO'S NATIONAL AND INTERNATIONAL ENERGY TRANSITION AND INFLUENCE STRATEGIES

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INTRODUCTION

The digital revolution, characterized by the advent of information and communication technologies, is profoundly redefining economic, social and geopolitical balances on a global scale. This transformation impacts not only modes of production and consumption, but also relations between individuals, companies and states, thus modifying traditional dynamics of power and influence.

The meteoric growth of artificial intelligence has brought about a rapid and profound transformation of our societies. This technological advance also raises major challenges in terms of energy, requiring in-depth reflection on the consumption and management of energy resources. In 2022, the International Energy Agency (IEA) reported that data centers had already consumed an impressive 460 terawatt hours (TWh) of electricity. The digital industry, with its rapid expansion and growing demand for technological equipment, plays a major role in the competition for supplies of strategic raw materials. Faced with the current challenges, major companies in the digital sector are taking steps to step up their investments in energy. They are seeking to secure their growth by supporting a variety of power generation projects, whether linked to nuclear sources or renewable energies.

The African continent is virtually lacking in digital infrastructures dedicated to artificial intelligence. Africa has considerable potential for exploring artificial intelligence applications and creating new business and service models. Over the past decade, Chinese investment in Africa has seen a notable intensification, positioning China as the leading trading partner of African nations, ahead of India, France, the USA and Germany (Miailhe 2018). Artificial Intelligence applications to renewable energies in Africa aim to harness technological advances to optimize the production, distribution and management of clean energies such as solar and wind power. These innovative technologies make it possible to collect and analyze large amounts of data in real time, helping to improve the efficiency of energy infrastructures and promote sustainable development in the energy sector.

Morocco has embarked on a number of projects aimed at ensuring a solid, sustainable energy future, opting for a diversified strategy that includes different energy sources and technologies. This is a field of study that takes into account both geopolitical aspects, i.e. the power relationships between the various players on a global scale, and economic aspects, which concern international trade, investment and wealth creation. This situation suggests that Morocco could play a key role in resolving Europe's energy crisis. Moreover, the country could contribute to the pacification and economic development of the African nations served by the Africa-Atlantic gas pipeline.

Renewable energy systems, such as wind farms and solar power plants, are becoming increasingly complex. Indeed, this complexity is mainly due to the uncertainty associated with variable weather conditions and significant fluctuations in energy production. These factors make the management and optimization of these systems more delicate, and require advanced technological solutions to guarantee stable, reliable energy production. Traditional approaches, based on the use of pre-established models, may prove insufficient to meet the complex challenges associated with the analysis, planning and control of future renewable energy systems. These challenges include the variability of energy sources, the management of smart grids and the need to effectively integrate new technologies into existing infrastructures. Thanks to the applications of artificial intelligence, Morocco is currently implementing a dynamic energy strategy that could help solve Europe's energy crisis. Various tangible and perceptible indicators show that Morocco is increasingly asserting itself as a significant player in the energy sector, whether on the regional or global stage, assuming a crucial central role. In parallel with its national strategy of radically transforming its energy sector and strengthening its sovereignty in this field (I), Morocco is implementing infrastructure and economic projects that could significantly influence energy geopolitics in Africa, the Mediterranean and Europe (II). These moves could not only consolidate Morocco's status as a major player in the energy sector, but also shape regional and global energy dynamics.

1. ARTIFICIAL INTELLIGENCE AT THE SERVICE OF A NATIONAL ENERGY TRANSITION STRATEGY

The impact of artificial intelligence on Morocco's energy sector can be seen in the optimization of renewable energy resources. Morocco stands out for its pioneering role in the integration of renewable energies, notably through large-scale initiatives such as the Noor solar complex.[1]

Artificial intelligence plays a crucial role in improving the performance of these solar panels by anticipating weather conditions and cloud movements, enabling the inclination of the panels to be adjusted to ensure optimum exposure to the sun. Today, drones equipped with artificial intelligence are commonly used to carry out periodic maintenance inspections, anticipate failures and minimize service interruptions.

The impact of artificial intelligence is also significant in the field of energy distribution. Conventional energy networks frequently face challenges such as energy losses during transmission and distribution. Artificial intelligence algorithms are used to analyze large quantities of data generated by smart grids, with the aim of optimizing the distribution of electricity from the point of generation to the consumer, leading to reduced energy losses and financial savings. Artificial intelligence also helps to manage electrical load during periods of high and low demand, ensuring a stable and efficient energy supply.

Artificial intelligence thus plays a revolutionary role in optimizing energy efficiency, whether in the industrial or residential sector. Connected homes equipped with AI-powered systems are able to autonomously manage electricity consumption by switching off unused appliances, adjusting thermostats and scheduling energy-hungry activities during periods of lower demand. This leads to significant savings while helping to reduce overall energy demand.

[1] The Noor Ouarzazate complex represents the first solar project designed as part of Morocco's energy strategy, aimed at increasing the share of renewable energies in the national energy mix to over 52% by 2030. In 2016, His Majesty King Mohammed VI presided over the inauguration of the first phase of the complex, Noor Ouarzazate I. Covering an area of over 3,000 hectares, the Noor Ouarzazate complex consists of four solar power plants employing distinct technologies: Noor Ouarzazate I and II (using parabolic trough technology), Noor Ouarzazate III (based on solar tower technology) and Noor Ouarzazate IV (based on photovoltaic technology). The complex has an installed capacity of 580 MW.

The integration of artificial intelligence therefore brings many benefits to grid management. Morocco's traditional power grid currently faces a number of challenges, including power outages and inefficient energy storage. Artificial intelligence addresses these issues by anticipating demand patterns and recommending the most efficient storage solutions to ensure optimal use of energy, without waste. The use of artificial intelligence for predictive maintenance makes it possible to identify and correct any network faults before they become major problems.

The socio-economic importance of artificial intelligence in Morocco's energy sector should also be emphasized.

Efficient management of energy resources relies not only on the ability to exploit these resources optimally, but also on in-depth, accurate analysis of energy requirements. Thanks to technological advances in the field of artificial intelligence, it is now possible to use sophisticated algorithms to carry out in-depth analyses of consumer purchasing habits. These analyses also make it possible to accurately predict periods when demand for a product or service will be particularly high. During a period of intense summer heat, characterized by high temperatures and increased demand for air conditioning, an intelligent system equipped with advanced sensors could anticipate this significant increase in air conditioning use. Using this information, the system would be able to proactively regulate energy distribution, adjusting the electricity supply to avoid overloading the power grid.

The strategic use of artificial intelligence represents a major asset for companies operating in the industrial sector, as well as for local authorities. Indeed, this technology enables them to significantly optimize the use of their resources, reduce their environmental impact by reducing their carbon footprint, and better control their energy-related expenditure.

1.1 Legal And Instıtutıonal Transıtıon

The transition to renewable energies is gathering pace. At the heart of this dynamic, new laws are being introduced to reshape the country's energy panorama, broadening its energy sources and simultaneously strengthening its energy autonomy. The year 2023 was marked by the promulgation in February of two significant laws. The first, Law no. 40-19, amends and supplements both

Law no. 13-09 on renewable energies and Law no. 48-15 on the regulation of the electricity sector and the establishment of ANRE. The second law, n°82-21, provides a framework for self-generation of electricity. These two pieces of legislation represent major advances in the promotion of renewable energies in Morocco.

They put in place a complete overhaul of the legal and regulatory framework, with the aim of supporting and accelerating the implementation of the national energy strategy and the recommendations of the new development model. They also bring the field into line with current technological advances in the renewable energies sector.

These new laws have several objectives, including guaranteeing transparency for investors, ensuring access to competitive electricity throughout Morocco, and creating an environment conducive to private investment, whether national or international, in the electricity sector, particularly in renewable energies. This range of laws also enables every citizen to generate their own electricity for personal consumption, meeting only their individual needs. However, the application of these laws requires the creation of other regulatory texts, which must be drawn up by the legislator within a maximum period of 4 years from the date of publication of these laws in the Bulletin Officiel.

In all, 14 articles of law n°40-19 and 12 articles of law n°82-21 stipulate that their implementation will be achieved through regulatory texts. In this context, the current year has also been characterized by the preparation of most of the draft decrees concerning these provisions, which are currently the subject of discussions and exchanges with all stakeholders in the electricity sector with a view to their official approval.

1.2 The Energy Transıtıon

In 2009, the Kingdom of Morocco launched the implementation of an ambitious energy strategy, under the direction and supervision of His Majesty King Mohammed VI. This strategy aims to diversify energy sources, promote renewable energies and guarantee the country's energy security. The main aim of this strategy was to promote the development of renewable energies, by encouraging the use of clean, sustainable energy sources such as solar, wind and hydro power. In addition, the strategy aimed to increase energy efficiency by encouraging the introduction of technologies and practices that reduce energy consumption. Finally, it also sought to foster regional integration in the energy field, encouraging cooperation between neighboring countries to develop joint energy projects and promote a stable, diversified energy supply.

The main aim of Morocco's energy strategy is to implement a plan to diversify the country's available energy sources. The strategy also aims to promote the use of renewable energies, such as solar and wind power, to reduce dependence on fossil fuels. It is vital for the country to develop technologies that integrate seamlessly with existing infrastructures using renewable energy sources. This transition requires a thorough analysis of the ethical and confidentiality issues involved.

Over the last twenty years, the electricity sector in Morocco has undergone significant change. This evolution is characterized by a significant increase in demand for electricity, constant recourse to energy imports and a preponderance of fossil fuels in the overall composition of energy sources used. In 2022, Morocco produced around 43 TWh of electricity. Despite this high figure, inefficiencies were observed in electricity storage and distribution processes, which ultimately limited the amount available for end use to 38 TWh. Fossil fuels, such as coal, oil and natural gas, accounted for 83% of the country's total electricity production. This heavy reliance on fossil fuels has resulted in a significant 48% contribution to greenhouse gas emissions from the energy sector, with a consequent impact on the environment and climate. In order to comply with international climate agreements, Morocco has set itself particularly ambitious decarbonization targets. These aim to increase the share of renewable energies in its energy mix, with an intermediate target of 52% by 2030, and a higher target of 70% by 2050.

In Morocco, various initiatives are currently being implemented in the renewable energy sector. These include the development of solar energy, with an installed capacity of 1.6 GW and an annual production of 4.14 TWh. The country is also committed to wind power, with a capacity of 1.28 GW and an annual production of 4.29 TWh. Finally, hydropower also plays an important role, with a capacity of 1.1 GW and an annual production of 1.7 TWh. By the year 2050, specific efficiency improvements are planned for various renewable energy sources. For solar energy, a 28% increase in efficiency is envisaged. For wind power, an improvement of 55% is planned, while for hydro power, efficiency is expected to rise from 90 to 94%. These improvements will be accompanied by corresponding cost reductions, estimated at $37 per megawatt-hour for solar power, $41 per megawatt-hour for wind power and $26 per megawatt-hour for hydro power. The integrated energy sectors play a key role in reducing greenhouse gas emissions, resulting in a reduction of 41 million tonnes of CO2 equivalent. This reduction is made possible by the promotion and development of renewable energies in various fields, such as solar irrigation with a capacity of 125 megawatts, industrial energy with a capacity of 480 megawatts, and transport with a capacity of 91 megawatts.

1.2.1. Improvıng Energy Productıon Methods

Artificial intelligence is widely used to predict and optimize the production of energy from renewable sources such as solar and wind power. This technology makes it possible to collect and analyze large quantities of data to anticipate production variations and optimize processes, thus contributing to more efficient and sustainable use of renewable energy resources. According to various scientific studies, it has been proven that the use of artificial intelligence algorithms can have a significant impact on improving the accuracy of weather forecasts, which are essential for the smooth operation of management systems linked to this field.

In Morocco, recent studies have been carried out to closely analyze how artificial intelligence algorithms can be used to improve and maximize the efficiency of wind farms. This research focuses on exploring the different ways in which these innovative technologies can be applied in the wind energy sector, with a view to optimizing energy production and ensuring more efficient operation of wind farms. As a concrete example, it is worth mentioning that a fruitful collaboration has been established between the Moroccan Agency for Sustainable Energy (MASEN) and various national academic institutions. The aim of this collaboration was to further investigate the use of advanced predictive models to optimize wind power generation. It should be noted that this study specifically took into account local meteorological conditions specific to the region, with the aim of improving the overall efficiency of the energy production process. The main aim of these initiatives is to put in place measures to improve energy utilization in a more efficient way, while ensuring that the reliability and robustness of the power grid is maintained over the long term.

1.2.2. Improvıng Energy Networks

Intelligent optimization of energy networks involves implementing advanced technological solutions and innovative strategies to improve the efficiency, reliability and sustainability of energy distribution and transmission networks. This approach aims to integrate intelligent management tools, such as automated control systems, intelligent sensors and optimization algorithms, to optimize energy production, distribution and consumption more efficiently and economically.

Artificial intelligence, the ability of machines to mimic human intelligence, plays a crucial and essential role in the monitoring and management of energy networks. Its use facilitates the optimal integration of intermittent renewable energy sources, contributing to greater efficiency and reliability of the energy system as a whole.

This technology could reduce energy losses by up to 15% and increase the reliability of large-scale interconnected networks.

Today, we are seeing a significant increase in the use of artificial intelligence in the field of predictive maintenance of equipment within facilities dedicated to the production of renewable energy. This emerging technology makes it possible to predict potential equipment failures, optimize performance and reduce maintenance costs, thus contributing to greater efficiency and sustainability of energy installations based on renewable sources.

In Morocco, solar installations are benefiting from advances in artificial intelligence, enabling them to optimize their performance and efficiency. Thanks to the integration of intelligent technologies, these installations can adjust their operation in real time according to weather conditions and energy demand, thus contributing to a more efficient use of solar energy in the country. It is also essential to implement measures to improve energy efficiency in order to reduce energy consumption and minimize environmental impact.

This means limiting the amount of energy used in various processes and activities, thereby preserving natural resources and combating climate change. Artificial intelligence systems, which are computer technologies capable of simulating human intelligence, are deployed with the specific aim of optimizing energy consumption and boosting the energy efficiency of buildings and industrial facilities. These systems take into account the constant variations in renewable energy sources, such as solar and wind power, to optimize and better control energy consumption. By analyzing data from these intermittent energy sources in real time, these systems can effectively adjust power generation and distribution to meet energy demand more sustainably and efficiently.

1.3 Issues And Challenges

The implementation of specific programs, accompanied by clearly defined objectives and supported by targeted legislative and institutional reforms, has proved its effectiveness in generating positive results and responding appropriately to identified needs. Morocco has succeeded in diversifying its energy sources by implementing specific policies and projects focused on the development of renewable energies. These initiatives have enabled the country to reduce its dependence on fossil fuels and promote a transition to more sustainable, environmentally-friendly energy sources. Thanks to this diversification, the country has been able to reduce its dependence on imported fossil fuels and meet its energy demand more autonomously and sustainably.

Renewable energies, including solar energy from the sun's rays, wind power from the wind, hydropower from water and biomass energy from organic matter, play an essential and central role in Morocco's overall energy policy. In fact, the country has considerable potential in terms of renewable energies, giving it the opportunity to vary its energy sources and reduce its dependence on fossil fuels. The advancement and implementation of these new, innovative and environmentally-friendly energy technologies will play a crucial role in meeting a growing share of the country's ever-increasing energy demand. What's more, these advances will offer an environmentally-friendly alternative to the fossil fuels that are widely used today. As part of its energy strategy, Morocco has set an ambitious target to increase the proportion of renewable energies in its installed electricity capacity. This initiative aims to reduce the country's dependence on fossil fuels and promote sustainable development by encouraging the use of clean, renewable energy sources such as solar, wind and hydro power. This increase is expected to reach a rate of over 52% by the year 2030, representing significant growth over a ten-year period.

The Kingdom recently took the decision to adopt an ambitious new strategy to improve the supply of drinking water. This strategy includes the implementation of a complementary program aimed at strengthening and extending existing infrastructures, as well as raising public awareness of the importance of preserving water resources. The aim of this program is to set up renewable energy production units at each of the planned seawater desalination plants. This will promote the use of clean, sustainable energy sources to power these essential drinking water production facilities. Energy self-sufficiency for these individuals means that they are able to meet their energy needs without having to rely on external energy sources. This autonomy gives them greater independence and freedom in their consumption, as they are not subject to fluctuations in energy prices or possible shortages. What's more, energy autonomy offers individuals the chance to make substantial savings over the long term. Indeed, this translates into lower electricity costs and a reduced impact of energy price fluctuations on their budget.

The aim of this innovative approach is to analyze in detail and put into practice innovative energy solutions. In particular, this includes exploring the possibilities of waste-to-energy conversion, especially biomass, in Morocco's major conurbations. The aim of this initiative is to raise awareness of the importance of using renewable energies wherever possible. The aim is to promote an energy transition that is both sustainable and respectful of the environment. This will optimize the energy consumption of public buildings, helping to reduce their ecological footprint. This initiative is part of a wider program designed to encourage and promote the State's sustainable energy practices, demonstrating its commitment to the energy transition.

There are currently over a hundred projects playing a key role in the transition to more sustainable, environmentally-friendly energy sources. These projects are actively committed to promoting greener energy practices and reducing the carbon footprint of our societies.

The installed capacity of renewable energy sources recently reached 3950 MW. This includes technologies such as wind, solar, hydro and biomass. This capacity, which corresponds to around 37% of all energy sources used, bears witness to a significant increase in the share of renewable energies within the energy sector. This development highlights the growing importance of clean energies in the overall energy mix, underlining a positive shift towards more sustainable and environmentally-friendly energy sources. Total renewable energy capacity is evenly distributed between different sources such as solar, wind, hydro, biomass and geothermal. As part of this project, a total of 710 megawatts is specifically earmarked for solar power generation. A further 1,430 megawatts are earmarked for wind power, while 1,770 megawatts are earmarked for hydroelectric power generation.

Today, renewable energies - including solar, wind, hydro and biomass - play a significant role in electricity generation, accounting for around 20% of total production. The energy dependency ratio, which is the percentage of a country's energy needs met by external sources, has fallen significantly in recent years. This decrease reflects the country's greater energy autonomy , with a reduction in its reliance on external sources to meet its energy needs. In fact, the rate of energy dependence has fallen significantly over the years, from 97.5% in 2009 to 90.51% today. This development reflects a trend towards reduced energy dependency and increased self-sufficiency in energy production.

However, current infrastructures in Morocco, which were put in place before the advent of digital innovations, can often prove inadequate to integrate them effectively without requiring significant modifications and consequent adjustments. Traditional energy management systems, often based on obsolete protocols, need to be updated to ensure optimal communication with modern AI tools. This adaptation is essential to enable smooth and efficient integration between these two technologies. Implementing this change can be costly, due to the many aspects that need to be taken into account. It requires careful planning, including the precise allocation of human and financial resources. Not to mention the need to modernize power grid infrastructures to make them more efficient and sustainable. In addition, it is essential to implement advanced planning and management strategies to ensure optimal network operation.

In addition, promoting research and development is crucial to reducing energy losses, lowering the costs of renewable energies and enhancing overall grid stability.

In order to effectively counter this phenomenon, known as the "renewable energy curse", which can hinder the development of this sector in Morocco, it is imperative to take several measures. It is essential to strengthen the role and competencies of the Autorité Nationale de Régulation de l'Electricité (ANRE) to ensure adequate and effective market supervision. In addition, simplifying the administrative procedures involved in accessing the electricity grid would facilitate the integration of new renewable energy installations. Encouraging local production of green energy would help reduce dependence on imported fossil fuels and promote the country's energy independence. In addition, promoting decentralized energy systems would offer a more resilient solution, adaptable to local needs. Finally, consolidating partnerships between the public and private sectors would encourage the development of sustainable infrastructures and innovative renewable energy projects.

It's clear then that AI offers the potential to optimize various aspects of energy production and distribution, creating new job opportunities in the fields of AI development and energy management. Specialized training in artificial intelligence and data science is becoming increasingly essential to provide workers with the skills required to succeed in this ever-changing context.

2. ARTIFICIAL INTELLIGENCE AT THE SERVICE OF AN INTERNATIONAL ENERGY TRANSITION STRATEGY

Morocco's current energy drive along the Atlantic coast is seen as an initiative that could help provide solutions to Europe's energy crisis. It can be seen from a number of concrete, observable facts that Morocco is becoming a major player in the energy field, both regionally and internationally, playing an essential pivotal role. In addition to embarking on a national strategy to fundamentally transform its energy sector and strengthen its sovereignty in this field, Morocco is currently developing infrastructure and economic projects that could have a major impact on energy geopolitics in Africa and Europe.

These initiatives could not only strengthen Morocco's position as a key energy player, but also influence regional and international energy dynamics. Intelligent algorithms, with their ability to process large quantities of data and make decisions in real time, can play a crucial role in improving the performance of these energy infrastructures. By analyzing energy consumption and production data, these algorithms can optimize energy efficiency, reduce costs and minimize environmental impact. Thanks to their ability to adapt to variations in demand and anticipate needs, they help guarantee a reliable and sustainable energy supply. To anticipate changes in climate and quickly adjust equipment settings, they carefully analyze a wide variety of meteorological and environmental data. Predictive capability, which involves anticipating energy and maintenance requirements, not only helps optimize the energy efficiency of infrastructures, but also contributes to extending their lifespan by preventing damage and reducing premature wear and tear.

2.1 A Strategic Gateway To Africa

His Majesty King Mohammed VI has consistently advocated development with a "human face" in Africa, emphasizing the collective mobilization of African nations to achieve the goal of unity and strengthen the continent's leadership on a global scale. It was against this backdrop that the monarch announced the Royal Atlantic Initiative in his speech on November 6, 2023, marking the 48th anniversary of the Green March. The aim of this initiative is to strengthen common security, stability and prosperity among the 23 Atlantic African states, while facilitating access to the Atlantic Ocean for the Sahel states.

His Majesty King Mohammed VI emphasized that Morocco is closely linked to Europe by its Mediterranean coastline, while its openness to the Atlantic offers direct access to Africa and a gateway to America. In addition, he advocated a structuring of African scope for this geopolitical space.

The royal vision is to transform the Atlantic seaboard into a center of human gathering, a hub of economic integration, and a point of convergence on a continental and international scale, while taking into account the challenges and issues facing African countries, particularly those located along the Atlantic seaboard.

Indeed, Atlantic Africa presents significant geostrategic, economic and human opportunities, yet suffers from a significant lack of infrastructure and investment.

The royal address of November 06, 2023 underlined the importance of modernizing the infrastructure of the Sahel states and integrating them into regional transport and communications networks for the success of the Atlantic Africa Initiative.

The Head of State also affirmed that, while convinced that this initiative will have a significant impact on the economies of these neighboring nations and the region as a whole, Morocco is ready to make its road, port and rail infrastructures available to them.

The Atlantic African Gateway Project (AAGP) was launched in 2016 by Morocco and Nigeria. Since then, it has evolved and reached an advanced phase in 2022, demonstrating significant progress over the years. Initially limited to a simple agreement between two parties, this agreement has taken on a broader regional dimension following the signing of a Memorandum of Understanding involving the Economic Community of West African States (ECOWAS), Nigeria and Morocco. The aim of the project is to establish a system for transporting gas resources from Nigeria to Morocco, in order to meet the energy needs of both countries and promote trade between them. This transport system will enable natural gas extracted in Nigeria to be efficiently transported to Morocco, where it can be used for power generation, heating and other energy needs.

This initiative will help strengthen economic and energy cooperation between the two nations, while promoting economic development and job creation in the region. This natural gas transport system will run through eleven West African countries, passing through territories such as Nigeria, Benin, Togo, Ghana, Côte d'Ivoire, Burkina Faso, Mali, Senegal, Mauritania, Morocco and Algeria. Once it reaches Algeria's northern border, it will be connected to the Maghreb Europe pipeline, which crosses the Mediterranean to reach Europe. As a result, natural gas extracted in West Africa will be able to feed the European energy grid, contributing to energy security and trade between the two continents. In June 2023, an official announcement was made concerning the signing of a Memorandum of Understanding, a cooperation and mutual understanding agreement, with several West African countries. These countries include Guinea, Côte d'Ivoire, Liberia and Benin, marking a strengthened commitment to collaboration and partnership between these nations. Thanks to this approach, it has been possible to confirm that these nations are fully committed to joining the project in question. This underlines their clear willingness to collaborate closely and become actively involved in the initiative.

The pipeline, which will be laid on the seabed, will meticulously follow the course of Africa's west coast, passing through the Gulf of Guinea region in particular. The aim of this ambitious multilateral project is to create and implement a gas connection infrastructure linking all West African countries as far as Morocco. This infrastructure is intended to promote energy exchanges between the participating countries and strengthen regional cooperation in the energy field. The aim of this initiative is to promote the creation of a regional natural gas market. The aim is to strengthen economic and energy integration between the countries involved, by promoting energy exchanges and cooperation. This initiative would provide the countries of the region with a stable and affordable source of energy, helping to boost their energy security and stimulate their economic development. It should also be emphasized that the implementation of this measure would open up new export prospects for natural gas-producing countries. Indeed, it would give them the opportunity to diversify their outlets and explore new markets for their natural gas, which could have a positive impact on their economies.

It should be stressed that other West African countries could play an important role in future gas supplies, despite the fact that Nigeria remains by and large Africa's main potential gas supplier, owing to its possession of most of the continent's gas reserves. These countries, although less publicized, also possess significant gas resources and could make a significant contribution to regional gas supplies. Another crucial and relevant objective in the current European context is that this gas, whose supply is essential, should ultimately be redistributed efficiently and equitably to the various European countries. This redistribution aims to meet the region's growing energy demand, ensuring a stable supply and promoting the economic and industrial development of the countries concerned.

The project has been carefully planned to guarantee an annual production capacity of 30 billion cubic meters of natural gas, representing a significant quantity of this essential resource. This significant natural gas production, amounting to 18 billion cubic meters, opens up the prospect of supplying a substantial quantity of this gas to Europe, thus meeting a specific demand in the field of energy exports.

In January 2025, Morocco signed a memorandum of understanding with Mauritania. It concerns an electricity interconnection project to link the power grids of the two countries, in addition to that of Spain. This project represents an essential preliminary step in the process of electricity interconnection with the West African Power Pool (WAPP). It is also part of the Desert-to-Power Initiative, which aims to link North Africa to West Africa, and more generally to sub-Saharan Africa. It offers the possibility of exporting electricity to Southern Europe via the Senegal-Mauritania-Morocco axis, an interesting opportunity for the development of energy exchanges between these regions.

2.2 A Strategic Gateway To The Mediterranean

The Blue Plan's MED 50 report and the consultation workshops on scenarios for the Mediterranean to 2050, held by the Royal Institute for Strategic Studies (IRES) in Tangier on February 4 and 5, 2025, as part of the Blue Plan's regional initiatives on the future of the Mediterranean, revealed that the changing global context highlights the need for the Euro-Mediterranean region to be integrated into wider dynamics encompassing Africa as a whole, Asia and the Americas.

The phenomenon of climate change predicts a rise in temperatures of around 2.3°C by 2050, leading to a sea-level rise of over 40 cm. This could lead to flooding, in addition to extreme weather phenomena such as heatwaves on land and at sea, as well as droughts.

Demographic transition is considered complete in around two-thirds of countries, but global population growth of 20-30% is forecast by 2050, which would translate into a population of 520-630-690 million.

Urbanization is characterized by significant urban growth, with the urbanization rate exceeding 70% in all countries (on average 82%).

Land use is characterized by a growing concentration of populations and activities in metropolises and along the coast, with over 50% of the total population forecast for 2050, compared with 30 to 40% in 2020.

Changes in the marine ecosystem are characterized by a trend towards tropicalization and structural transformation, leading to the replacement of biodiversity by non-indigenous species, disruptions to plankton ecology, the proliferation of jellyfish, and the deterioration of coral reefs and Posidonia meadows.

Water: the deterioration of water stress, which will affect at least 290 million people in 2050, compared with 180 million in 2020.

Morocco is then encouraged to strengthen international cooperation in the long term (2040-2050):

- Strengthen its advanced position within the European Union, by establishing this status as a genuine framework for mutually beneficial cooperation.
- Establish collaborations with other nations and international institutions, particularly in the fields of climate change, natural resource management and the promotion of sustainable development.
- Consolidate regional cooperation in the Mediterranean by encouraging the sharing of experience and best practices, as well as collaborative projects.
- Allocate resources to research and development to devise sustainable solutions to environmental, economic and social challenges. This means promoting innovation in sectors such as renewable energies, energy efficiency, the circular economy, sustainable agriculture, digital technologies and artificial intelligence.
- Encourage cooperation between researchers, companies and public bodies to stimulate the spread of new technologies and innovative solutions.
- Incorporate climate challenges into all public policies. By taking account of the impact of climate change in all political and economic decision-making, particularly in the fields of land-use planning, urban development, agriculture, energy, tourism and transport.

Develop strategies for adapting to climate change by anticipating risks and implementing actions to reduce the vulnerability of populations and infrastructures.

- Encourage the adoption of sustainable consumption and production practices, notably by promoting the use of renewable energies, waste reduction and responsible consumption.

2.3. A Strategic Gateway To Europe

Morocco has set itself the target of generating 52% of its electricity from renewable sources by 2030. This involves massive investment in infrastructure such as wind farms, solar power plants and hydroelectric dams, in order to reduce its dependence on fossil fuels and foster a transition to a more environmentally-friendly economy. The main aim of this project is to be able to export a significant amount of the electricity generated to European countries using specially designed submarine cables. Morocco occupies a strategically important position as a connection point between Europe and Africa, particularly in terms of electricity interconnections. This is particularly evident in its links with Spain, established via two submarine power lines with a total capacity of 1,550 MW. A third power connection, with a capacity of 700 megawatts, has been installed to reinforce the existing power grid. This new connection will increase power transmission capacity and improve grid reliability to meet growing energy demand. A submarine interconnection project with a transmission capacity of 1,000 MW was recently initiated between Morocco and Portugal. This interconnection aims to strengthen energy links between the two countries, enabling a more fluid and efficient exchange of electricity.

Following ratification of the SET Roadmap joint declaration agreement at COP-22 in Marrakech, which concerns electricity exchanges between Morocco, Germany, France, Spain and Portugal, Morocco is committed to supplying 8% of the UK's electricity needs. This supply will come from renewable energy sources produced in Morocco at an affordable cost, as part of the XLinks Morocco/UK project. This project will consist of a new electricity generation facility, powered exclusively by solar and wind energy, and including a battery storage system.

Artificial intelligence can be an extremely valuable and beneficial tool in this context. It can significantly improve energy production and guarantee maximum energy efficiency. Thanks to its advanced analysis and automated decision-making capabilities, AI helps to optimize production processes, anticipate energy needs and implement strategies to take full advantage of available renewable resources. For example, a wind turbine can adapt the angle of its blades in real time to make the most of every variation in wind strength and direction. Similarly, solar panels can be equipped with an automated system enabling them to tilt so as to precisely follow the sun's trajectory throughout the day, thus optimizing their energy yield.

CONCLUSION

Current regulations, including laws 57-09, 37-16, 13-09 and 48-15, have played a key role in promoting and developing renewable energies in Morocco. These laws have established a legal framework favorable to the emergence of new, clean and sustainable energy sources, thereby contributing to the energy transition and the fight against climate change.

Morocco stands out for its leading role in the integration and innovation of renewable energy technologies, incorporating advances in artificial intelligence. This leading position represents a significant contribution to the fight against climate change, both nationally and internationally. Despite the persistent data security challenges facing players in the energy sector, it is positive to note that researchers, companies and governments remain strongly committed to the development of solutions exploiting artificial intelligence. This sustained involvement suggests the prospect of a smarter, more resilient energy future, in which technological advances can be fully exploited to meet growing energy demands. However, a paradox lies behind these two parallel transitions, namely the digital transition and the energy transition: while the energy transition depends on AI, the latter requires a significant amount of energy. Focusing exclusively on the USA, annual electricity demand from data centers is forecast to exceed 580 Terawatt-hours (TWh) by 2028, according to the IEA, compared with 176 TWh in 2023, far exceeding the total annual consumption of African countries. This rapid and significant increase raises questions about the positive impact of digital technology on Morocco's energy transition. This transition aims to optimize energy infrastructures and promote sustainable development in the energy sector, thereby strengthening the country's position on the regional and international scene.

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CHAPTER 4

THE TRANSFORMATION OF THE GLOBAL ENERGY MARKETS AND THE PROBLEM OF ENSURING THE SUSTAINABILITY OF THEIR DEVELOPMENT

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INTRODUCTION

The significance of energy in the functioning of a nation's economy and society cannot be overstated. Nevertheless, the bulk of global energy demand is still satisfied by non-renewable fossil fuels like oil, coal, and natural gas (Abban et al., 2022; Amin et al., 2022). Nonetheless, these sources are finite, contribute to environmental pollution and climate change, and are progressively more arduous and costly to extract. Consequently, an urgent and imperative need exists to shift towards sustainable energy alternatives that are both renewable and cleaner, capable of mitigating the detrimental impacts of climate change. This transition towards sustainable energy presents a spectrum of challenges and opportunities for the global economy. Fossil fuels have long served as the predominant energy source worldwide due to their high energy density and affordability. However, the combustion of these fuels has resulted in emissions that have caused escalating global temperatures, an increase in extreme weather events, and a myriad of other catastrophic environmental transformations (Ansari et al., 2022; Asif et al., 2022; Chenic et al., 2022). As a result, numerous scholars have extensively investigated this subject matter through the utilization of modeling, empirical investigations, and optimization techniques (Li et al., 2018; Xu et al., 2022; Tong et al., 2023; Xie et al., 2023; Yin et al., 2023).

The primary objective of every society is to achieve development in all its dimensions (Meinshausen et al., 2022). Access to high standards of energy production and consumption is a key indicator of a country's success in achieving development. However, energy production and consumption, whether fossil or non-fossil, pose significant threats and challenges to the environment and sustainable development, despite their role in contributing to economic growth and development (Chien, 2022; Fang et al., 2022; Farghali et al., 2023). Sustainable energy can only be achieved through the integration of the environment, energy, and development sectors. Conversely, the absence of integration can lead to conflicts between the objectives of these sectors, which can hinder the achievement of sustainable development (Holechek et al., 2022; Ishaq et al., 2022; Islam et al., 2022). At the international level, policies related to energy and development have been largely aligned, while environmental policies have not. The misalignment between these factors can create difficulties and discord, and resolving this dilemma requires the development of effective solutions by the global community that strike a balance between energy supply security, economic advancement, and environmental safeguarding. Hence, the primary obstacle to sustainable development in the energy industry is to ensure that the advantages of energy services are extended to the world's population and future generations without causing harm to the environment (Nnabuife et al., 2022; Meydani, 2023; Mohideen et al., 2023).

During the 1980s and 1990s, energy-related matters garnered considerable attention; however, environmental considerations within the energy sector were largely overlooked by governments. The intricate nature and diverse array of interests involved posed challenges in implementing substantial policy changes. Moreover, many countries possessing oil and gas resources faced constraints in terms of political, economic, and technological capacities, impeding their ability to transition towards sustainable development by reducing dependence on fossil fuels and transforming core economic strategies. The substantial reliance on non-renewable fossil fuels in global energy production and consumption has proven to be a significant obstacle in achieving sustainable development objectives (Kanwal et al., 2022; Jie et al., 2023; Kocak et al., 2023). Sustainable energy is characterized by a lower *per capita* production of greenhouse gases. However, unstable energy production and consumption patterns have led to several environmental problems, including climate change, acid rain, ozone depletion, nuclear radiation, urban air pollution, and marine pollution caused by oil transportation. Developing and developed countries have blamed each other for these issues, with developing countries accusing developed countries of environmental destruction due to excessive energy consumption resulting from increased demand, and developed countries accusing developing countries of environmental degradation due to increased consumption resulting from population growth (Nnabuife et al., 2022; Meydani, 2023). Both claims are valid, but research indicates that developing and developed countries face different challenges in relation to the environment and energy. Developing countries face energy resource scarcity and lack of access to energy, while developed countries face pollution and energy waste (Luo et al., 2013; Gielen et al., 2016).

The international community eventually recognized that sustainable development cannot be achieved without sustainable energy (Adamowicz, 2022).

When discussions about the pollution caused by traditional energy sources arise, there is often a shift towards non-conventional energy sources (Ramzan et al., 2022; Mohideen et al., 2023). Lovin’s guidelines, introduced in 1972, provide a precise framework for establishing acceptable and conventional energy policies using both hard and soft methods. In Lovin’s model, the hard path emphasizes the rapid development of energy resources such as coal and nuclear energy, with sustainable energy production for low consumption and efficiency being highlighted. This approach involves extensive research on nuclear energy and rapid development of energy resources like coal. Lovin’s theory suggests that the hard path leads to the creation of elite technology, concentration of economic and political power, vulnerability to technological threats, and the potential for social and economic injustice and complexity (Lovins, 1974; Lovins, 1976). On the other hand, the soft energy path focuses on limiting energy production and maximizing efficiency in consumption. Soft energy leads to a small, decentralized system and is flexible, sustainable, and environmentally safe. The advantages of this approach are manifold and include the potential to extend energy generation beyond centralized production centers, self-sufficiency in energy supply, reduced reliance on public or private energy infrastructure, a preference for renewable energy over non-renewable sources, eliminating the use of uneven energy resources, prioritizing energy conservation, and employing low-risk technology that is suitable for energy sources with high risk factors (Takase et al., 2022; Yasmeen et al., 2022; Sharma et al., 2023).

Renewable energy technologies have experienced significant advancements in recent years, with increased efficiency and declining costs. They offer a promising pathway to a sustainable energy system, but significant investments and policy changes are still necessary to facilitate the transition. The high upfront costs associated with renewable energy infrastructure remain a significant barrier for many. Government policies and incentives that favor renewable energy development and use are crucial to overcoming the obstacles to adoption and accelerating the transition towards sustainability.

Some key policies that can support renewable energy include tax incentives, direct subsidies, renewable energy mandates, and carbon pricing (Siddik et al., 2023; Zakaria et al., 2023). Through appropriate policies and economic support, renewable energy has the potential to surpass fossil fuels in competitiveness. The transition to renewable energy offers various economic advantages, including the creation of new job opportunities in the sustainable energy sector, enhanced energy security and independence, and long-term cost savings. The renewable energy industry is generating numerous employment opportunities in manufacturing, technology, installation, and related fields. Shifting towards locally available renewable sources also enables countries to achieve greater energy security and independence. While renewable energy technologies often involve initial high costs, their operating costs remain low as the sun or wind (as fuel sources) is freely available. Over time, these technologies can yield cost savings alongside environmental benefits. Nevertheless, the transition presents economic challenges that necessitate attention. Established interests striving to maintain the *status quo* may pose social and political obstacles. A successful transition requires initiatives such as worker retraining programs, support for affected communities, and effective communication with citizens and policymakers to highlight the advantages of renewable energy. Nonetheless, with the rapid decline in the costs of renewable technologies, the economic arguments in favor of sustainability and renewables are becoming more compelling over time (Takase et al., 2022; Yu et al., 2023; Zhang et al., 2023).

The implementation of blockchain technology presents a significant opportunity for advancing sustainable energy systems. This technology operates as a decentralized ledger that records transactions in a permanent and unalterable manner, thereby enabling transparent monitoring of energy production and consumption throughout the network. Numerous projects are leveraging blockchain to enable peer-to-peer energy trading between producers and consumers, monitor the origin of renewable energy generation, and facilitate innovative financing models for renewable energy projects. The intermittency of renewable energy sources poses a significant challenge for renewable energy. Blockchain can help address this by enabling decentralized energy trading networks. When a solar panel owner generates excess energy, they can sell it to neighboring buildings using smart contracts on the blockchain. Neighbors who need additional energy can buy it instantly in a transparent marketplace, resulting in minimal waste and improved overall efficiency and reliability of renewable energy (Afzal et al., 2022; Gawusu et al., 2022; Dwivedi et al., 2023). Several startups facilitating these energy trading networks have launched in New York, California, and European countries. Another promising application of blockchain for sustainable energy is renewable energy certification and tracking the origin of energy. Certification systems like Renewable Energy Certificates (RECs) help fund renewable energy projects by enabling businesses and individuals to purchase renewable energy credits. However, the current system for RECs involves cumbersome paperwork, administration fees, and a lack of transparency. Implementing RECs on an open blockchain platform can reduce costs, simplify the process, and provide a clear link between the generation and consumption of renewable energy. Several companies are piloting blockchain-based renewable energy certificate platforms (Juszczyk and Shahzad, 2022; Polas et al., 2022; Wu et al., 2022).

Although there has been a proliferation of research on sustainable energy and the potential of emerging technologies, there still exists a discernible gap in knowledge regarding the assimilation of blockchain technology in the shift towards sustainable energy alternatives. Additionally, the interplay between energy policy, economic factors, and technological advancements in facilitating this transition has not been comprehensively explored. Thus, the importance of this study lies in addressing this research gap and providing valuable insights into the challenges, opportunities, and implications of transitioning to sustainable energy sources, while emphasizing the role of blockchain technology and policy changes. The primary objective of this investigation is to examine the intricate facets of the worldwide energy milieu and assess the viability of blockchain technology in advancing sustainable energy solutions. The research methodology employed in this study is a qualitative research design, which includes an extensive literature review and content analysis. This systematic approach facilitates a thorough examination of the interconnections among energy, policy, technology, and the economy in the transition towards sustainable energy sources. The study’s findings have multiple practical implications, including offering evidence-based insights for policymakers and industry stakeholders in the formulation of sustainable energy strategies. Moreover, the research outcomes inform future studies in this field. These insights play a crucial role in enhancing policy effectiveness, encouraging investments in renewable energy technologies, and fostering the expansion of the sustainable energy sector. Ultimately, this study aims to advance the understanding of the role of blockchain technology and policy changes in facilitating the transition to sustainable energy sources, and the benefits and challenges associated with this transition, thereby contributing to the development of a more sustainable and resilient global economy.

1. FUNDAMENTAL CONCEPT OF THE STUDY AND DEFINITIONS

1.1 Sustainable Energy and Technologies

The term sustainable energy pertains to energy resources that can fulfill existing energy requirements while preserving the capacity of future generations to meet their own energy needs. This widely accepted definition is supported by scientific literature and the international community. The adoption of sustainable energy solutions is essential in curtailing the release of greenhouse gases into the environment and ameliorating the impacts of climate change. Moreover, it promotes energy security by decreasing reliance on fossil fuels and promoting energy independence. The development and implementation of sustainable energy technologies require a complex process that involves technological innovation, policy support, and public awareness (Chai and Zhang, 2010; Qazi et al., 2019).

Various sustainable energy technologies are currently being developed, including solar PV, wind turbines, geothermal energy, energy storage, smart grids, hydrogen fuel cells, and biofuels. Solar PV technology converts sunlight into electricity through solar panels and is rapidly advancing, becoming more efficient and cost-effective. Biofuels, derived from renewable biomass sources, are becoming more sustainable and environmentally friendly than traditional fossil fuels due to advances in technology. These technologies aim to provide a stable and reliable supply of electricity while balancing energy supply and demand, integrating renewable energy sources into the grid, and offering a clean source of energy for transportation and other applications. Also, they are expected to become more efficient, cost-effective, and widely adopted as research and development continue. They hold the potential to build a sustainable energy future, addressing the world's growing energy needs while reducing the environmental impact of energy production and use (Chu and Majumdar, 2012; Vujanović et al., 2021).

1.2 Economic Benefits Of Sustainable Energy Transition

Sustainable energy practices, policies, and technologies offer numerous economic benefits, including cost savings, job creation, and increased competitiveness. The adoption of renewable energy sources can reduce dependence on fossil fuels, which are susceptible to price volatility and supply disruptions. Renewable sources like solar and wind power have become cost-competitive with traditional sources in many regions, with costs expected to decrease further. Energy efficiency measures can also reduce energy costs by improving energy use efficiency and decreasing waste. The development and deployment of sustainable energy technologies create new job opportunities in industries such as renewable energy, energy efficiency, and energy storage. Businesses that adopt sustainable energy practices and technologies can reduce energy costs, enhance their reputation, and meet the growing demand for sustainable products and services, leading to increased market share and profitability (Bulavskaya and Reynès, 2018; Osorio-Aravena et al., 2021; Dong et al., 2022; Tirkolaee et al., 2022; Wang H. et al., 2023). The shift towards a sustainable energy future can have a positive impact on public health by decreasing air pollution, which has severe health consequences. The costs of air pollution to the environment and public health can be considerable, and the adoption of sustainable energy practices and technologies can help to minimize these costs. The integration of sustainable energy practices and technologies can also decrease the environmental impacts related to energy production and use, such as land use impacts and greenhouse gas emissions. The environmental costs of conventional energy sources can be significant, and the adoption of sustainable energy practices and technologies can help to address these costs and promote a more sustainable and resilient energy system. To conclude, the implementation of sustainable energy practices, policies, and technologies can offer numerous economic benefits, including job creation, cost savings, improved public health outcomes, and reduced environmental impacts. By leveraging technologies like blockchain to enhance the efficiency and transparency of energy systems, we can expedite the transition to an energy system that is both sustainable and resilient and that benefits the economy and the environment (Jenniches, 2018; Gielen et al., 2019; Ghasemi et al., 2021; Mirzaei et al., 2021).

1.3 Blockchain for Sustainable Energy

Distributed ledger technology, known as blockchain, facilitates secure, transparent, and tamper-proof recording of data and transactions. It operates by using a decentralized network of computers to validate and verify transactions, thereby eliminating intermediaries like banks or governments. The integration of blockchain technology presents significant potential in the shift towards a sustainable energy future, as it enables more efficient and transparent energy systems. It can address many of the challenges associated with the transition by enabling more effective management of energy systems, improving energy efficiency and reducing waste, and increasing transparency and accountability in energy systems (Arabian et al., 2022; Barenji and Nejad, 2022). Blockchain technology can provide a secure and transparent platform for tracking the production and consumption of energy and enables peer-to-peer energy trading (Wu and Tran, 2018; Ahl et al., 2020; Otoum et al., 2022; Goli, 2023). Additionally, blockchain-based smart contracts can automate energy transactions and incentivize energy conservation, leading to more efficient and sustainable energy use. Blockchain technology can help address this challenge by enabling the development of smart grid systems that use real-time data to optimize energy production, storage, and consumption. These systems can automate energy transactions and incentivize energy conservation through blockchain-based smart contracts, leading to more efficient and sustainable energy use (Andoni et al., 2019; Akram et al., 2020).

1.4 Policy Changes for Sustainable Energy

This study highlights the significance of policy adjustments in facilitating the transition towards a sustainable energy future. Policy modifications encompass the development and implementation of new regulations and policies designed to promote sustainable energy practices and technologies. These policy changes can manifest at different levels, ranging from local to global, and can take various forms. Examples of policy changes that can advance sustainable energy practices include the implementation of incentives and targets for renewable energy adoption, the establishment of standards and incentives for energy efficiency improvements, and the enactment of policies that impose a price on carbon emissions (Kern and Smith, 2008; Kuzemko et al., 2016). According to scientific literature, policy changes are essential in promoting a sustainable energy future. As a result, policymakers must meticulously design policies that can achieve the desired outcomes while minimizing potential negative impacts. The use of blockchain technology can also be critical in enabling more efficient and transparent energy systems. Therefore, policymakers must prioritize policy changes that promote sustainable energy practices and technologies to expedite the transition to a sustainable and resilient energy system. The success of these policies depends on meticulous consideration of political, economic, and social factors, along with the potential role of blockchain technology in facilitating more efficient and transparent energy systems (Streimikiene and Šivickas, 2008; Lu et al., 2020; Yildizbasi, 2021).

2. RESEARCH METHODOLOGY

The current research employs a qualitative research methodology to investigate the potential of blockchain technology in promoting the adoption of sustainable energy alternatives. The choice of a qualitative research design is deemed appropriate as it allows for a comprehensive understanding of complex social phenomena, specifically the global energy system and the transition towards sustainable energy sources. By utilizing a qualitative approach, this study can explore the intricate relationships between energy, sustainability, policy, technology, and the economy in an open-ended and flexible manner.

To gather data, an extensive review of pertinent scientific literature, policy documents, industry reports, and media articles was undertaken. The literature review encompassed various domains, including sustainable energy, renewable energy policy, energy economics, blockchain technology, and innovation. This comprehensive review provided a foundation for identifying key themes, challenges, opportunities, and arguments concerning the transition towards sustainable energy sources and the potential role of blockchain technology and policy changes in facilitating this transition.

In this research study, the analysis primarily relied on secondary data obtained from reliable sources. Through this analysis, the study aimed to identify and examine the main themes and insights related to the transition towards sustainable energy sources and the potential of blockchain technology. By drawing upon a wide range of sources, this study sought to gain a deeper understanding of the challenges, opportunities, and arguments surrounding the integration of blockchain technology in the pursuit of sustainable energy alternatives.

The collected data underwent qualitative content analysis, which involved identifying key concepts, themes, and arguments. The data was categorized based on focal areas such as sustainable energy technologies, economic factors, policy issues, blockchain applications, challenges, and opportunities. Through this coding process, relationships between categories and overarching themes were established. The study synthesized the significant findings and insights, leading to a comprehensive discussion of various aspects. These included the current state of the global energy system, the imperative need for transitioning to sustainable energy sources, challenges and opportunities associated with the transition, the role of policy changes and blockchain technology in facilitating the transition, and the implications for the economy.

To minimize bias, the data collection and analysis process incorporated multiple perspectives from diverse and reputable sources. Various viewpoints were considered to ensure a comprehensive analysis. The study substantiated its findings with evidence from the literature, while also considering alternative explanations or counterarguments.

The research process was transparently documented, allowing for scrutiny of the logical reasoning behind the analysis and conclusions. Additionally, member checking was conducted by presenting the preliminary findings to experts in the fields of energy policy and blockchain technology. Their feedback was incorporated, further enhancing the credibility, transferability, dependability, and confirmability of the study.

Consequently, this study adopted a qualitative research design that encompassed an extensive literature review and content analysis to comprehensively investigate the research topic and fulfill the study objectives. By employing this methodology, a systematic and rigorous process was established to gain profound insights into the intricate relationships among energy, policy, technology, and the economy within the context of transitioning towards sustainable energy sources.

3. FINDING AND DISCUSSION

3.1 Exploring the Environmental Impacts of Sustainable Energy

The overconsumption of fossil fuels has resulted in an increase in air pollution and global warming, which has propelled climate change to the forefront of public discourse (Leiserowitz, 2007; Perera, 2018). As a result, there is a growing demand for alternative energy sources, particularly renewable energy. However, research has indicated that renewable energy sources may also have negative environmental impacts (Al-Shetwi, 2022; Rahman et al., 2022). This section focuses on the environmental effects of solar energy, wind energy, and hydroelectric systems, including their impact on air pollution, soil quality, noise levels, and wildlife.

3.1.1 Environmental Impacts of Solar Energy

Solar energy is acknowledged as the most significant renewable energy source due to its simplicity of deployment and eco-friendly characteristics in contrast to other energy sources. There are various methods of converting direct solar energy into useable energy, such as solar heating systems, building systems, and photovoltaic systems. The installation of solar energy production systems requires large ground components that can absorb a significant amount of solar energy without being too expensive. It is ideal that these components are not placed in agricultural or forested areas, and they should be located near population centers to reduce transportation costs and energy loss. The northwestern region of the unit is the ideal location for the central system due to its high sunlight exposure (Xu et al., 2021; Jiang J. et al., 2022; Cai et al., 2022; Yu and Zhou, 2023). However, the effects of large-scale solar units on desert ecosystems need to be investigated. Additionally, the construction and equipment protection of solar units utilize many materials such as glass, cement, and steel. During the construction phase, pollution effects need to be studied, as it is estimated that the amount of materials required for solar units is greater than that of fossil-fuel units. Photovoltaic-based units use unconventional and toxic materials such as cadmium sulfide, which is flammable. Large-scale use of solar energy creates significant problems in terms of water pollution due to the use of anti-icing agents, anti-corrosion agents, and metals that enter the water during system washing. The use of herbicides to prevent weed growth around collectors also indirectly leads to water pollution (Mahajan, 2012; Hosenuzzaman et al., 2015; Tawalbeh et al., 2021).

The environmental impacts of solar energy production systems are significant and include permanent land use during the unit's operation, as well as the production of non-renewable materials such as insulation and glass. Photovoltaic-based systems also produce toxic materials such as cadmium and arsenic. Other adverse effects include damage to the landscape, eye damage due to reflection of solar radiation, and land erosion and compaction, wind deflection, and increased potential for soil evaporation. An analysis conducted in 1977 compared the particulate pollution associated with the construction of a solar unit to that of oil or coal-based units producing the same amount of energy. The study found that solar units produced significantly less particulate matter. It is important to carefully consider the costs, hazardous waste, and land use associated with solar energy production compared to other forms of energy. Although there is potential for large-scale replacement of nuclear and fossil-fuel units with solar units, the risks posed by solar technologies, such as safety and health risks, must also be taken into account.

For photovoltaic-based units, the most significant negative effect is water consumption for cooling, which can lead to the destruction of surface and underground units. This can also destroy the habitats of soil-dwelling organisms and other animals that live in the desert. Additionally, the energy produced must be transported to residential and industrial centers, resulting in significant energy loss during transmission (Hernandez et al., 2014; Mahmud et al., 2018; Sánchez-Pantoja et al., 2018).

Solar energy is deemed an eco-friendly energy option for temperature regulation through heating and cooling. Research has shown that the only negative consequence of this method is the potential for urban aesthetic issues. In some cases, compatibility issues may arise between solar systems and trees near homes, and the extensive use of collectors installed on roofs can alter reflection and have minor impacts on weather patterns. However, these changes are not considered significant threats to the environment. The only environmental risk associated with solar energy for heating and cooling is during the construction of the equipment in factories (Kumar et al., 2020; Rabaia et al., 2021; Tang et al., 2022; Yavari et al., 2022).

3.1.2 Environmental Impacts Of Wind Energy

Wind energy is considered the least risky among energy sources due to its lack of need for a cooling system. However, wind energy has its disadvantages, such as noise pollution, interference with nature, and reduction of the area’s aesthetic appeal. Wind turbines may also cause damage to the ecosystem by reducing wind speed, leading to warmer lakes and decreased surface evaporation. Nonetheless, the environmental effects of wind turbines are not significant. Risks to human safety during construction and operation are similar to those in other industries, with small wind turbines in densely populated areas posing a greater risk to human health. Wind turbines can pose a risk to birds since they may not be able to avoid the high-speed blades. There are two types of pollution associated with wind turbines: machine noise, which can be mitigated through proper design and sound insulation measures, and rotational noise generated by the vortex flow of air.

Additionally, wind motion can produce noise, which is often perceived as pleasant and enjoyable, particularly at higher wind speeds (Wang and Wang, 2015; Dhar et al., 2020; Nazir et al., 2020). However, low-frequency and subsonic sounds may cause vibrations in houses and metal structures, particularly in turbines that react with the tower based on blades. Wind turbines may also create signals that interfere with television waves and cause disturbances in rainfall and surface evaporation from the ground due to wind movement resulting from windmills on the ground. Despite limited cases of such disturbances reported in 1995, the impact is not considered significant. Energy storage or auxiliary systems are required for wind energy, though it should be noted that these systems are more vulnerable to wind energy. Auxiliary facilities are used in high-risk situations (Etheridge, 2000). Distributed wind energy systems are considered more environmentally compatible than other energy sources if wind turbines are scattered throughout the country's agricultural lands and connected to a network. In this scenario, only a small portion of the turbines would be considered undesirable (Jaber, 2013; Mendecka and Lombardi, 2019).

3.1.3 Environmental Impacts Of Large And Small Hydroelectric Projects

While large hydroelectric energy production projects are considered renewable energy sources, micro and small water systems are classified as unconventional energy sources. Before discussing the potential effects of small and micro water systems projects, it is important to briefly examine the main findings of experiments conducted by scientists. Although environmental impacts are expected to be smaller and different in smaller systems (Egré and Milewski, 2002; Abbasi and Abbasi, 2011; Başkaya et al., 2011).

Hydroelectric energy production projects have been extensively studied alongside thermal units in terms of their environmental impacts. While some experts believe that hydroelectric units, particularly large ones, have negative effects on the environment and have the greatest destructive impact compared to other renewable energy sources, there is not a complete consensus. In the 1950s, when only a few of these units were in use worldwide, it was believed that this energy source was the cleanest form of energy compared to other sources. Water is one of the most expensive and even the most expensive natural resource, and dams provide this water in abundant quantities and in a way that can be used several times. Dams provide the possibility of water use throughout the year (for public use, fishing, and recreation). After electricity is obtained from water, it can be used for irrigating agricultural lands downstream of the dam. During this process, it is possible to recharge underground water resources. This energy and these benefits will be obtained without creating any smoke from thermal units or any hazardous waste from nuclear power plants (Jumani et al., 2017; Nautiyal and Goel, 2020; Oladosu et al., 2021). However, now, after 50 years, such units are considered hazardous by some experts. The most important environmental effects caused by large hydroelectric units are storing rainfall in the area, creating an artificial lake, reducing water flow downstream, and changing the flow of the river. Changes in the water flow can have various environmental effects, including increased water evaporation and potential soil leakage, displacement of small aquatic organisms, formation of distinct temperature layers, alterations in habitat and food availability, and reduction of inhabitable lands due to the creation of artificial lakes. Moreover, there is a risk of nutrient accumulation in the lake area and downstream river regions. Organisms located at river mouths may experience negative impacts due to the mixing of saltwater and the diminished flow of freshwater. Reproduction of organisms, fish, and other aquatic conditions are affected by changes in river flow and move towards the river's border areas. Increased water stagnation and human activities in the lake area lead to increased deforestation and reduced animal habitats. Often, water-borne diseases increase in these areas. The latest research shows an increase in the production of greenhouse gases such as methane from the lakes created by human-made dams. Some researchers believe that the amount of gas emitted by these units is comparable to the gases emitted in fossil fuel units, although there are differences between the greenhouse gases produced by humans. This recent issue is more significant in terms of weight and size than other problems resulting from hydroelectric systems (Pinho et al., 2007; Pang et al., 2015).

Small and micro-hydro systems are created by constructing numerous small dams with low heads or generators placed in the path of water flow. China leads other countries in having small hydro units, with approximately 100,000 units in rural areas. In 1980, the Philippines generated 4 MW of electricity from these units. However, these units are not without their problems, and their production in kilowatts is not significantly higher than centralized energy units. Some of the environmental impacts associated with these units include hindering animal movement, increasing water evaporation due to slow movement, reducing river boundaries and animal habitats, which incurs high costs to create such habitats elsewhere. Access roads must be built to reach these units, which in turn harms the environment. These units also contribute to environmental degradation by producing sediment and accumulating nutrients, which is a significant problem in large and small hydro units, leading to a decrease in the depth and size of the space. The production of greenhouse gases is another problem associated with these units, as they act as shallow water reservoirs that emit gases such as methane. Therefore, the environmental impacts of small and dispersed hydro units are significant and influential in all cases, and more attention should be paid to their potential negative effects (Gleick, 1992; Hennig et al., 2013; Zeleňáková et al., 2018).

Figure 1 presents an outline of the environmental consequences of renewable energy sources, with particular emphasis on wind energy, solar energy, and hydroelectric systems. The figure highlights the potential adverse effects of these energy sources on greenhouse gas emissions, wildlife habitats, noise pollution, water pollution, and land use. A thorough evaluation of the costs and benefits of each energy source, as well as careful consideration of these impacts, is crucial when transitioning to renewable energy sources.

FIGURE 1. *Assessing the environmental impacts of renewable energy*
Source: *a comprehensive overview of solar, wind, and hydroelectric energy.*

3.2 Challenges And Opportunities In The Transition To Sustainable Energy Sources

The shift towards sustainable energy sources poses both opportunities and obstacles. One of the most significant obstacles is the requirement for investment in renewable energy technologies, as the current energy infrastructure is heavily reliant on traditional energy sources. The adoption of sustainable energy sources necessitates substantial investment in renewable energy technologies such as hydro, wind, solar, and geothermal, which is essential in ensuring their accessibility and affordability, facilitating widespread implementation (Liu L. et al., 2022; Chen, 2022; Guo B. et al., 2023; Liu et al., 2023). Another significant challenge is policy changes to incentivize sustainable energy use. Governments play a critical role in promoting sustainable energy use through policy changes. These policies create a favorable environment for renewable energy technologies to thrive, making them more accessible and affordable for consumers. However, implementing these policies can be challenging, requiring political will and public support (Dominković et al., 2018; Hassan et al., 2019; Ghasemi et al., 2022; Al-Housani et al., 2023; Ibeanu et al., 2023).

Despite these challenges, the transition to sustainable energy sources presents significant opportunities, such as job creation in the sustainable energy sector. The sustainable energy sector is an industry that is expanding rapidly, offering significant potential for generating new jobs. Job opportunities in the sustainable energy sector range from manufacturing and installation to research and development, offering a wide range of opportunities for workers with diverse skill sets. The shift towards sustainable energy sources also presents an opportunity for a more environmentally-friendly world. The adoption of sustainable energy sources like hydro, wind, and solar can mitigate the adverse environmental effects of traditional energy sources, resulting in a cleaner and healthier environment. Additionally, renewable energy technologies are inexhaustible and do not produce greenhouse gas emissions (Armaroli and Balzani, 2007; Magar et al., 2023; Owusu and Asumadu-Sarkodie, 2016; Bahlouli et al., 2023).

The sustainable energy sector offers promising prospects for job creation, yet it faces various challenges. One of the significant challenges is the skills gap, requiring a highly skilled workforce with specialized technical skills, including engineering, science, and technology. Nonetheless, the sustainable energy sector is relatively new, and many workers may not have prior experience in this field. As a result, companies may face challenges finding experienced workers, leading to longer training periods and additional costs. Another challenge is the uncertainty of government policies, such as tax incentives and renewable energy standards, which can make it difficult for companies to plan and invest in their workforce. Moreover, funding challenges pose a significant hurdle for the sustainable energy sector, as it requires significant investment to develop and expand (Vidadili et al., 2017; Pérez et al., 2019; Bayulgen, 2020; Ishaq et al., 2022). Many companies may not have the resources to invest in expanding their workforce, and securing funding can be difficult due to the high risk associated with the sector. Additionally, the competition with established industries, such as oil and gas, makes it challenging for the sustainable energy sector to attract workers and establish a foothold in the job market. To overcome these challenges, a collaborative effort between governments, businesses, and educational institutions is required to create the necessary skills, policies, and funding to support job creation in this critical sector. This effort can include upskilling workers in specialized technical skills, providing training and education programs to develop experience, and creating more predictable and supportive government policies. Furthermore, funding opportunities and incentives can be developed to support the growth of the sustainable energy sector and reduce the risk associated with investing in it (Erat et al., 2021; Kabeyi and Olanrewaju, 2022; Guo L. et al., 2023; Japir Bataineh et al., 2023).

Academic institutions have a crucial role to play in filling the skills gap in the sustainable energy sector. To tackle this challenge, there are a variety of approaches that educational institutions can take to narrow this gap. One such step is to offer targeted programs tailored to the specific needs of the sustainable energy sector. These initiatives aid students in acquiring the technical skills and understanding necessary to excel in the sustainable energy sector, such as sustainable energy management or renewable energy engineering.

Collaborating with industry partners can also help ensure that educational programs align with current and future industry needs, enabling students to acquire the necessary skills and knowledge to work in the sustainable energy sector. In addition, hands-on training is crucial in the sustainable energy sector. Educational institutions can provide students with access to labs, workshops, and internships to gain practical experience working with renewable energy technologies. Furthermore, incorporating sustainability into existing programs, such as business or engineering, can help students understand the importance of sustainability in all fields. Continuing education programs can also help bridge the skills gap by providing established industry workers with the necessary skills and knowledge required to work in renewable energy. Finally, educational institutions can provide career services to help students and graduates find jobs in the sustainable energy sector, including job fairs, networking opportunities, and career counseling (Di Somma and Graditi, 2002; Kyriakopoulos et al., 2022).

The sustainable energy sector holds a plethora of opportunities for job creation, but it is not without its challenges. One such challenge is the skills gap, which necessitates a workforce with specialized technical skills in engineering, science, and technology. Unfortunately, there is a shortage of skilled workers in this area, and the supply of qualified candidates does not always align with the demand, posing a significant challenge for companies seeking to expand their workforce. Another challenge is the limited experience of workers in the sustainable energy sector, a relatively new field. As a result, companies may face difficulties finding experienced workers, which can lead to lengthier training periods and additional expenses. Moreover, government policies play a crucial role in job creation in the sustainable energy sector. Furthermore, the sustainable energy sector requires substantial investment to develop and expand, and securing funding can be challenging due to the high risk associated with the sector. Consequently, many companies may not have the resources to invest in expanding their workforce. Furthermore, the sustainable energy sector faces competition from established industries such as oil and gas, which have a well-established workforce and infrastructure. This competition can make it difficult for the sustainable energy sector to attract workers and establish a foothold in the job market (Sakellariou and Mulvaney, 2013; Sen and Ganguly, 2017; Inês et al., 2020).

In order to attract workers to the sustainable energy sector, businesses can implement a number of strategies to compete with established industries. These strategies include providing competitive salaries and benefits packages that are comparable to those offered by established industries. Companies can also offer training and development opportunities to help workers build the necessary skills and knowledge required to work in the sustainable energy sector. This can include on-the-job training, mentorship programs, and professional development opportunities. Highlighting the impact of the work being done in the sustainable energy sector can also be an effective strategy to attract workers. This emphasizes the importance of creating a sustainable future and reducing the environmental impact of energy production, which can be instrumental in attracting workers who value environmental sustainability. Furthermore, partnering with educational institutions to develop programs that prepare students for careers in the sustainable energy sector can be an effective means of recruiting new talent. This includes providing internships, mentorship programs, and other opportunities for students to gain hands-on experience in the field. Finally, businesses can connect with the community to enhance consciousness of the importance of sustainability and to advocate for the advantages of working in the sustainable energy sector. This includes participating in community events, hosting workshops, and partnering with local organizations to support sustainability initiatives. These strategies can help companies effectively compete with established industries and attract workers who are passionate about creating a sustainable future (Stolten and Scherer, 2013; Surendra et al., 2014; Quitzow et al., 2019).

The shift towards a sustainable energy infrastructure is not without its difficulties. One of the primary hurdles is the considerable initial costs required for constructing sustainable energy infrastructure. Although renewable energy has long-term cost advantages, governments, investors, and businesses must be willing to make substantial financial commitments to develop new sustainable energy initiatives and modernize existing infrastructure. Another critical challenge is the political and social resistance to change (Hu et al., 2021; Luo et al., 2023; Wu et al., 2023; Yi et al., 2023). The fossil fuel industry has a strong presence in many countries, which may resist efforts to transition to renewable energy. Additionally, local communities may be resistant to large-scale renewable energy projects due to concerns about potential impacts such as noise pollution or changes to the landscape. Technical impediments also represent a significant challenge to the adoption of sustainable energy. Aslo, there is a need for more research and development in renewable energy technologies to improve their efficiency, reduce costs, and enhance their scalability. Technological advancements will be critical to the continued growth and adoption of renewable energy (Bose et al., 2019; Pietrosemoli and Rodríguez-Monroy, 2019; Popescu et al., 2022). Figure 2 provides a comprehensive overview of the obstacles and possibilities in the shift towards sustainable energy alternatives. The figure shows the need for investment in renewable energy technologies, policy changes to incentivize sustainable energy use, and the potential for job creation in the sustainable energy sector. It is important to consider these challenges and opportunities when transitioning to sustainable energy sources and to carefully evaluate the costs and benefits of each energy source.

FIGURE 2. Challenges and opportunities in the transition to sustainable energy
Source: investment in renewable energy technologies, policy changes to incentivize sustainable energy use, and job creation in the sustainable energy sector.

Table 1 compares the challenges, opportunities, advantages, and disadvantages of transitioning to sustainable energy sources in developed and developing countries (Herzog et al., 2001; Verbruggen et al., 2010; Broman and Robèrt, 2017; Safari et al., 2019; Hoang et al., 2021; Mourtzis et al., 2022; Neacsa et al., 2022; Tian et al., 2022; Usman et al., 2022). Attaining a sustainable and resilient future through sustainable energy alternatives is a global challenge that necessitates cooperation from individuals, businesses, and governments. Although there are similarities in the challenges and opportunities associated with the transition, regional differences must be taken into account. The table highlights the significant differences in challenges, opportunities, advantages, and disadvantages between developed and developing countries. Recognizing these regional disparities is crucial in designing effective policies and strategies to promote sustainable energy solutions and foster a more sustainable and resilient future.

TABLE 1. Comparing challenges, opportunities, advantages, and disadvantages of the transition to sustainable energy sources in developed and developing countries.

Criteria	Developed countries	Developing countries
Challenges	- High upfront costs	- Limited financing
	- Social/political resistance	- Limited infrastructure
	- Technological barriers	- Limited institutional capacity
Opportunities	- Job creation	- Economic benefits
	- Economic growth	- Cleaner environment
	- Energy security	
Advantages	- Reduced dependence on fossil fuels	- Reduced dependence on fossil fuels
	- Mitigation of climate change impacts	- Mitigation of climate change impacts
	- Improved energy security	- Improved energy security
	- Potential for increased economic growth	- Potential for increased economic growth
Disadvantages	- High upfront costs	- Limited financing
	- Social/political resistance	- Limited infrastructure
	- Technological barriers	- Limited institutional capacity
	- Energy insecurity	- Energy insecurity
	- Environmental degradation	- Environmental degradation

In developed countries, the transition towards sustainable energy sources is accompanied by various challenges, including substantial initial investments, resistance from social and political entities, and technological barriers. Despite these obstacles, this transition also offers opportunities for job creation, economic growth, and enhanced energy security. The adoption of sustainable energy alternatives in developed nations yields multiple benefits, such as mitigating the impacts of climate change, reducing dependence on traditional energy sources, and stimulating economic progress. However, this transition is not without drawbacks, as it involves high upfront costs, encounters opposition from social and political forces, and may contribute to environmental degradation. Conversely, developing countries confront distinct challenges as they strive to transition to sustainable energy sources, including limitations in financial resources, inadequate infrastructure, and institutional capacity constraints. Despite these difficulties, transitioning to sustainable energy sources in developing nations also presents opportunities for economic advantages, environmental improvements, and enhanced energy security. However, this process brings disadvantages in the form of limited financing options, insufficient infrastructure, energy insecurity, and potential environmental degradation (Press and Arnould, 2009; Peeters, 2012; Nejad and Kashan, 2019; Majid, 2020; Wang H. et al., 2023).

3.3 Economic Benefits of the Transition To Sustainable Energy

The shift towards sustainable energy sources has the potential to yield substantial economic advantages, such as enhanced energy security, decreased reliance on traditional energy sources, and a rise in economic growth. This section will provide a detailed explanation of these benefits. One of the key economic advantages of adopting sustainable energy alternatives is the enhancement of energy security. By diversifying the energy mix and decreasing reliance on a solitary energy source, countries can bolster their energy security and decrease their susceptibility to supply interruptions. Sustainable energy sources like solar and wind power are readily accessible and can be sourced locally, resulting in decreased necessity for transporting energy resources over long distances. This can help to mitigate the risk of supply disruptions due to geopolitical tensions or natural disasters. Another economic benefit of transitioning to sustainable energy is the potential for reduced dependence on fossil fuels. This can improve their energy security and reduce the economic risks associated with fossil fuel dependency. Furthermore, the transition to sustainable energy can spur economic growth. The creation and implementation of renewable energy technologies can generate novel job opportunities and stimulate economic activity in the sustainable energy field. This can result in the emergence of new industries and the expansion of new markets for sustainable energy commodities and services. Additionally, the transition to sustainable energy can lead to cost savings over the long term, as renewable energy sources are generally cheaper than fossil fuels once the initial investment is made (Perelman, 1980; Merven et al., 2019; Siampour et al., 2021; Wang et al., 2022; Wang X. et al., 2023).

The adoption of sustainable energy alternatives is instrumental in reducing the economic costs associated with climate change. The combustion of conventional energy sources emits greenhouse gases, which contribute to global warming and the exacerbation of climate-related impacts, including more frequent and severe weather events. By reducing reliance on traditional energy sources, countries can help mitigate the economic consequences of climate change, such as infrastructure damage, increased insurance premiums, and decreased productivity. Therefore, transitioning to sustainable energy is an essential step towards building a more resilient and sustainable economy. Another notable economic advantage of adopting sustainable energy alternatives is the potential for enhanced energy efficiency. Sustainable energy sources, such as solar and wind power, are intrinsically more efficient than traditional energy sources, as they convert a greater percentage of the energy input into practical energy. This can help to reduce energy waste and lower energy costs. Additionally, the adoption of sustainable energy alternatives can encourage the implementation of energy-efficient technologies, such as energy-efficient appliances and smart meters, which can further decrease energy consumption and expenses. This can result in substantial economic benefits for individuals, businesses, and governments, while also diminishing greenhouse gas emissions (Tirkolaee et al., 2020a; Cantarero, 2020; Liu H. et al., 2022; Wang and Razzaq, 2022).

The adoption of sustainable energy alternatives can have a significant impact in decreasing the economic expenses related to air pollution. Fossil fuels, when burned, release pollutants into the air, contributing to significant health impacts and increased healthcare costs. Through the adoption of sustainable energy alternatives, nations can diminish their dependence on traditional energy sources, resulting in decreased air pollution and associated health expenses. Consequently, this can lead to noteworthy economic benefits for individuals, businesses, and governments. Another significant economic benefit of transitioning to sustainable energy is the potential for increased energy independence. Furthermore, renewable energy sources are abundant and widely available, reducing the need for countries to rely on foreign energy sources and thereby lowering their vulnerability to geopolitical tensions (Van Der Schoor and Scholtens, 2015; Chen J. et al., 2023).

The shift towards sustainable energy alternatives can also yield noteworthy economic advantages for rural communities. Renewable energy can be located in rural areas, creating new economic opportunities and stimulating local economic growth. This can help to create new jobs and generate income for rural communities. Moreover, renewable energy projects can provide a new source of income for farmers and landowners, as they can lease their land for renewable energy projects and receive regular payments. Furthermore, transitioning to sustainable energy can help to attract investment and improve a country's competitiveness. Investors and businesses are increasingly looking for opportunities to invest in sustainable energy projects, and countries that have a strong commitment to sustainability and renewable energy are likely to be more attractive to these investors. This can lead to increased investment in sustainable energy projects, creating new jobs and economic growth opportunities. Additionally, countries that are investing in sustainable energy are likely to be more competitive in the global economy, as they will have lower energy costs and a more diversified and secure energy mix. This can help to attract new businesses and industries to the country, further stimulating economic growth and job creation (Kemp and Loorbach, 2006; Barbir, 2009; Salam and Khan, 2018; Tirkolaee et al., 2020b).

The relationship between energy and the economy is a complex one with many facets. Energy is a crucial input for economic growth and development. Nevertheless, the manners in which energy is generated, dispersed, and consumed can result in significant effects on both the economy and society. Energy's impact on the economy is mainly through its role as an input for production. It is used in various economic activities such as manufacturing, transportation, agriculture, and services. The cost and accessibility of energy exert substantial influence on production costs and the competitive edge of industries, particularly energy-intensive sectors like manufacturing. The pivotal role of energy in shaping frameworks for economic growth and progress is of great significance. Historically, access to affordable and abundant energy sources has been a crucial catalyst for economic development, particularly in economies undergoing industrialization. Additionally, the connection between energy and the economy is influenced by political and institutional factors. Energy policy choices, such as subsidies and regulations, can significantly shape the distribution of economic advantages and costs. Moreover, aspects such as vested interests, international trade, and resource allocation can influence the political economy of energy production and consumption. Energy's role in shaping patterns of social inequality and vulnerability is also important. Access to reliable and affordable energy services is a fundamental aspect of meeting basic human needs such as heating, lighting, and cooking, as well as accessing education, healthcare, and other services. However, patterns of energy access and consumption can be shaped by economic and social inequalities, leading to higher energy costs and exposure to energy-related risks such as energy poverty, energy insecurity, and environmental pollution for low-income households and marginalized communities (Kelly-Richards et al., 2017; Bogdanov et al., 2021; Kabeyi and Olanrewaju, 2022). Technical aspects also have a notable impact on shaping the correlation between energy and the economy. However, the adoption and diffusion of new energy technologies can be influenced by factors such as financing, regulation, and cost-benefit analysis. Therefore, the relationship between energy and the economy is a complex one with many facets, shaped by a range of economic, social, political, institutional, and technological factors.

Understanding this relationship is essential for developing effective policies and strategies for achieving sustainable and equitable economic development while addressing the environmental and social challenges associated with energy production and consumption. Further research is needed to deepen our understanding of this complex relationship and identify effective strategies for promoting sustainable energy transitions and building more resilient and inclusive economies (Quitzow et al., 2019; Emna et al., 2022; Neacsa et al., 2022; Zhou et al., 2022; Zhu et al., 2023).

Figure 3 shows an overview of the economic benefits associated with transitioning to sustainable energy. The figure emphasizes the potential for enhanced energy security, decreased reliance on fossil fuels, job creation and economic growth, cost savings and improved energy efficiency, reduced economic costs related to climate change and air pollution, augmented energy independence, economic advantages for rural communities, and improved competitiveness and investment attraction. Each category represents a core aspect in which transitioning to sustainable energy could generate considerable economic benefits, and comprehending these benefits is pivotal in developing effective policies and strategies for achieving sustainable and equitable economic growth while addressing the environmental and social challenges linked with energy production and consumption.

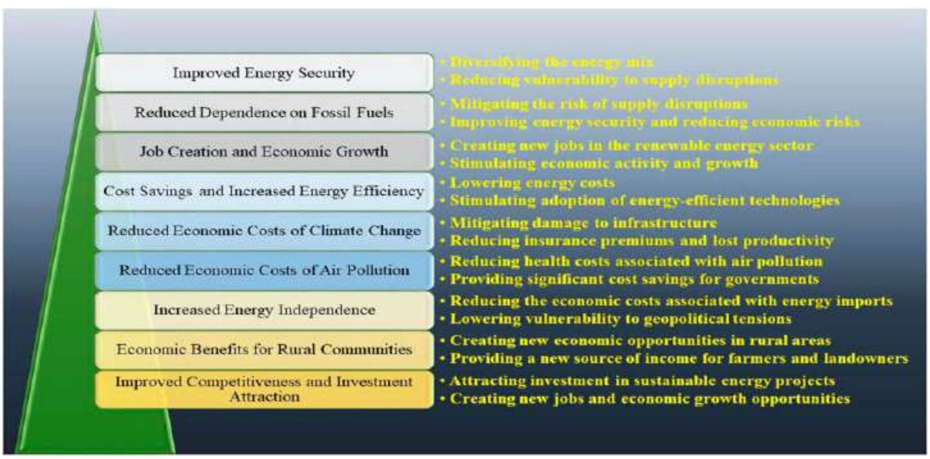

FIGURE 3. Economic benefits of the transition to sustainable energy.

3.4 The Role of Blockchain Technology In The Transition Towards Sustainable Energy

The equilibrium of smart grids can be disturbed by changes in consumer behavior. Blockchain technology can provide solutions to integrate new disruptors into the existing industrial structure of the electricity market. By enabling peer-to-peer transactions, blockchain technology can enhance consumer empowerment, but it also poses challenges to the existing regulatory frameworks in the industry (Brilliantova and Thurner, 2019; Jiang S. et al., 2022). Hence, it is crucial to design blockchain technology that addresses trust and regulatory structures in the industry. The electricity market is continuously changing, and blockchain technology offers solutions to integrate new disruptors into the existing industrial structure. Peer-to-peer (P2P) transactions using blockchain technology can increase consumer empowerment and challenge traditional regulatory frameworks in the industry. To address trust and regulatory structures, the text discusses four different approaches to designing blockchain technology for the electricity market: unlicensed, licensed, private, and a combination of both. Each approach has its own unique features and implications for consumer trust and regulatory structures in the industry. Comprehending the necessities of each strategy is crucial for the energy sector to assess the significance of developing blockchain technology for the electricity market. The article emphasizes that technological design is critical in determining the influence of commercial structures on consumer conduct and regulatory frameworks (Liu et al., 2021; Nygaard and Silkoset, 2022).

P2P transactions facilitate the direct exchange of electricity between consumers, eliminating the need for traditional intermediaries such as utility companies. This decentralized trading approach empowers consumers by granting them the authority to determine the price of electricity and enables them to sell any excess energy they generate. This level of control over energy consumption and production represents a significant advantage of P2P transactions. Furthermore, the utilization of blockchain technology enhances transparency and security within the energy market, thereby fostering consumer trust. Transactions are recorded in an immutable ledger, reducing the risk of fraudulent or erroneous transactions and promoting market efficiency. By leveraging blockchain for P2P transactions, consumers are afforded increased empowerment in the electricity market, allowing them to actively participate and make informed decisions regarding their energy consumption and production (Mannaro et al., 2017; Di Silvestre et al., 2020; Afzal et al., 2022; Chen W. et al., 2023).

The potential of blockchain technology lies in its ability to combat the problem of energy poverty in developing nations by boosting access to inexpensive and dependable energy sources. One of the primary hurdles in addressing energy poverty is the dearth of access to established financial systems and infrastructure, which makes it challenging to finance and distribute energy resources to underprivileged communities. Blockchain technology provides a decentralized platform for energy transactions, enabling peer-to-peer energy trading and facilitating the distribution of energy resources to underserved communities. Blockchain-based energy platforms can also address trust and transparency issues in the energy sector. By utilizing a tamper-proof and transparent ledger system, blockchain technology increases accountability and reduces the risk of fraud and corruption in energy transactions. This helps to establish trust between energy producers, distributors, and consumers, creating a more efficient and equitable energy market. Furthermore, blockchain technology can facilitate the integration of sustainable energy sources into the energy grid, which is critical in developing nations where sustainable energy sources like wind or solar may be more accessible and economical than conventional fossil fuel-based energy sources (Enescu et al., 2020; Mukherjee et al., 2021; Almutairi et al., 2022; Govindan, 2022).

The implementation of blockchain-based energy platforms in developing countries is accompanied by various challenges that need to be addressed. The first challenge pertains to limited infrastructure, which includes insufficient access to reliable electricity, inadequate internet connectivity, and a lack of necessary hardware to support blockchain-based energy platforms. These infrastructure limitations can impede the deployment and maintenance of blockchain technology in developing countries. The second challenge revolves around the scarcity of technical expertise required for the successful implementation of blockchain technology. Proficiency in areas such as software development, cryptography, and cybersecurity is vital for the development, deployment, and upkeep of blockchain-based energy platforms. The limited availability of technical expertise in these domains poses difficulties in incorporating blockchain technology in developing countries. The third challenge involves the absence of a comprehensive regulatory framework that supports the deployment of blockchain technology in developing countries. The lack of regulatory guidelines creates ambiguity, heightening the risk of non-compliance, deterring investment, and impeding the growth of blockchain-based energy platforms. The fourth challenge concerns the economic viability of blockchain-based energy platforms in developing countries. Due to low levels of energy consumption and limited access to financing, attracting investments and achieving the economies of scale necessary for the financial sustainability of blockchain-based energy platforms can be challenging. Lastly, social and cultural factors play a significant role in the adoption of blockchain-based energy platforms in developing countries. Some communities may exhibit skepticism towards new technologies or have a preference for traditional energy sources, thereby creating obstacles to the widespread adoption of blockchain-based energy platforms. Addressing these challenges is crucial to ensure the successful implementation of blockchain-based energy platforms in developing countries. By overcoming these obstacles, the potential benefits of blockchain technology in enhancing energy access, efficiency, and transparency can be harnessed to support sustainable development and address energy challenges in these regions (Giungato et al., 2017; Truby, 2018; Aybar-Mejía et al., 2021; Popkova et al., 2023).

The licensed approach to designing blockchain technology for the electricity market involves the use of licensed and regulated intermediaries to facilitate transactions between producers and consumers. This approach aims to provide a higher level of trust and security than unlicensed approaches, while still enabling the benefits of blockchain technology. In the licensed approach, licensed intermediaries act as trusted third parties to validate transactions and ensure compliance with regulatory requirements. These intermediaries are usually regulated by government agencies and must adhere to specific standards for security, transparency, and integrity. Additionally, they may be required to maintain records of transactions and provide reports to regulators. The primary advantage of the licensed approach is the higher level of trust and security it provides compared to unlicensed approaches.

By utilizing licensed intermediaries, consumers can have greater confidence in the integrity of transactions and the regulatory compliance of market participants. This can help to reduce the risk of fraudulent and illegal activities in the electricity market. However, the licensed approach has some drawbacks. For instance, the use of licensed intermediaries can increase transaction costs and reduce market efficiency. Furthermore, the regulatory requirements for licensed intermediaries can be complex and may vary across different jurisdictions, making it challenging to implement a standardized approach to blockchain-based energy platforms (Svetec et al., 2019; Yildizbasi, 2021; Lei et al., 2022).

Thus, blockchain technology holds the potential to make a substantial impact in promoting a sustainable energy future by augmenting the efficiency and transparency of energy markets and streamlining the incorporation of sustainable energy sources. The technology can aid in addressing some of the primary challenges confronting the worldwide energy sector, such as energy security, climate change, and sustainable growth. As mentioned, one of the ways that blockchain technology can enhance the efficiency and transparency of energy markets is through peer-to-peer energy trading. This allows consumers to determine electricity prices and sell any excess energy they generate, giving them greater control over their energy consumption and production. The transparency and security afforded by blockchain technology can also increase consumer trust in the market, as transactions are recorded in a tamper-proof ledger, reducing the risk of fraudulent or inaccurate transactions and increasing market efficiency. Blockchain technology can also contribute to promoting a sustainable energy future by simplifying the integration of sustainable energy sources into the energy grid. The technology can aid in addressing the obstacles presented by the sporadic nature of sustainable energy sources and the insufficiency of energy storage capacity. Decentralized energy systems can be built on blockchain-based energy platforms that allow for the seamless integration of sustainable energy sources. These platforms can streamline the effective administration and synchronization of energy resources, enabling the maximization of energy production and consumption. For example, blockchain-based energy platforms can be used to create virtual power plants that aggregate sustainable energy sources and use energy storage systems to smooth out fluctuations in energy supply and demand. Lastly, blockchain technology can have a pivotal function in promoting sustainable development by enhancing access to energy resources in underprivileged communities. Blockchain-based energy platforms provide a decentralized platform for energy transactions, enabling P2P energy trading and facilitating the distribution of energy resources to underserved communities. This is particularly beneficial in developing countries where traditional energy infrastructure may be lacking or unreliable (Sweeney et al., 2020; Ante et al., 2021; Wünsche and Fernqvist, 2022; Mao et al., 2023).

The application of blockchain technology in the energy industry could face various potential challenges or limitations. Scalability is a major challenge, where an increase in the number of transactions on a blockchain can lead to slower transaction times and higher transaction fees, making blockchain-based energy platforms less efficient and less cost-effective than traditional energy systems. Another challenge is the technical complexity of blockchain technology, which necessitates specialized technical expertise to develop and maintain, making it difficult for energy companies and regulators to adopt and implement blockchain-based energy platforms. Interoperability is another issue of concern, as there are presently numerous distinct blockchain platforms, each with its distinct features and stipulations, making the consolidation of various blockchain-based energy platforms with one another and with conventional energy systems challenging. Furthermore, the highly regulated nature of the energy sector can create regulatory challenges that require new or updated regulations to ensure compliance with existing laws and regulations, leading to uncertainty and delaying the adoption of blockchain-based energy platforms. The security and privacy of user data are also significant concerns, and any breach of this data could result in significant risks for both consumers and market participants. Furthermore, there could be apprehensions about the storage and dissemination of confidential energy data on a public blockchain network. Furthermore, while blockchain technology can promote energy efficiency in certain contexts, it also requires significant energy consumption, particularly with proof-of-work consensus mechanisms, creating concerns about the environmental sustainability of blockchain-based energy platforms. In conclusion, the implementation of blockchain technology in the energy sector requires careful consideration of potential challenges and drawbacks, including scalability, technical complexity, interoperability, regulatory challenges, data privacy and security, and energy consumption. Addressing these challenges will require collaboration between stakeholders across different sectors, such as governments, energy companies, technology providers, and regulators (Wang and Su, 2020; Wang et al., 2021; Juszczyk and Shahzad, 2022).

Policy frameworks play a pivotal role in supporting the implementation of energy systems based on blockchain technology. The successful integration of blockchain platforms into the energy sector necessitates the establishment of specific policy measures and regulatory frameworks. Standards aimed at ensuring interoperability between blockchain platforms and existing energy infrastructure are crucial for facilitating seamless integration and optimizing the exchange of data. Regulations governing peer-to-peer energy trading, smart contracts, and the protection of customer data are vital for ensuring equitable and transparent transactions while safeguarding individual privacy. By offering incentives such as tax credits, governments can stimulate investments in blockchain energy projects, thereby fostering innovation and encouraging the widespread adoption of this technology. The integration of renewable energy certificates and carbon trading systems with blockchain platforms enhances the transparency and accountability of renewable energy markets. Policies that support decentralized energy production, smart grid infrastructure, and net metering are instrumental in effectively integrating distributed energy resources into the existing energy landscape. Additionally, the establishment of blockchain sandboxes provides controlled testing environments where policymakers can evaluate the feasibility and impact of new regulatory frameworks. By implementing these comprehensive policy frameworks, governments can foster an enabling environment for the successful deployment of blockchain-based energy systems, thereby promoting transparency, efficiency, and sustainability within the energy sector.

Figure 4 depicts the primary advantages and potential applications of blockchain technology in the energy sector. The first category, P2P Energy Trading, elucidates how blockchain technology can empower consumers, enhance transparency, and augment security in the energy market.

The second category, Integration of Renewable Energy Sources, illustrates how blockchain technology can enable the seamless integration of renewable energy sources, energy storage systems, and smart grid technologies. The third category, Addressing Energy Poverty, explores how blockchain technology can offer a decentralized platform for energy transactions, enabling peer-to-peer energy trading and facilitating the distribution of energy resources to underserved communities. Finally, the fourth category, Challenges and Potential Drawbacks, highlights the primary challenges and potential drawbacks associated with implementing blockchain technology in the energy sector, such as scalability, technical complexity, regulatory, data privacy and security, and environmental sustainability concerns. Comprehending these advantages and challenges is imperative in determining the significance of designing blockchain technology for the electricity market and promoting a sustainable energy future.

FIGURE 4. Potential benefits and challenges of implementing blockchain technology in the energy sector.

CONCLUSION

A qualitative research methodology was used in this study, which involved an extensive literature review and content analysis, enabling an in-depth exploration of the research topic and addressing the study objectives. The objective of the study was to comprehensively investigate the challenges, opportunities, and role of blockchain technology in facilitating the transition towards sustainable energy sources. The transition towards sustainable energy is essential for environmental and economic reasons, as it reduces dependence on fossil fuels, mitigates the impacts of climate change, and promotes economic growth. Thus, the findings from this study can inform policy decisions and future research to promote sustainable energy solutions.

Several challenges were identified in the transition to sustainable energy, including high upfront costs, social and political resistance, and technological barriers. However, opportunities such as job creation, economic benefits, and a cleaner environment also exist. Blockchain technology has the potential to enable more efficient and transparent energy markets through peer-to-peer transactions and a distributed ledger. It can also facilitate the integration of renewable energy sources. However, addressing challenges such as scalability, technical complexity, and security risks is necessary for blockchain technology to effectively contribute to a sustainable energy transition. Policy changes that incentivize sustainable energy use and investment in renewable energy technologies are also crucial enablers.

The transition to sustainable energy sources offers promising economic prospects, including improved energy security, reduced dependence on imports, and potential for increased economic growth. However, achieving sustainable development requires policies that balance energy supply, economic growth, and environmental protection. The sustainable energy sector faces the challenge of attracting and developing a skilled workforce to meet growing demand. Educational institutions have an important role to play in bridging the skills gap and preparing students for careers in sustainable energy.

Also, addressing the skills gaps and implementing effective training strategies is crucial for building a proficient workforce in the renewable energy sector. The identified skills gaps encompass technical proficiencies, understanding of renewable energy technologies, engineering expertise, data analytics skills, and knowledge of regulations and policy frameworks. Educational institutions play a vital role in developing these skills through targeted sustainable energy programs, cross-disciplinary courses, apprenticeships, and vocational training. Integrating renewable energy and blockchain topics into mainstream engineering and business curriculums ensures that graduates are well-equipped for the evolving energy landscape. Reskilling programs are also essential for enabling a smooth transition for individuals from fossil fuel-related occupations to renewable energy careers. By addressing these skills gaps and implementing comprehensive training strategies, stakeholders can foster a competent workforce capable of driving the successful implementation of renewable energy technologies and the integration of blockchain platforms. This, in turn, will contribute to the advancement of sustainable energy systems and the achievement of global climate goals.

Looking towards the future, there are several promising trends that have the potential to accelerate the transition towards sustainable energy systems. Advancements in renewable energy technologies, coupled with declining costs, are expected to drive their widespread adoption on a global scale. Policy frameworks at various levels of governance have the capacity to evolve progressively, becoming more supportive of sustainability initiatives, as public concern over climate change continues to grow. The emergence of potentially disruptive technologies such as blockchain, artificial intelligence, and advanced data analytics holds promise for unlocking new capabilities and business models within the energy sector. Furthermore, the green energy workforce is anticipated to experience significant expansion, supported by targeted training initiatives offered by educational institutions and industry partners. Innovative financing mechanisms can play a pivotal role in making the economics of sustainability more viable, while community-based approaches offer creative solutions to overcome local resistance. By comprehensively capitalizing on these opportunities, a future can be envisioned where affordable, decentralized, and clean energy empowers societies worldwide. To translate these promising trends into tangible reality, further rigorous interdisciplinary research and enhanced collaboration among diverse stakeholders will be crucial.

In conclusion, transitioning to sustainable energy sources is crucial for environmental and economic sustainability but faces significant challenges that require concerted efforts from governments, companies, and educational institutions. The utilization of promising technologies such as blockchain and policy changes incentivizing renewable energy can help enable a sustainable energy transition. This transition offers promising economic benefits and prospects for job creation in the sustainable energy sector. However, addressing the skills gap through targeted training programs and continued education is critical to realize the full potential of the sustainable energy transition. The insights from this study can inform policies and strategies to promote sustainable energy solutions and build a more sustainable and resilient economy.

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ISBN: 979-8-89695-115-5