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Author(s): Rahman, Saleem ur; Shakeel, Shah Rukh

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Challenges in Renewable Energy Supply Chains: Strategies for a Sustainable Energy Future

*Saleem ur Rahman[1]**
Shah Rukh Shakeel[2]

1. Rabat Business School, the International University of Rabat (Université Internationale de Rabat), Parc Technopolis, Shore Rocade, Rabat, 11103, Morocco
rahman.saleem@uir.ac.ma

2. School of Marketing and Communication, and Innovation and Entrepreneurship InnoLab, University of Vaasa, Wolffintie 34, Vaasa, Finland
shah.rukh.shakeel@uwasa.fi

**Corresponding author*

Abstract

Mitigating climate change is one of the most pressing issues today. A key step in addressing climate change is reducing reliance on fossil fuels, which requires a global shift toward renewable energy. However, this transition faces numerous supply chain challenges, including unpredictable resource availability, financial limitations, regional political instability, technological gaps, social and environmental impacts, and inconsistent regulations and policies. These challenges lead to production delays, power interruptions, decreased energy efficiency, and disruption of the smooth flow of materials, slowing the global adoption of renewable energy technologies. This chapter addresses these critical challenges in the renewable energy sector. The findings indicate that geographical, technological, geopolitical, infrastructural, social and environmental, financial, regulatory, and governmental challenges significantly affect the entire supply chain, from extraction to the production of renewable energy technologies between technology-rich and resource-rich countries. The chapter also suggests future trends for overcoming supply chain disruptions and fostering greater cooperation, innovation, and sustainability in transitioning to a renewable energy-based future.

Keywords: Renewable Energy, Supply chain, Challenges, Energy transition, Sustainability

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1. Introduction

Climate change affects every region worldwide and will cost more than preventing its negative impacts (International Renewable Energy Agency (IRENA), 2021). In recent years, human activities have set new records for greenhouse gas emissions (GHG), rising sea levels, increased waste, ocean acidification, and deforestation (United Nations (UN), 2024a). The Intergovernmental Panel on Climate Change (IPCC) has called for immediate and strict actions to address these accelerating climate change issues (IPCC, 2018). Conventional hydrocarbons, including coal, oil, and gas, are the largest contributor to climate change, accounting for over 90% of carbon emissions and over 75% of global greenhouse gas emissions (UN, 2024b). Therefore, to mitigate the worst effects of climate change, carbon emissions must be cut by nearly half by 2030 from the current levels and should reach net zero levels by 2050. Transitioning to clean energy systems based on renewable energy sources such as solar, wind, hydro, and other renewables offers a promising path to a more sustainable future (Yu et al., 2024; Paris Agreement, 2024).

Renewable energy sources (RETs) are sustainable, clean, affordable, reliable, and accessible (United Nations Environment Programme (UNEP), 2024; Shakeel et al. 2017). Currently, renewable energy sources play a significant role in addressing some countries' primary energy needs. However, despite these developments, their overall contribution to global energy remains limited. Nevertheless, RETs are emerging as a promising alternative to conventional hydrocarbons, which are associated with numerous issues. Excessive reliance on finite hydrocarbons, emissions from generation processes, the need for massive infrastructural investments, concerns over energy access and poverty, and energy security are some of the primary challenges plaguing conventional energy systems. These challenges have prompted countries worldwide to accelerate the development of renewable energy technologies and increase their share in primary energy supplies.

Technological advancements and improved efficiency at lower costs support the expansion of renewable energy generation, while supportive policy instruments have also been introduced to stimulate growth. As a result, the contribution of renewables to global energy supplies is projected to increase significantly in the coming years. According to IRENA (2024), 29.1 percent of the existing power generation facilities installed worldwide in 2022 were based on renewable sources, totaling 8,440 TWh, a 7.2 percent increase from 2021. Altogether, over $2 trillion has been invested in the cleantech sector (IEA, 2024), with more than $619 billion directed explicitly toward renewable energy initiatives globally (Statista, 2024). Furthermore, more than 130 countries have developed various policy supports or regulations to promote the growth of renewable energy technologies (REN21, 2024; IEA, 2024).

However, to reach the stated target and increase the share of renewables, the production of renewable energy technologies must be continuously scaled up. A significant technical challenge associated with the development of RETs is their heavy reliance on a wide range of materials and minerals, such as lithium, cobalt, nickel, and other rare earth elements (IEA, 2022), which are essential for the development of technologies and components like solar panels, wind turbines, and storage systems. The global distribution of these resources is highly uneven, with many resource-rich countries, in terms of mineral deposits, being geographically distant from the industrial centers where RETs are manufactured. For instance, cobalt is predominantly extracted from the Democratic Republic of Congo, while major lithium reserves are found in Chile and Australia.

This geographical disparity creates significant challenges for the supply chain, as manufacturing regions such as North America, Europe, and East Asia depend on long-distance transportation of materials. This reliance heightens the risk associated with the supply chain, including geopolitical tensions, trade wars or restrictions, complex and costly logistics, transparency issues, and safety and security concerns. These factors can lead to supply chain disruptions and price volatility, ultimately affecting renewable energy markets' development, growth, and stability. With the increasing utilization of RETs, the demand for essential materials will increase rapidly, making achieving sustainable development goals more complex and highly dependent upon an efficient supply chain. Interruptions in the supply of renewable energy materials can lead to significant delays in development (World Future Council, 2024).

This growing demand for renewable energy sources underscores the evolving and interdependent relationship between resource-rich and technology-advanced countries, which is essential for ensuring a smooth transition to clean energy (Feng et al., 2024). Building on this background, this chapter focuses on the complex issues surrounding the extraction, supply, and delivery of renewable energy materials. It addresses the geographical, logistical, geopolitical, financial, social, environmental, and policy challenges that impact both resource-rich and technologically advanced countries. Additionally, it examines the crucial role and effects of market dynamics, trade regulations, and technological breakthroughs in shaping the distribution and supply of renewable energy materials. Lastly, the chapter discusses strategies and suggestions to overcome supply chain barriers, promoting resilience and enabling a more effective transition within the renewable energy industry.

2. Challenges in the renewable energy supply chain

The development of renewable energy technologies encounters numerous challenges within the supply chain that hinder the smooth transition to a sustainable energy future. These challenges range from the sourcing and availability of critical materials to broader issues such as technological discrepancies, logistical and infrastructural constraints, geopolitical tensions, and governmental challenges. Social and environmental concerns, policy and regulatory challenges, and financial considerations further complicate supply chain dynamics. Each of these factors plays a critical role in influencing the effectiveness and sustainability of the supply chain, both independently and in combination with others. The following section explores these challenges, their impact on renewable energy supply chains (see Figure 1.0), and measures to address them (see Figure 2.0).

2.1 Geographical disparities

Geographical disparities in the renewable energy supply chain refer to the uneven distribution of energy resources and the geographical distances between resource-rich and resource-deprived regions. Countries across the globe possess varying degrees of energy resources, and their transition to a clean energy future is heavily influenced by the uneven distribution of these resources and the technologies required to harness them (REN21, 2021). This dynamic creates a complex interplay between resource-rich and technologically advanced countries (Feng et al., 2023). Resource-abundant countries often export renewable energy materials, while resource-scarce countries depend on imports to meet their needs. This interdependence between resource-rich nations and technologically advanced countries, with knowledge, skills, capacities, and expertise to develop RETs, significantly shapes the global energy landscape, driving trade patterns and influencing policies worldwide.

A significant challenge in this global energy landscape is the geographical distance between resource-rich and technology-intensive regions (Bridge et al., 2013). The largest importers of renewable materials include the European Union (EU), China, the United States, Japan, and South Korea (WTO, 2024). On the other hand, countries like Australia (lithium), Chile (copper and lithium), the Democratic Republic of Congo (cobalt), Indonesia (nickel), and South Africa (platinum and iridium resources) dominate the supply side (IRENA, 2021). This geographical disparity results in significant logistical challenges, as these resources must travel long distances, adding financial and operational complexity to the supply chain.

In some cases, the proximity of resource-rich and technology-rich countries creates a natural pull effect for renewable energy materials. For instance, countries like Germany, Spain, Italy, and France, known for their excellence in RET development (e.g., solar panels and wind turbines), actively invest in and collaborate with resource-rich nations to secure necessary materials. By developing partnerships and collaborations, they can leverage resources from nearby regions, such as Africa, to meet their technology development needs (Samadi, Fischer, & Lechtenbohmer, 2023). Countries that are close to each other have a natural comparative advantage in the energy supply chain, as shorter distances reduce logistical costs and ensure quicker access to resources.

Several strategies can be employed to mitigate the challenges posed by geographical disparities. Strengthening international relations through bilateral agreements can foster cooperation between resource-rich and technologically advanced countries, facilitating the sharing and management of resources and technologies for mutual benefit. Additionally, enhancing transparency in trade policies can minimize barriers to fair trade in energy resources. Supporting the development of regional processing hubs near extraction sites to refine material before long-distance transportation can help manage the volume and costs, offsetting the challenges posed by geographical distances. Moreover, adopting innovative supply chain management approaches, including digitalization and novel technological solutions, can further address challenges raised by geographical distances. While geographical disparities pose significant challenges to the renewable energy supply chain, they also present opportunities for collaboration and infrastructure development. By implementing these strategies, countries can address the challenges associated with geographical distances and work toward a more efficient and resilient supply chain.

2.2 Technological discrepancies

The efficient, sustainable, and steady extraction, supply, distribution, and availability of raw materials are crucial for manufacturing renewable energy technologies. The integration of digital technology is essential in optimizing these processes. Technology is instrumental in the transition to cleaner energy by creating new opportunities in the energy industry. For example, the integration and use of digital technologies not only reduce operational costs and the carbon footprint of supply chain networks but also improve efficiencies and enhance safety aspects.

Advanced technologies also enable enhanced visibility by offering real-time tracking and monitoring of goods, maintaining inventory levels, and optimizing transportation routes. Advanced algorithms and machine learning models can optimize demand forecasts, contributing to efficient inventory management (Li et al., 2023). Similarly, they increase agility and responsiveness, promoting quicker decision-making and faster responses in the event of disruptions or changes in market dynamics. Additionally, advanced technologies enable improved interaction with customers through digital interfaces and personalized solutions. They also ensure that quality standards are maintained using IoT sensors and data analytics to monitor quality throughout the supply chain. The use of digital platforms enhances collaboration and communication between stakeholders.

Digital technologies such as artificial intelligence (AI), machine learning (ML), blockchain, the Internet of Things (IoT), and cloud computing can be promising for optimizing supply chains, improving renewable energy product lifecycle management, and enhancing efficiency, including providing economic, social, and environmental benefits of using renewable energy sources (Almutairi et al., 2023; Sánchez-García et al., 2024). The integration of technologies can also help avoid delays, shortages, and supply disruptions caused by unforeseen circumstances, contributing to more resilient, efficient, and sustainable supply chain networks.

For example, a pilot project initiated in cobalt mining in the Democratic Republic of Congo (DRC), where numerous issues related to human rights and environmental concerns were identified, highlighted the advantages technologies can offer (Lewis, 2018; Mugurusi, 2022; IBM, 2019). The implementation of blockchain helped address challenges related to transparency, sourcing, and efficiency. Once the material is mined, a unique identifier is assigned and registered on the blockchain platform, initiating a traceable journey throughout the supply chain. This measure improved transparency by offering traceability from mine to end user, ensuring the authenticity of ethically sourced minerals. It also increased efficiency by reducing supply chain delays by 25% through better coordination and real-time tracking, while administrative costs were cut by 20% through streamlined operations. Additionally, it strengthened trust and confidence in the process, enhanced regulatory compliance by reducing the time and resources needed for reporting by 40%, and bolstered supply chain resilience through real-time tracking and data analysis. Overall, implementing blockchain has demonstrated the potential to significantly improve operations and enhance efficiency.

Similarly, Vestas, a global leader in wind turbine manufacturing, has incorporated AI to optimize supply chain operations for wind energy projects (Vestas, 2019; Choney, 2022). AI has helped the company improve demand forecasting, monitor the availability of critical components, and optimize logistics to ensure the timely delivery and installation of turbines. These AI-driven improvements have reduced delays and material waste that might otherwise occur in the supply chain. Moreover, Vestas uses AI to efficiently identify optimal installation sites based on logistical, environmental, and technical factors, thereby improving overall output.

Technological innovations drive renewable energy, but there is a notable technological and innovation discrepancy between resource-rich and technology-rich countries (Wen et al., 2022). Chile, for instance, has some of the largest reserves of renewable energy materials but lacks the technology to efficiently process those materials domestically (UNCTAD, 2023). As a result, these materials are often transported to foreign countries for processing. This creates dependency on external processing capabilities, making the local renewable energy supply chain vulnerable to disruptions and inefficiencies. Integrating digital technologies can help facilitate the smooth transition and flow of global renewable energy sources. There are several ways to address technological discrepancies in renewable energy supply chains. One approach is capacity building through technology transfer, which can be achieved by encouraging partnerships and joint ventures and implementing training and education programs (Zhang and Gallagher, 2016). These efforts can help develop local capacity and enhance a country's technical skills, reducing dependence on external expertise (Pandey et al., 2023).

One of the many challenges that resource-rich countries face is the lack of adequately educated and trained human resources to manage and operate renewable energy technologies, which also pose significant challenges across the entire value chain. These gaps in skills leave supply chain systems vulnerable to internal and external challenges, deteriorating overall operations. Investments in education and training programs can not only create employment opportunities but also protect the supply chain from disruption, theft, and misuse while building supply chain resilience. Moreover, direct investment by technology-rich countries in resource-rich countries through funding, public-private partnerships, and establishing research and development centers is essential (Ankrah and Lin, 2020). Collaborating on renewable energy projects through aid and alliances with private and public organizations can build renewable energy capabilities in both technologically rich and resource-rich countries (Kruckenberg, 2015).

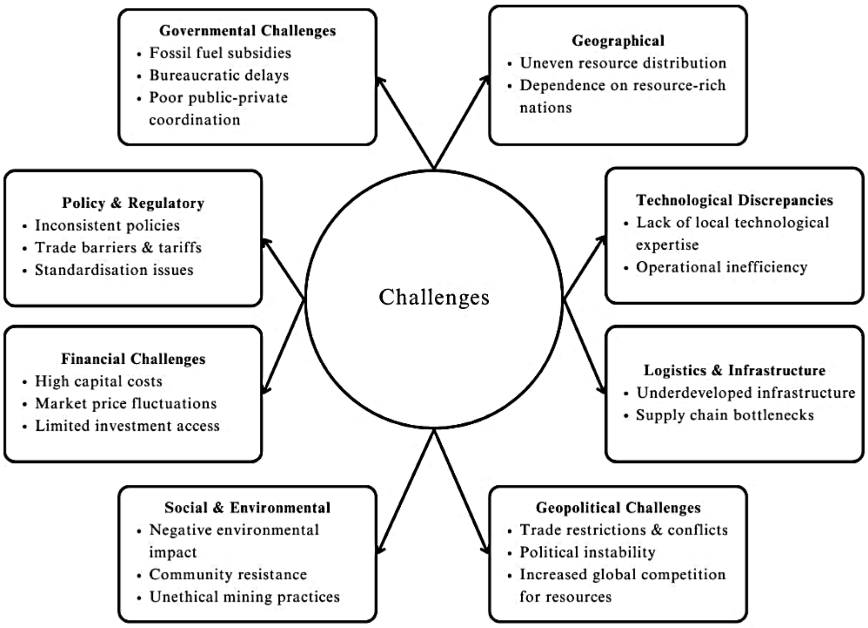

Figure 1.0 Challenges in Renewable Energy Supply Chain Networks (Authors' work)

2.3 Logistics and infrastructure challenges

Logistics and infrastructure challenges are associated with transportation, distribution, and management of resources essential for renewable energy supply chains. These challenges are often exacerbated by underdeveloped infrastructure and logistical networks, which negatively influence the efficient movement of renewable energy technologies.

The increasing demand for renewable energy technologies has heightened the vulnerability of supply chain networks to unforeseen events, including logistics and infrastructure-related disruptions. In many resource-rich countries, inadequate infrastructure, such as limited road and rail networks and insufficient access to ports or logistical routes, poses significant barriers to the effective extraction and distribution of essential raw materials. This underdevelopment complicates the establishment of resource-based linkages between technologically advanced and resource-rich countries, impacting collaborative efforts in RET production (Gabriel et al., 2016).

Moreover, the fragmented nature of cross-border supply chains further complicates renewable energy operations (UNECA, 2011). Raw materials are often located in remote areas, far from urban centers, creating logistical challenges for their extraction, transportation, and distribution. For instance, in the Democratic Republic of Congo, the sourcing of cobalt is often significantly impacted by the lack of adequate transportation infrastructure, causing delays in shipment. These logistical challenges can lead to inefficiencies, such as prolonged mining project lead times. During periods of high demand for renewable energy technologies, such disruptions can result in supply shortages, exacerbating the situation. This scarcity of essential materials can trigger price hikes, causing manufacturing delays and placing an additional burden on companies to maintain their competitiveness. Consequently, production companies may be compelled to make additional investments, which can disrupt the entire supply chain cycle.

In this context, optimizing logistics through enhanced route planning and infrastructure development can help control costs and minimize the carbon footprint associated with these activities, ensuring the overall efficiency of the supply chain. Improved logistical operations can enhance operational performance and contribute to the industry's overall advancement, leading to a more sustainable and economically viable energy landscape. Technologically advanced countries are typically better positioned to invest in transportation infrastructure. They could contribute to building infrastructure in resource-rich countries, such as roads, high-speed rail, and routes to extraction sites. This requires significant investments in infrastructure development, including ports, railways, and highways, to facilitate the transportation of large components and materials. Such investments can lead to reduced transit time, minimized transportation costs, improved material safety, and overall efficiency in the supply chain. Likewise, fostering international cooperation on shared infrastructure projects can also improve long-distance material transportation efficiency. For example, investment in port facilities in Morocco has significantly enhanced the logistics infrastructure, facilitating the transportation of solar energy technologies. Moreover, countries should diversify their supply chains to minimize dependence on a single supplier while improving production capacities to mitigate potential logistical challenges (UNIDO, 2015).

2.4 Geopolitical challenges

Geopolitical challenges refer to the complex and multifaceted interplay of social, economic, and political dynamics resulting from the interaction between countries and regions, often driven by controlling and distributing resources or pursuing dominance and control. In the context of renewable energy, these challenges include trade wars, international conflicts, local, regional, or international tensions, political instability, and uneven distribution of energy resources across geographic locations. These issues significantly impact the sustainability of supply chains, energy security, and a country's approach to energy production and consumption patterns as they pursue sustainability transitions.

Unlike fossil fuels, concentrated in specific regions and transported through established routes, the renewable energy supply chain is often scattered across multiple countries and continents. While renewable sources like wind and solar energy can be deployed almost anywhere, the materials and minerals necessary are unevenly distributed, complicating the sourcing and distribution capabilities of the actors involved (ERM, 2023). The concentration of these resources in politically sensitive regions and the need to transport them through unstable areas increase supply chain vulnerability. Geopolitical risks such as deglobalization, wars, trade rivalries, ethnocentrism, polarization, and political instability exacerbate these vulnerabilities. Escalating political and ethnic tensions increases the likelihood that powerful groups and cartels will control critical materials. Emerging political and trade tensions, as well as threats like terrorist attacks and military conflicts, negatively influence strategic sourcing and distribution decisions in the renewable energy sector (Riti et al., 2022). Since essential materials are in different countries, political developments within these nations significantly impact the global supply chain, raising concerns regarding energy security, especially rare metals used in manufacturing renewable energy technologies (Su et al., 2021).

Another significant geopolitical challenge in today's world is growing competition for critical raw materials such as lithium, cobalt, and rare earth elements, which are essential for the development of RETs. Global powers, like China and the United States, have been increasingly asserting political pressure on resource-rich countries to secure these supplies, often using trade restrictions on opposing parties to attain political objectives. The emergence of new trade alliances and recent geopolitical developments has also resulted in disruptions to the renewable energy supply chain. For example, the war in Ukraine has disrupted the container routes in the Black Sea, while the continuous threat of attacks from the Houthi rebels has affected logistical movements in the Red Sea and the Gulf of Aden region. Additionally, the sanctions imposed on Russia have triggered price increases and supply shortages, further complicating the supply chains.

Additionally, the act of a country or nation's block can also lead to issues. For instance, military exercises by China in the Taiwan Strait have created uncertainty as stakeholders fear that a major conflict could devastate global supply chains, severely impacting the flow of renewable energy materials and equipment. These geopolitical disruptions can significantly impact the renewable energy sector by increasing prices, delaying delivery, and impacting project outcomes. For instance, shortages of minerals like lithium, cobalt, and other rare earth elements drive up market prices, hampering production capacity and creating a ripple effect throughout the supply chain.

In addition to regional or global challenges, renewable energy supply chains are also vulnerable to the influence of domestic policies within the resource-owning countries. For example,

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restrictions on exports or nationalization of resources by resource-owing countries can create fear and uncertainty for importing nations. For instance, Indonesia's decision to ban nickel exports to assert sovereignty over its national resources alarmed global manufacturers relying on stable nickel supplies for production. These geopolitical challenges add complexity and instability to global renewable energy supply chains, undermining international efforts to achieve energy transitions and meet climate change goals (IEA, 2022). Such descriptions erode the confidence of industry players and commercial actors, making it crucial to develop resilient supply chains that can withstand geopolitical uncertainties.

To minimize geopolitical risks in supply chain networks, actors and stakeholders can implement several strategies. For example, building resilient supply chains through diversification is essential. Technology-rich countries need to source critical resources from multiple suppliers to reduce over-reliance on a single source. Establishing stable trade and political relations that can endure growing geopolitical volatility is key to ensuring a consistent supply of renewable energy materials. For instance, initiatives like Global Battery Alliance, which promotes sustainable battery supply chains through collaboration among different businesses, governments, and non-governmental organizations, highlight the benefits of cooperative action (GBA, 2024).

Additionally, international collaboration and diplomacy are also central to promoting stability. Bilateral and multilateral agreements that ensure fair practices and protect shared interests can help maintain continuity. In addition, the governments of resource-rich countries must ensure the safe and responsible extraction of resources. Transparency, accountability, and sustainability initiatives can reduce risks associated with resource extraction and minimize negative impacts on the supply chain. To sum up, addressing geopolitical challenges can play an important role in devising resilient, agile, and supply chain networks.

2.5 Social and environmental challenges

Critical minerals and materials are concentrated in a few places, but their demand is increasing in every part of the world. The supply and demand of these materials radically shape the economic, environmental, and social dynamics of many countries. Each country's environmental and social characteristics are different, which can either hinder or support the flow of resources in the supply chain. While the growth of the renewable energy sector may economically benefit technologically rich countries, logistical activities could pose social and environmental challenges for resource-rich countries. Therefore, achieving efficient, sustainable supply chain management requires considerable focus on the environmental and social impacts of supply chain activities (Cucchiella and D'Adamo, 2013). The logistics and mobility of renewable resources have several environmental impacts (such as greenhouse gas emissions and habitat disruption) and social impacts (such as affecting local communities and changes in land use) (Zang et al., 2020; Abbasi & Nilsson, 2016). Therefore, the identification, monitoring, and addressing of potential negative impacts and consequences along the renewable energy materials supply chain are significant challenges for companies and policymakers (Kügerl, Hitch, and Gugerell, 2023). Energy networks can be affected by community concerns and resistance over the aesthetic intrusion of renewable energy technology deployment and the loss of jobs due to the decline of the domestic use of fossil fuel resources (Stigka, Paravantis, and Mihalakakou, 2014). Similarly, countries and regional economies dependent on fossil fuel industry profits can hinder supply chain transition policies (Spencer et al., 2017). Moreover, environmental factors, such as preserving natural resources (Paravantis et al., 2014), public concerns over the disruption of the seascape (Seetharaman et al., 2019), and opposition from environmental groups, also impede development (Nasirov et al., 2015).

In developing energy supply networks, there is a need to simplify energy supply chains by focusing on increased transmission capacity, network resilience and security, and reducing the energy supply chain's complexity (Obrecht, Kazancoglu, and Denac, 2020). Smart mining initiatives, such as sustainably managing mineral resources while fostering economic growth and development, can help resource-rich countries benefit from their resources. At the same time, technologically rich countries can contribute by scaling up their technical assistance and investments in resource-rich countries to ensure minimal environmental and social impacts on supply chain activities (World Bank, 2019). Accordingly, balancing the environmental and social impacts of supply chain activities is crucial for ensuring a sustainable transition to renewable energy.

2.6 Financial challenges

Renewable energy offers long-term and cost-effective advantages. Although the renewable energy sector has gained traction among investors, new sustainable energy initiatives require substantial financial investments. Financial challenges are significant in renewable energy chain networks' investment, development, and operational activities (Fernando et al., 2018).

However, difficulties in securing initial financing, high costs of initiating projects, market price instabilities, and increased operational costs impact the profitability and planning of activities involved in supply chain networks (Infield and Freris, 2020; Cheng et al., 2023). COVID-19 also severely affected the flow and stability of renewable energy materials; consequently, renewable energy supply chain networks are facing a lack of financing. For example, the financial support given by governments worldwide has been substantially reduced due to the severe effects of the COVID-19 pandemic on their economies (Tsao Thanh and Wei, 2021). Geopolitical situations, such as the current Russia-Ukraine war, the war in Israel, and US-China trade tensions, have also disrupted global renewable energy supply chain networks, increasing the prices for materials needed to create renewable energy technologies, including sharp fluctuations in energy prices worldwide (Cui, 2023). Furthermore, another critical challenge is the low attraction of investors in the clean energy sector due to the high environmental impact and less favorable financial perspectives of renewable energy projects (UNCTAD, 2023).

Addressing financial challenges is fundamental to mitigating risk and building a more resilient renewable energy network. For instance, secure initial financing, financial burdens, and risks can be minimized through public-private partnerships. Initial costs can be reduced with cost-sharing arrangements among stakeholders, such as a partnership between the resource-rich government and a private renewable energy solar farm in a technology-rich country. The government might offer land, tax incentives, and low-interest loans for the project. This arrangement will lower the company's financial burden and encourage investment in renewable energy projects.

Another example is cost-sharing between stakeholders, such as jointly investing in renewable energy infrastructure to build a grid accommodating multiple renewable energy sources. For instance, this model can work in Africa by constructing hydroelectric dams with the help of international financial institutions and private sector entities to share the costs. Moreover, companies from technologically rich countries could purchase political risk insurance to mitigate the risk of government actions in politically unstable countries that could disrupt renewable energy projects. Market price and geopolitical instabilities can be tackled by making long-term contracts, diversifying sourcing, and using financial instruments against price fluctuations. Additionally, operational costs can be reduced using advanced technology and investing in human resources. Lastly, low investor interest can be addressed by presenting compelling returns on investment models and reducing the social and environmental impacts of renewable energy supply chain activities.

2.7 Policy and Regulatory Challenges

A solid legislative framework is required to facilitate the transition to sustainable energy and maintain increased investment in renewable energy (Nathwani and Ng, 2010). Accordingly, developing policies and regulations with lasting and positive implications requires broader engagement from multiple stakeholders to establish and consolidate renewable energy development baselines. Policy and regulatory challenges significantly impact the development and implementation of renewable energy supply chain networks (Yahyazadeh, 2022). For example, the successful development, implementation, and completion of renewable projects require a supportive policy and regulatory framework (Enerdatics, 2023). Research shows that the regulatory environment, natural resources, trade agreements, and social and environmental policies can significantly impact the import and export of energy products (Górecka, Skender, and Zaninović, 2022). Regulatory inconsistencies across different regions create complexity and uncertainty for businesses, hindering the smooth flow of materials between resource-rich and technology-rich countries. Frequent policy changes also create an unstable environment for renewable energy projects. Additionally, the lack of standardization for materials, technologies, human resources, and practices can significantly impact the resource flow from extraction to usage. Trade and tariff barriers to the supply of materials are also significant challenges for companies, affecting costs and limiting access to essential materials required to produce renewable technologies. Social and environmental impact regulations can also hinder renewable energy supply networks (Abate, Nielsen, and Tveterås, 2016). For instance, resource extraction may severely impact the environment and nearby communities. Accordingly, heightened awareness of the negative environmental and social impacts of resource depletion has led to stringent regulatory policies in many countries (UCSUSA, 2017).

The policy and regulatory challenges can be tackled with various steps to ensure a smooth flow of materials and cooperation in regulatory matters. For instance, regulatory inconsistencies can be addressed by establishing bilateral agreements, creating regulatory liaisons, and harmonizing regulatory policies. Policymakers in both resource-rich and technology-rich countries should work on policy stability by engaging different stakeholders and monitoring the impact of policy changes on supply chain networks. Trade and tariff barriers on materials can be tackled through agreements and the provision of incentives and subsidies to resource-rich countries, supported by technology-rich countries, to bolster the renewable energy sector. Most importantly, the social and environmental impacts of resource extraction and production can be managed by following sustainable practices and codes, engaging with communities, and providing compliance support.

2.8 Governmental Challenges

Uneven government subsidies and support remain one of the biggest challenges for companies developing renewable energy supply chains (Fernando et al., 2018). Although numerous governments globally are encouraging businesses to switch to renewable energy with tax advantages, investments, subsidies, and other favorable measures, this support is not consistent across all regions. Due to the Russia-Ukraine war and the recovery from the COVID-19 pandemic, governments have supported businesses and consumers, leading to increased fossil-fuel subsidies worldwide. The International Monetary Fund (IMF) has reported that to decrease fuel prices, both implicit and explicit fossil-fuel subsidies have surged to a record 7 trillion dollars, especially in developing countries with higher pollution levels generated by factories and vehicles (IMF, 2023).

In some instances, governments favor fossil fuel industries over renewable energy companies under the guise of environmental and community protection, complicating the situation and making compliance with such regulations challenging for new entrants. Developed countries' governments often favor the fossil fuel industry because they enjoy sizable revenue flows from fossil fuels in terms of royalties and taxes. Inflexible tender designs to procure and contract raw materials further add cost pressure along the supply chain (Fischer, Frankl, and Bahar, 2023). The lack of qualified human resources, complex authorization procedures for renewable energy projects, and poor coordination among governmental agencies further complicate the smooth flow of renewable energy resources between resource-rich and technology-rich countries. This means that renewables are not entering the market conveniently, competing with fossil fuel industries, which are favored and encouraged by subsidies and incentives, while polluters are not being penalized (UCSUSA, 2017).

Governments can play a crucial role in transitioning from fossil fuels to renewable energy sources. For example, together with technology-rich country governments, resource-rich governmental organizations can create public awareness and drive political change. They can agree on common goals and objectives to devise policies that help businesses streamline supply chain networks. To reduce the lengthy process of project approval, there should be clear guidelines, decentralization, and the use of digital technologies to streamline the process. In developing countries, poverty is one of the biggest causes and effects of environmental problems. Therefore, technology-rich countries can help resource-rich countries separate environmental development issues from economic development issues. Resource-rich governments should be incentivized and assisted in policy reforms by technology-rich countries to remove biases favoring the fossil fuel industry. To enhance the resilience of renewable energy supply networks, it is important that governments reduce subsidies to fossil fuel industries and encourage the renewable energy industry, resulting in improved supply and increased energy efficiency.

Figure 2.0 Addressing Supply Chain Network Challenges (Authors' work)

3. Conclusion and Future Trends

The unprecedented increase in population worldwide necessitates a significant increase in energy demand. For many years, countries have relied on fossil fuels for consumption and industrial energy needs. Although energy is crucial for economic and human advancement, using fossil fuels contributes to global warming by releasing carbon dioxide (CO2) and greenhouse gases (GHG) into the atmosphere, thereby exacerbating climate change issues. Alternatively, renewable energy sources reduce global warming without degrading the ecosystem. However, given the increased demand for renewable energy technologies, the global renewable energy market is affected by intermittent resource availability, leading to production and installation delays, power disruptions, consumer distrust and discouragement, and decreased energy efficiency. Supply chains play a central role in the renewable energy transition by delivering the technology's essential materials and minerals. However, many challenges may stall this transition. Supply chain disruptions not only hurt renewable energy companies but also slow down the transition to renewable energy. Therefore, there is a pressing need for sustainable, efficient, and secure supply chain networks to streamline the flow of renewable energy resources.

The findings of this study may guide policymakers, companies, and developers in understanding the range of supply chain challenges hindering progress toward renewable energy in both resource-rich and technology-rich countries. For example, geographical advantages and disadvantages are becoming major limitations impacting the development and deployment of renewable energy. Geographical challenges can be addressed by strengthening bilateral relationships between countries to facilitate and manage resources, supporting political stability, and developing infrastructure. Similarly, technological challenges can be addressed through capacity building, technology transfer, investments in education and training programs, and the establishment of research and development centers through private-public partnerships. This chapter further identifies that logistical challenges significantly hinder the efficiency of the entire supply chain network. In this situation, the resilience of supply chain networks can be enhanced through infrastructure development and searching for alternate suppliers. Likewise, geopolitical risks can be managed by diversifying energy supply away from politically unstable countries, establishing stable trade and political relations, and ensuring the safe and responsible extraction, transmission, and distribution of resources through accountability, transparency, and sustainability efforts.

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To avoid social and environmental risks, corporations may implement smart mining initiatives to sustainably manage materials while supporting the development and growth of the local economy. Scaling up investments and providing technical assistance may ensure minimal social and environmental impact from supply chain activities. Additionally, with the help of research and development initiatives, operational costs can be reduced, the efficiency of supply chain networks can be enhanced, and social and environmental risks can be mitigated. The importance of financial challenges in the smooth functioning of supply chain networks cannot be underrated. Renewable companies are heavily dependent on critical materials, and the increase in the cost of even a single item can hinder the progress of entire projects. In this situation, firms cannot bear the financial burden of rising raw material prices due to inflation and persistent disruptions in supply chains. The financial challenges in supply chains can be minimized through public-private partnerships, using financial instruments against price fluctuations, and addressing investors' concerns by presenting compelling investment returns.

To address policy and regulatory challenges, decision-makers in resource-rich and technology-rich countries need to collaborate on streamlining their policy and regulatory mechanisms. For example, when devising policies and making regulations, monitoring their impact on renewable energy projects, and considering different stakeholders should be kept in mind. Most importantly, drafting supportive social and environmental policies, such as following sustainable codes, engaging with communities, and providing compliance support, can reduce issues in supply chain networks. Similarly, the lack of public awareness about the benefits of renewable energy and the governmental will to continue using non-renewable energy sources can pose significant challenges to the success of renewable energy projects. Creating public awareness and driving political change can be achieved through mutual collaboration, agreements on common goals and objectives, and pushing governments to reduce reliance on fossil fuels. Additionally, supply chain challenges can be minimized by strategies such as providing a supportive environment to renewable energy companies, incentivizing them through tax incentives, easing trade barriers, and implementing renewable energy-friendly measures to facilitate the transition toward renewable energy.

Rapid growth and dependency on renewable energy resources would further require resilient supply chain networks. Accordingly, using emerging technologies requires addressing future challenges to improve efficiency, reduce operational costs, provide a transparent and secure system, and improve scalability (Taherdoost, 2024). For example, using blockchain in the supply chain would improve transparency, security, and trust among stakeholders. At the same time, using artificial intelligence and data analytics can help predict disruptions, price fluctuations, human resource management, and enhance material flow, including helping manage material and overall project management. Furthermore, the use of 3D printing technology in the manufacturing of the components of renewable energy technologies can save costs and ensure the availability of needed parts. In addition, to effectively manage and quickly respond to disruptions in the supply chain, companies can use the Internet of Things (IoT). Digital Twin Technology can also help companies simulate supply chain activities to identify bottlenecks, thus optimizing the whole supply chain. Supply chain network challenges in the future can be effectively managed with the help of robotics and automation in material extraction and manufacturing. (See Figure 3.0).

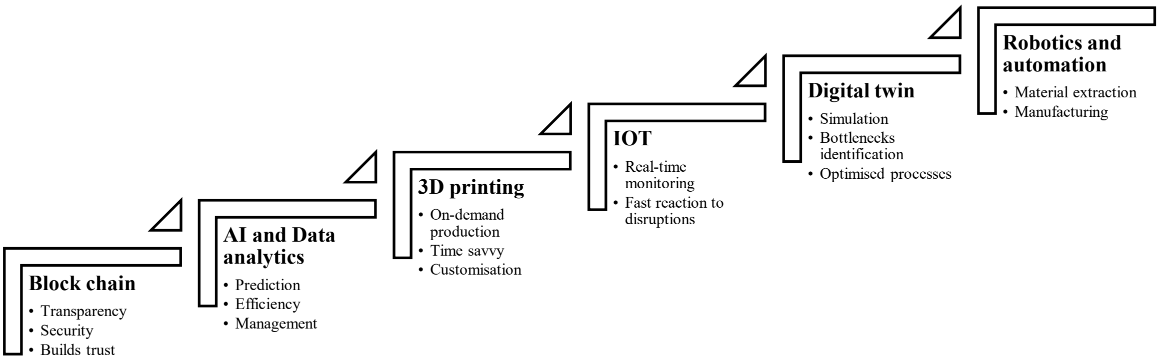

Figure 3.0 Future Trends to mitigate challenges in Renewable Energy Networks (Authors' work)

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