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The Deployment of Renewable Energy Sources in the Context of Energy Security

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Contents

1. Introduction

The deployment of renewable energy sources (RES) has become a cornerstone in addressing global energy challenges, particularly in the context of energy security. Historically, energy security was primarily concerned with the uninterrupted availability of energy resources at affordable prices, often focusing on fossil fuels such as oil and gas (Cherp & Jewell, 2011). However, contemporary understandings of energy security have expanded to include resilience, sustainability, and equity, reflecting the multifaceted challenges posed by climate change, geopolitical tensions, and economic transitions (Sovacool et al., 2011). These evolving priorities underscore the critical role of renewable energy in reshaping energy systems to meet current and future demands.

Renewable energy sources -such as solar, wind, hydro, and geothermal- offer several advantages over traditional fossil fuels in the context of energy security. By leveraging domestically available resources, renewables can reduce dependence on imported energy and associated geopolitical vulnerabilities. For instance, regions that traditionally rely heavily on oil and gas imports can enhance their energy autonomy through localized solar and wind energy projects (Cherp et al., 2012). Furthermore, the decentralized nature of many renewable systems, such as rooftop solar panels or community wind farms, enhances the resilience of energy grids by reducing the risk of large-scale disruptions (Nguyen et al., 2015).

Environmental considerations also play a significant role in the discourse on renewable energy and energy security. The transition to RES is pivotal in reducing greenhouse gas emissions and mitigating climate change, aligning energy systems with global sustainability goals such as the Paris Agreement (IRENA, 2020). Additionally, the operational stability of renewables—driven by free and inexhaustible "fuels" like sunlight and wind—contributes to long-term price stability, addressing economic dimensions of energy security (Brown et al., 2018). These characteristics position renewables as a dual solution to environmental and energy security challenges.

However, integrating renewables into existing energy systems is not without challenges. Intermittency issues, such as the variability of solar and wind resources, pose significant obstacles to ensuring consistent energy supply (Sioshansi, 2011). Advances in energy storage technologies, such as lithium-ion batteries and hydrogen storage, and the development of smart grids are critical to overcoming these challenges (Denholm et al., 2010). Moreover, scaling renewable energy systems requires addressing the environmental and social impacts of resource extraction for components like solar panels and wind turbines, which often depend on critical minerals sourced from ecologically sensitive areas (Bazilian, 2018).

This thesis explores the multifaceted relationship between renewable energy deployment and energy security, economic, and geopolitical dimensions. By examining the interplay between renewable energy systems and traditional energy frameworks, the study highlights both opportunities and challenges for states in integrating renewables into the energy mix. Particular attention is given to the resilience benefits of renewable energy, including

diversification of energy sources and decentralization, and the technological and policy innovations required to mitigate intermittency, ensure grid stability and decrease costs.
Ultimately, this research examines the role of renewable energy in terms of energy security within a rapidly evolving global energy landscape, as nations navigate the complex interplay of energy and financial security, resilience and sustainability. By exploring these dynamics, the thesis contributes to ongoing academic and policy debates on the potential of renewable energy and its implications for global energy security.

2. Literature Review

Energy security is a crucial concept in global policy and international relations, closely linked with economic stability, geopolitical dynamics, and environmental sustainability. Over time, the definition and scope of energy security have expanded from a narrow focus on fossil fuel supply to a more comprehensive understanding that includes sustainability, resilience, and socio-economic equity. This chapter discusses the evolution of energy security, key metrics for its measurement, and the interdisciplinary nature of the concept, especially in light of global challenges such as climate change, geopolitical tensions, and technological advances.

2.1 Defining Energy Security

Traditionally, energy security has been defined as the reliable availability of energy resources at affordable prices. This approach primarily focused on fossil fuel security, particularly for oil and gas, with emphasis on securing supply chains, maintaining energy affordability, and ensuring self-sufficiency (Cherp & Jewell, 2011; Sovacool & Mukherjee, 2011). These concerns were primarily geopolitical, shaped by the 1970s oil crises[1], which exposed the vulnerability of energy-imports dependent nations (Chester, 2010).

In more recent years, the concept has broadened to include environmental sustainability and technological resilience. The International Energy Agency (IEA, 2014) defines energy security as "the uninterrupted availability of energy sources at an affordable price", while also stressing the need for a transition to cleaner energy sources in the face of climate change (Sovacool & Saunders, 2014). As a result, energy security now encompasses not only energy supply but also environmental, social, and governance aspects, reflecting a more holistic approach to energy management (Cherp & Jewell, 2011).

2.1.2. Key Metrics for Measuring Energy Security

Energy security is measured using various quantitative and qualitative indicators that reflect the availability, affordability, sustainability, and resilience of energy systems. These metrics can be grouped into several dimensions:

Availability: This dimension relates to the physical availability of energy resources, particularly fossil fuels and renewables. Common metrics include reserve-to-production ratios[2] for fossil fuels and the proportion of renewable energy in the energy mix (Sovacool & Mukherjee, 2011; NREL, 2018).

Affordability: Energy affordability is essential for national economies and households. Key metrics include energy price volatility[3], energy expenditures as a percentage of GDP, and energy poverty levels (Knox-Hayes et al., 2013).

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[1] A period of significant oil price shocks caused by geopolitical tensions and embargoes which exposed vulnerabilities in energy-importing nations.

[2] A metric indicating how long proven reserves of a resource will last at current production rates.

[3] Fluctuations in energy prices due to global market dynamics and geopolitical tensions.

Reliability and Resilience: This dimension focuses on the ability of energy systems to withstand shocks such as natural disasters or geopolitical conflicts. Indicators include the frequency and duration of power outages and the robustness of distributed energy systems that can continue functioning during grid disruptions (NREL, 2018).

Sustainability: With growing concerns about climate change, sustainability has emerged as a component of energy security. Metrics include greenhouse gas emissions, energy intensity (the amount of energy used per unit of GDP), and the share of renewable energy in the total energy mix (Cherp & Jewell, 2011).

Governance and Policy: Effective governance is vital for long-term energy security. This includes regulatory frameworks, market transparency, and international cooperation, all of which safeguard the efficient functioning of energy systems (Sovacool & Mukherjee, 2011).

2.1.3. Traditional vs. Contemporary Views of Energy Security

Historically, energy security has been viewed through a geopolitical lens, with a focus on the ability to secure access to fossil fuel resources. During the Cold War, energy security was tightly linked to national security, with countries striving to reduce their energy dependence on foreign actors, in order to protect themselves from both political and economic pressure (Klare, 2004). This traditional perspective emphasized fuel stockpiling, strategic alliances, and investments in energy infrastructure to ensure a stable energy supply for military and industrial purposes (Yergin, 1991).

In contrast, contemporary views of energy security have evolved to incorporate broader concerns such as sustainability[4], resilience, and equity. As the world looks towards reductions in greenhouse gas emissions, attention is given into developing diverse energy sources, including renewable energy, and improving the resilience of energy systems to withstand disruptions from extreme weather or cyberattacks (Sovacool et al., 2011). Additionally, distributed energy systems, which decentralize energy production across smaller, modular units, are regarded as part of a strategy to enhance resilience and reduce vulnerability to large-scale system failures (NREL, 2018).

2.1.4. Global and Interdisciplinary Perspectives

Energy security today is deeply intertwined with global challenges such as the COVID-19 pandemic, geopolitical conflicts like the war in Ukraine, and the fast-moving transition to renewable energy. Crises such as the above, have exposed the vulnerability of global energy markets to supply disruptions and have underscored the need for a more resilient and sustainable energy system (Osička & Černoch, 2022).

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[4] The ability to meet current energy needs without compromising future generations, focusing on reducing environmental and social impacts.

Moreover, the concept of energy security is increasingly linked to social justice and equity. Addressing energy poverty[5], the inability of households to afford adequate energy services, has become a critical aspect of energy security in both developed and developing nations (Siksnelyte-Butkiene, 2021). Ensuring universal access to affordable energy services is now recognized as a key factor for national and global energy security goals (Valentine, 2011).

2.1.5. Summary

Reviewing the available literature, renders quite obvious the fact that energy security constitutes a dynamic and evolving concept. While traditional views focused exclusively on securing fossil fuel supplies and ensuring national energy independence, contemporary perspectives emphasize the importance of aspects such as sustainability, resilience, and equity. As global energy systems evolve, the matter of energy security will surely face new challenges, including environmental concerns, technological innovation, and geopolitical instability.

2.2. Renewable Energy and Energy Security

In the global energy landscape, as states look to meet climate-related goals, diversify their energy portfolios and ensure energy security, renewables such as solar, wind, hydro, and geothermal power come into play. This shift is not only fueled by environmental concerns but also by the need to enhance energy security. However, the interactions between renewable energy deployment and energy security are complex and subject to both consensus and debate within the academic community.

2.2.1. Renewable Energy and Energy Security: Areas of Consensus

One of the main benefits of renewable energy is its potential to assist in reducing reliance on fossil fuel imports, thereby enhancing energy security. Renewable energy sources, such as solar and wind, are locally available in many regions, which reduces a nation's vulnerability to externalities such as the global energy market fluctuations. According to Cherp et al. (2012), the decentralized nature of renewable energy systems allows for greater energy autonomy, especially in regions that rely heavily on imported oil and gas. This local sourcing of energy improves resilience and stability by diversifying energy portfolios (Sovacool & Mukherjee, 2011).

Renewable energy can provide stable energy prices in the long run, an advantage generally not associated with fossil fuels. Unlike fossil fuel markets, which are prone to price volatility due to fluctuations in supply and demand, the "fuel" for renewable sources, whether it is sunlight, wind, or water is free, making the long-term operational costs more predictable

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[5] The International Energy Agency (IEA) and the United Nations Development Programme (UNDP) define energy poverty as the absence of access to clean, commercial energy and efficient equipment, coupled with a heavy dependence on traditional energy sources for cooking (Lu, S., Ren, J., 2023).

(IRENA, 2016). Brown et al. (2018) argue that the initial capital costs associated with renewable energy infrastructure, while high, are offset by the low maintenance costs and zero fuel expenses, thus contributing to long-term price stability.

The deployment of renewable energy technologies has been shown to yield significant environmental and socioeconomic benefits. A study by the International Renewable Energy Agency (IRENA, 2020) highlights that the transition to renewable energy reduces greenhouse gas emissions, contributing to efforts for climate change mitigation. Additionally, the renewable energy sector has proven to be a catalyst for job creation, both directly within the industry and indirectly in related sectors. This contributes to a more secure economic environment, where local communities benefit from employment and income opportunities (IRENA, 2016).

2.2.2. Debates and Challenges in the Energy Security Discourse

One of the most frequently debated aspects of renewable energy in relation to energy security is intermittency concerns. Solar and wind energy, in particular, are inherently variable because they depend on weather conditions, making them less predictable compared to fossil fuels (Sioshansi, 2011). While technological advancements in energy storage, such as battery technologies, and the development of smart grids, offer solutions to this issue (Denholm et al., 2010), some scholars remain skeptical about whether these technologies can be scaled up quickly enough to ensure reliable energy supply (Lund et al., 2015). This intermittency poses significant challenges for grid management, especially during peak demand periods when renewable energy output may be insufficient.

The geopolitical implications of the renewable energy transition have sparked significant debate, particularly concerning the equity of the transition between the Global North and South[6]. Scholars like Newell and Mulvaney (2013) argue that developing countries, especially in the Global South, face a dilemma: while they are being encouraged to adopt renewable energy technologies in order to contribute to global carbon emissions reduction, they are often held back by a lack of financial resources and infrastructure. Furthermore, many of these nations argue that they should not bear the cost of such transition, given their relatively small historical contribution to global emissions (Sovacool, 2016). This geopolitical divide raises questions of climate justice and whether the renewable energy transition is achievable in an agreed upon, equitable manner across the globe.

A critical issue that has emerged in the academic literature is the environmental impact of scaling up renewable energy technologies, especially when it comes to the extraction procedure of raw material. The production of solar panels, wind turbines, and battery storage systems requires significant amounts of rare earth elements[7], lithium, and other minerals, often sourced from regions with fragile ecosystems and vulnerable communities (Ali et al., 2017). Bazilian (2018) argues that the environmental and social impacts of mining for these

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[6] Refers to disparities between developed and developing countries in accessing resources for renewable energy.

[7] Minerals critical for renewable energy technologies, primarily controlled by China, creating new geopolitical dependencies.

materials could counteract some of the positive benefits of renewable energy, particularly if extraction processes are not conducted sustainably. This raises questions about the true environmental impact of renewable energy technologies and whether these impacts can be scaled without exacerbating existing environmental and social challenges.

2.2.3. Summary

The interaction between renewable energy and energy security presents both opportunities and challenges. While renewable energy can enhance energy independence, stabilize long-term prices, and contribute to socioeconomic development, it also faces significant obstacles related to intermittency, geopolitical tensions, and material sustainability. Addressing these challenges will require coordinated efforts across governments, industries, and communities to ensure that the renewable energy transition is executed in the most secure and sustainable manner for the energy future.

2.3. Energy Transition and Climate Change, Reshaping the Geopolitical Landscape

The worldwide shift toward new energy sources during the last decade, driven by the demands of climate change, affected not only energy production but also the longstanding geopolitical dynamics shaping global relations. For over a century energy, particularly fossil fuels like oil, coal, and natural gas, has played a major role in shaping global power dynamics, contributing to the economic and political clout of nations in control these resources. However, the drive toward decarbonization[8], in line with global climate targets such as the Paris Agreement, introduced new dynamics in energy politics, defined by a movement away from fossil fuel dependency toward renewable energy systems. This transition carried profound implications for global power structures, energy security, and international trade, reshaping the geopolitical landscape in many ways (Goldthau, 2019; O’Sullivan & Bordoff, 2021).

2.3.1. The Historical Role of Energy in Shaping Geopolitics

Energy resources have long been an integral part of geopolitics. Throughout the 20th century, the control over oil and natural gas resources was critical to the global balance of power. Countries in the Middle East, in particular, have been at the center of energy-related geopolitical considerations due to their large oil reserves, which attracted investment, diplomatic leverage, and military involvement from global powers (O’Sullivan & Bordoff, 2021). The economic and political influence of oil-producing nations such as Saudi Arabia, Iraq, and Russia has underscored the link between energy resources and geopolitical

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[8] The process of reducing carbon dioxide emissions through energy system transformations.

influence (Van de Graaf & Bradshaw, 2018). These countries have been able to leverage their control over energy resources to influence global energy markets, using oil as a geopolitical tool (Mitchell, 2013). This dynamic is particularly evident in OPEC's ability to influence oil prices through coordinated production decisions, a practice that has often placed the organization at the center of global economic and political discussions (IEA, 2018).

Post-World War II, the control over fossil fuels helped establish a global energy order, particularly impactful on foreign policy. Energy security -in terms of a nation's ability to secure uninterrupted energy supply of at affordable prices- became a crucial consideration for major economies such as the United States, China, and Europe (Goldthau & Westphal, 2019). This security, however, was reliant on a relatively small group of energy-rich nations, granting these countries disproportionate influence over the rest of the world. As Mitchell (2013) notes, the fossil fuel economy fostered a global system of energy interdependence, yet it also heightened vulnerability to supply disruptions, making energy an instrument of political leverage.

2.3.2. From Fossil Fuels to Renewables: Decentralization of Energy and Its Implications

An energy transition poses the possibility of an upset of the traditional energy order. Unlike oil and gas, renewable resources are geographically widespread, allowing almost all countries to produce their own energy, at least to some degree (IRENA, 2021). This decentralization is expected to reduce the geopolitical power of traditional fossil fuel exporters while empowering nations that invest in renewable infrastructure (Amin, 2024).

Decentralization has the potential to reduce global dependency on energy-importing countries, particularly in Europe and Asia, which have long been reliant on oil and gas from the Middle East and Russia (Bhardwaj, 2024). As countries build domestic renewable energy capacity, they reduce their exposure to external geopolitical risks. The European Union, for example, has been accelerating its transition to renewables in the wake of energy security concerns exacerbated by Russia's invasion of Ukraine, which rendered the risks of dependency on fossil fuels from politically unstable regions clearer than ever (O'Sullivan, 2021). This shift is already beginning to erode the geopolitical influence of oil-rich nations like Russia and Saudi Arabia, as their ability to control energy markets diminishes along with the decline in global oil demand (Van de Graaf & Bradshaw, 2018).

2.3.3. New Geopolitical Tensions: Critical Minerals and Supply Chains

While renewable energy bears many promises, it also introduces new geopolitical complexities and uncertainties, particularly regarding the supply of critical minerals. Technologies essential for the renewable energy transition, such as electric vehicle batteries, wind turbines, and solar panels, rely on a range of critical minerals such as lithium, cobalt, nickel, and rare earth elements. These minerals are often concentrated in a few countries, notably China, which currently dominates the production and processing of many of these critical resources (IRENA, 2021; Lee, 2021). This concentration of supply chains has the potential to create new forms of energy dependency and geopolitical competition. As China continues to control the supply of rare earth elements and battery production, it could gain significant leverage over the global energy transition, much like oil-exporting countries have done in the past (Cox, 2021).

The scramble for critical minerals has already sparked concerns about resource nationalism[9] and protectionism. The United States and European Union have been working to diversify their supply chains by investing in alternative sources of critical minerals, including domestic mining and partnerships with countries outside of China (IEA, 2022). However, this diversification is complicated by environmental concerns surrounding mining and refining processes, which can cause significant ecological damage (Zhang et al., 2021). Furthermore, supply chain vulnerabilities[10] were highlighted during the COVID-19 pandemic, when disruptions in global trade revealed the fragility of existing energy supply networks (IRENA, 2021).

Another potential hotspot for geopolitical competition is the race to dominate hydrogen technology. Hydrogen, often promoted as the "fuel of the future," is emerging as a critical element in the global push toward decarbonization. Countries like Germany, Japan, and South Korea are investing heavily in hydrogen technology, with the aim of reducing their reliance on fossil fuels and emerging as leaders in the new energy economy. However, the development of a global hydrogen economy is expected to be faced with plenty of challenges, including the establishment of international standards, the coordination of supply chains, and the creation of new trade relationships (IRENA, 2021).

2.3.4. Challenges for Fossil Fuel-Dependent Economies

For countries whose economies are heavily reliant on fossil fuel exports, a global shift away from fossil fuels would introduce significant challenges in terms of their national economies. Some countries, such as the United Arab Emirates, have initiated ambitious economic diversification plans which include the incorporation of clean energy into their long-term development goals (Chatham House, 2024). Saudi Arabia's Vision 2030 plan, for example, aims to reduce the country's reliance on oil through investments in renewable energy, technology, and tourism (IEA, 2018). However, the speed at which the energy transition is happening may leave some countries behind, particularly those with typically weaker institutions and less access to capital (Bazilian et al., 2017).

The energy transition also carries the risk of creating a "green divide" between developed and developing countries. While wealthy nations are leading the charge in renewable energy investments, many developing countries still lack the infrastructure, technology, and financial resources to participate in the race for green energy. Without international support

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[9] A policy trend where countries seek to control their natural resources, impacting global renewable supply chains (Zhang et al., 2020).

[10] Disruptions in mining and production of materials critical for renewables (IRENA, 2021).

and investment, both crucial for renewable energy projects, these countries risk being left behind in integration renewables, exacerbating existing inequalities and possibly creating new sources of geopolitical instability (Bazilian & Sovacool, 2016).

2.3.5. Summary

The expressed will to collectively look at less climate-impacting energy sources has impacted the geopolitical landscape and international relations. Traditional energy superpowers like Saudi Arabia and Russia are losing part of their geopolitical influence, while new power centers emerge around critical mineral supply chains and clean energy technologies. The transition also presents new geopolitical challenges, from competition over critical minerals to the need for international cooperation in developing new energy systems. How countries manage these changes -whether through economic diversification, technological innovation, or strategic alliances -will determine the future contours of global geopolitics in the future.

3. The Impact of Renewable Energy on Energy Security

This chapter presents an in-depth analysis of the impact of renewable energy on energy security, affordability, and the broader geopolitical landscape. It explores how renewable energy contributes to resilience by diversifying and decentralizing energy sources, enhancing system stability, and integrating advanced technologies like energy storage and smart grids. Additionally, the chapter examines economic benefits and challenges, alongside the long-term implications of renewables on global energy markets. Finally, it discusses the geopolitical shifts resulting from the deployment of renewable energy sources, highlighting the new dynamics in energy independence, trade networks, and the evolving roles of both fossil fuel-dependent and renewable resource-rich nations.

3.1. The Impact of Renewable Energy on Energy Security Resilience

The integration of renewable energy sources is often framed as a solution to both environmental challenges and energy security concerns. While environmental benefits, such as reductions in greenhouse gas emissions, are well-established, the implications of renewable energy for energy security -specifically regarding resilience- require careful examination. Resilience, a key metric of energy security, refers to the ability of an energy system to withstand and recover from disruptions.

3.1.1. Enhancing Resilience through Diversification of Energy Sources

One of the primary ways renewable energy strengthens energy resilience is through diversification. Traditional energy systems are predominantly dependent on fossil fuels, which exposes them to a variety of risks such as geopolitical instability, price volatility, and supply chain disruptions. The integration of renewable energy sources into the energy mix mitigates these risks by reducing dependence on any single energy source or supplier. By diversifying energy inputs -such as incorporating solar, wind, hydropower, and biomass-systems become less vulnerable to supply shocks (Cherp & Jewell, 2014).

Renewables not only diversify supply but also decentralize generation. This decentralization further enhances resilience by reducing the risk of widespread disruptions. Distributed generation, especially through technologies like solar photovoltaic (PV) panels, enables localities to generate their own power. This reduces the system's reliance on large, centralized power plants, which can be single points of failure in the case of extreme events such as natural disasters (Barton, Huang & Infield, 2013).

3.1.2. Distributed Generation and Grid Resilience

The resilience of energy systems is increasingly linked to their ability to incorporate distributed generation[11]. Renewable energy technologies, particularly solar and wind, promote the decentralization of energy production. This is in contrast to traditional fossil fuel-based energy systems, which are heavily centralized. Decentralized renewable energy systems, such as microgrids, can operate independently of the main grid, providing essential energy services during grid failures, natural disasters or any other outage. In times of crisis, these microgrids ensure a more resilient energy system by minimizing the impact of localized outages (Barton et al., 2013).

Furthermore, the resilience benefits of decentralized renewable energy systems are not purely theoretical. Empirical evidence shows that renewable energy microgrids have been successful in providing energy security during emergencies. For example, during Hurricane Sandy in 2012, several microgrids in the United States continued to operate while the centralized grid experienced widespread blackouts (Nguyen et al., 2015).

3.1.3. Challenges to Resilience: Intermittency and Variability

Despite the resilience benefits of diversification and decentralization, renewable energy systems face significant challenges due to the intermittent nature of key resources like solar and wind. These energy sources are inherently variable as solar panels generate electricity when the sun is shining, and wind turbines only operate when the wind is blowing. The

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[11] A decentralized approach to energy production where electricity is generated at or near the point of use, often using renewable technologies like rooftop solar panels.

intermittency issue can lead to unstable energy supplies and complicates efforts to ensure a resilient, reliable energy system (Ellabban, Abu-Rub & Blaabjerg, 2014).

In regions with high renewable energy penetration, managing intermittency requires sophisticated balancing mechanisms. Without effective solutions, such as energy storage or flexible backup systems, the variability of renewable energy can compromise the resilience of the entire energy grid (Nguyen et al., 2015). Managing fluctuations is essential for maintaining stability, particularly during periods of low renewable generation and high demand.

3.1.4. Energy Storage: A Critical Component for Resilience

Energy storage systems have emerged as a vital component of resilient renewable energy systems. The ability to store excess energy generated during peak production times (e.g., midday for solar or during windy conditions for wind power) and use it during times of low generation is crucial for maintaining a stable energy supply. Large-scale storage solutions, such as lithium-ion batteries and pumped hydro storage, are particularly effective at mitigating the risks posed by renewable energy intermittency (Nguyen et al., 2015).

Academic studies emphasize the importance of integrating renewable energy with advanced storage technologies to ensure resilience. Nguyen et al. (2015) argue that energy storage not only enables better integration of renewables but also ensures grid reliability, providing energy security in the event of supply disruptions. Without these storage systems, renewable energy struggles to match traditional fossil fuel-based systems in terms of flexibility and reliability.

3.1.5. The Role of Smart Grids in Enhancing Resilience

Technological innovations, particularly the development of smart grids[12], enhance even further the resilience of renewable energy systems. Smart grids incorporate real-time data, automation, and advanced communication systems, allowing for the dynamic balancing of supply and demand. This flexibility is key for integrating intermittent renewable energy sources, ensuring that the grid can respond quickly and as effectively as possible to fluctuations in generation or demand (Ipakchi & Albuyeh, 2009).

Smart grids also increase resilience by enabling demand response strategies, where consumers reduce or shift their electricity usage during peak demand periods or times of limited renewable energy availability. Additionally, smart grids improve fault detection and grid management, further reducing the vulnerability of energy systems to disruptions (Ipakchi & Albuyeh, 2009).

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[12] Advanced electrical grids that thanks to smart meters, use real-time data to optimize energy supply and demand.

3.1.6. Regional and Policy Considerations for Resilience

The impact of renewable energy on resilience is highly dependent on regional and policy contexts. In regions with high renewable energy penetration, the development of supportive policy frameworks -such as subsidies for renewable projects, carbon pricing[13], and grid infrastructure investments- plays a critical role in realizing the resilience benefits of renewable energy (Sovacool & Brown, 2010).

Countries like Denmark and states like California have implemented aggressive renewable energy goals alongside robust policy measures that support grid modernization, energy storage development, and microgrid implementation. These policies have helped ensure that renewable energy enhances resilience rather than undermining it. Without such policy support, the transition to renewable energy may exacerbate vulnerabilities and uncertainties due to the technical challenges of intermittency and variability (Sovacool & Brown, 2010).

3.1.7. Emerging Vulnerabilities: Weather Extremes and Cybersecurity Risks

While renewable energy reduces reliance on fossil fuels and mitigates geopolitical risks, it also comes along with new types of vulnerabilities. For instance, extreme weather events can severely impact renewable energy infrastructure. Solar panels and wind turbines are exposed to environmental conditions, and their performance can be compromised by events such as hurricanes, extreme heat, or prolonged periods of low wind or sunlight (Bompard et al., 2017).

Moreover, the increasing digitalization of renewable energy systems, particularly through the use of smart grids and automation, introduces cybersecurity concerns. Cyberattacks targeting the control systems of renewable energy infrastructure could result in large-scale energy disruptions, undermining the resilience of energy systems if not properly and adequately safeguarded (Bompard et al., 2017).

3.2. Affordability and Energy Security

This section examines the intersection of affordability and energy security in the context of renewable energy technologies. Affordability refers to the cost of energy production, distribution, and consumption, while energy security pertains to the stability and reliability of energy supplies, particularly in relation to geopolitical and market volatility. The shift from fossil fuels to renewable energy has significant economic implications, including reductions in long-term energy costs and improvements in energy security. This chapter explores these economic implications through the lens of current renewable energy trends,

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[13] Assigning a cost to carbon emissions to encourage shifts to low-carbon energy (State Council, 2021).

analyzing the cost curve of renewable technologies and discussing both the benefits and challenges associated with this transition.

3.2.1. Decreasing Costs of Renewable Energy

One of the most critical trends in renewable energy is the rapid decrease in costs, especially for solar and wind technologies. Over the past decade, the levelized cost of electricity (LCOE) for solar photovoltaic (PV) and onshore wind has declined significantly due to technological advancements, economies of scale, and increased competition within the renewable energy sector. According to IRENA (2020), the cost of solar PV has dropped by almost 90% since 2010, making it one of the most affordable sources of energy generation in the world. Similarly, onshore wind energy has experienced a reduction of nearly 70% in costs over the same period (Lazard, 2021).

The cost reductions in renewable energy are largely attributed to a number of factors, including improvements in technology, increased manufacturing efficiency, and economies of scale. Solar PV benefited from innovations in cell design and manufacturing, leading to higher energy conversion efficiency at lower costs (Zhao et al., 2019). Onshore wind has seen significant reductions due to the development of larger and more efficient turbines that can harness wind more effectively (IRENA, 2020).

In addition to solar and wind, battery storage technologies are rapidly becoming more cost-competitive. Battery costs have fallen by more than 80% in the past decade, with improvements in lithium-ion battery technology playing a key role (Schmidt et al., 2019). This is crucial for mitigating the intermittency of renewable sources like wind and solar, as effective storage solutions ensure a more stable energy supply.

3.2.2. Long-Term Economic Benefits of Renewables

The economic implications of renewables extend beyond short-term cost reductions, presenting significant long-term benefits. While renewable energy technologies generally require higher initial capital investments compared to fossil fuels, their operating costs are much lower. Since renewable energy sources, such as wind and solar, do not rely on fuel, their marginal operating costs are minimal (IRENA, 2021). This results in long-term price stability, insulating economies from the price volatility associated with fossil fuels, which are and have historically been subject to fluctuations in global oil and gas markets (BP, 2022). Moreover, renewable energy deployment is a major driver of job creation. The renewable energy sector, particularly solar and wind, is expected to create millions of jobs globally by 2030, balacing job losses in fossil fuel industries (IRENA, 2019). According to a report by IRENA (2021), the renewable energy transition could lead to the creation of over 24 million jobs worldwide by 2030, significantly contributing to economic growth in both developed and developing nations.

3.2.3. Social Implications: Energy Access and Equity

Renewable energy technologies also hold promise for addressing energy poverty and improving access to energy in developing regions. Decentralized renewable energy systems are increasingly being deployed in remote and underserved areas, providing a reliable and cost-effective alternative to traditional grid-based energy (Bhattacharyya, 2019). This has transformative social and economic effects, particularly in regions where conventional energy infrastructure is either too costly and challenging to develop.

According to the International Energy Agency (IEA, 2020), renewable energy technologies can play a pivotal role in achieving universal energy access, particularly in Sub-Saharan Africa and Southeast Asia, where a significant share of the population still has no access to electricity. The affordability of decentralized solar solutions has been instrumental in bringing electricity to millions of people, improving health, education, and economic opportunities in these regions (Pueyo & Bawakyillenuo, 2017).

3.2.4. The Cost Curve for Renewable Energy Technologies

The cost curve for renewable energy technologies has declined rapidly due to the learning rate or experience curve effect, where costs decrease as cumulative installed capacity increases. According to Rubin et al. (2015), for every doubling of global solar PV capacity, costs decrease by approximately 22%. Wind energy also exhibits a similar trend, with costs decreasing by 9–15% with each doubling of capacity (IRENA, 2020).

This reduction in costs is driven by improved manufacturing processes, economies of scale, and enhanced installation and operational efficiencies. The solar industry has greatly benefited from increased investment in research and development (R&D) and the globalization of its supply chains, which has driven down production costs (IRENA, 2019).

The declining cost of renewables has enabled them to achieve grid parity in many regions, meaning that the cost of renewable energy is now equal to or even lower than that of traditional fossil fuels without subsidies (Lazard, 2021). In several regions, solar and wind are now the cheapest forms of new electricity generation. For example, at one point the cost of utility-scale solar had fallen to around $30 per megawatt-hour (MWh) in the U.S., compared to $50–60/MWh for natural gas (IEA, 2021).

While global trends indicate a sharp decline in renewable energy costs, regional variations persist, factors such as solar irradiance, wind speeds, and local policy frameworks significantly impact the affordability of renewable energy from region to region. Countries with abundant natural resources for renewables, such as sun-rich deserts or coastal areas with strong winds, typically achieve lower costs compared to regions with less favorable conditions (Bhattacharya & Kojima, 2020).

3.2.5. Challenges to Affordability and Energy Security

Despite the decreasing costs of renewable technologies, upfront capital costs remain a significant problem, especially for developing countries. The initial investment required for large-scale solar or wind projects can be impossible without access to financing or government support (Nelson & Shrimali, 2014). International financial institutions and governments have a critical role to play in terms of financial incentives, such as subsidies, tax credits, and low-interest loans, in order to reduce barriers related to upfront capital (IRENA, 2020). Transitioning to renewable energy also incurs transition costs[14], particularly in economies reliant on fossil fuel industries. These costs include the risk of stranded assets, economic dislocation in fossil fuel-dependent regions, and the need for substantial investment in grid infrastructure to accommodate renewable energy (Cochran et al., 2014).

The affordability and energy security metrics of renewable energy technologies demonstrate the significant economic potential of transitioning to a renewable energy-dominated system. Falling costs, long-term economic benefits, and improved energy security all suggest that renewable energy technologies will continue to grow in prominence in global energy systems. However, challenges such as upfront costs, intermittency, and the need for new infrastructure must be addressed to ensure a successful and equitable transition.

3.3. Challenges

While renewable energy offers environmental benefits, its deployment into existing energy systems poses numerous challenges. This section will explore four critical challenges: the intermittency of wind and solar energy, the need for energy storage solutions, the requirement for grid adaptation, and regional disparities in renewable energy potential.

3.3.1. The Challenge of Intermittency in Wind and Solar Energy

One of the primary challenges associated with wind and solar energy is their inherent intermittency. Unlike conventional energy sources such as coal or natural gas, which can generate electricity continuously, the output from wind and solar power fluctuates. Solar energy is only available during daylight hours and is further affected by cloud cover and seasonal variations. Similarly, wind energy generation is contingent on wind speeds, which are highly variable and sometimes unpredictable (Bessa et al., 2019).

The intermittency of these renewable energy sources creates significant challenges for grid operators, who must balance supply and demand in real-time to maintain grid stability. Periods of excess energy generation, such as during peak solar hours or windy conditions, can overwhelm the grid, while periods of low generation may lead to energy shortages. This

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[14] Economic losses associated with the shift from fossil fuels to renewables, such as decommissioned coal plants.

variability can result in situations where excess energy is wasted because it cannot be used or stored (Denholm et al., 2020).

Moreover, intermittency poses risks to energy reliability and grid stability, particularly in regions with high renewable energy penetration. Without adequate energy storage or backup power, fluctuations in renewable generation can lead to voltage imbalances or even blackouts. This challenge underscores the need for flexible grid management and supplementary technologies to ensure consistent and reliable energy supply (Díaz-González et al., 2016).

3.3.2. The Need for Energy Storage Solutions

Energy storage is widely recognized as a key issue for wind and solar power. Storage technologies enable excess energy generated during periods of high renewable output to be stored and later discharged when generation is low. This capability is essential for maintaining a stable energy supply and ensuring that renewable energy can meet demand at all times. Several energy storage technologies are currently being developed and deployed. Lithium-ion batteries[15] are the most common form of storage due to their efficiency and rapidly declining costs. However, they are generally used for short-duration storage (ranging from a few hours to a day) and may not be sufficient for longer-term energy balancing (Luo et al., 2015). Pumped hydro storage[16], which involves pumping water to a higher elevation during periods of excess energy and releasing it to generate electricity when needed, is the largest form of energy storage worldwide. However, it is geographically limited and often expensive to develop (Blakers et al., 2017).

Emerging technologies, such as flow batteries, compressed air energy storage, and hydrogen-based storage, offer potential solutions for long-duration storage. Hydrogen, in particular, is being explored as a means of storing renewable energy over extended periods by using excess electricity to produce hydrogen through electrolysis, which can later be converted back into electricity when required (Bailera et al., 2017). However, these technologies remain costly and are not yet ready to the extent required for widespread deployment.

The need for large-scale, cost-effective storage solutions is one of the major barriers to achieving a fully renewable energy system. Without adequate storage, the integration of intermittent renewables will remain limited, and reliance on fossil fuel-based backup generation will continue, undermining the environmental benefits of renewable energy (Shah et al., 2015).

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[15] A dominant energy storage technology known for its efficiency and declining costs, critical for renewable energy integration.

[16] A large-scale energy storage technology that pumps water to a higher elevation for later use in electricity generation.

3.3.3. Grid Adaptation and Infrastructure Requirements

The integration of renewable energy into the existing grid infrastructure also requires significant adaptation. Most power grids were originally designed to distribute electricity from centralized, predictable sources such as coal or gas plants. In contrast, renewable energy systems, particularly wind and solar, are more decentralized and variable, which necessitates new approaches to grid management and transmission (Li et al., 2020).

One of the key challenges is the need for greater grid flexibility. Flexible grids can respond more quickly to fluctuations in supply and demand by incorporating advanced monitoring and control systems, as well as integrating distributed energy resources (DERs) such as rooftop solar panels and small-scale wind turbines. Smart grid technologies, which use real-time data to optimize the flow of electricity, are essential to managing the variability of renewable energy and ensuring efficient grid operation (Fang et al., 2012).

Another significant requirement is upgrading transmission infrastructure. Wind and solar farms are often located in remote areas, far from population centers and industrial hubs where energy demand is highest. High-voltage transmission lines are essential to transport electricity from these generation sites to demand centers. However, building new transmission infrastructure can be expensive and faces regulatory and permitting problems, particularly in densely populated or environmentally sensitive areas (MacDonald et al., 2016).

3.3.4. Regional Disparities in Renewable Energy Potential

The potential for renewable energy generation varies significantly across regions due to geographic, climatic, and socio-economic factors. Solar energy is most abundant in regions such as deserts and areas near the equator, while wind energy potential is highest in coastal and offshore areas, as well as regions with large, open plains (Pfenninger & Staffell, 2016). These regional disparities create uneven opportunities for renewable energy deployment.

Regions with poor renewable energy resources may face higher costs to transition to clean energy, leading to disparities in energy access and affordability. For example, countries in northern Europe or parts of northern North America, which have less sunlight and lower wind speeds, may need to rely more on energy imports or invest in alternative renewable technologies, such as geothermal or hydropower (Jäger-Waldau et al., 2019). One solution to address these disparities is the development of interregional energy trade. By connecting grids across regions and countries, renewable-rich areas can export excess electricity to regions with less renewable output. This requires substantial investment in intercontinental transmission networks, as well as cooperation among governments to align regulatory frameworks and market structures (Schleicher-Tappeser, 2012). In Europe, for instance, plans for a transcontinental grid aim to link renewable energy resources across the continent, ensuring that solar energy from southern Europe and wind energy from the North Sea can be shared more efficiently (Grams et al., 2017).

3.4. Geopolitical Shifts

The shift to renewable energy is not only altering the structure of global energy markets but also has significant implications for geopolitical power dynamics, particularly in terms of energy independence, trade, and international alliances. The rise of renewables poses both opportunities and challenges for traditional fossil fuel exporting and importing countries. How is renewable energy reshaping global power dynamics and which are the geopolitical consequences for nations traditionally reliant on fossil fuels?

3.4.1. The Shift in Global Energy Independence and Security

The widespread availability of renewable energy in some form has enabled countries that were previously dependent on fossil fuel imports to develop more localized and secure energy systems. Germany's *Energiewende* policy serves as an example. The aim is to transition the country from nuclear and coal-based energy to renewable sources and highlights the strategic importance of energy security in modern economies (Mez, 2020). By increasing the domestic share of energy production, countries like Germany and Denmark are not only reducing their reliance on energy imports but also insulating themselves from geopolitical risks associated with fossil fuel supply chains (Lehmann et al., 2022).

In addition, countries with renewable energy resources have an opportunity to become net energy exporters by developing infrastructure to export electricity or hydrogen produced from renewable sources. For example, the European Union has pursued initiatives to import solar energy from North Africa, exemplified by projects like DESERTEC, which aims to leverage the region's abundant solar resources (Gnos, 2019). The move toward renewable energy sources is gradually undermining the traditional power dynamics that have been dominated by fossil fuel-exporting countries.

3.4.2. Decline in Geopolitical Leverage of Oil-Rich Nations

The transition to renewable energy is diminishing the geopolitical influence that fossil fuel-exporting nations, especially oil-rich states, have traditionally held. For decades, countries such as Saudi Arabia, Russia, and Iran have enjoyed considerable geopolitical influence due to their control over global oil and gas supplies (Yergin, 2020). However, as the global energy mix diversifies with the increasing deployment of renewables, these countries face diminishing power and economic influence. Organizations like the Organization of Petroleum Exporting Countries (OPEC) have played a critical role in regulating oil prices by controlling supply, but as demand for oil declines, the effectiveness of such strategies is likely to diminish. The International Energy Agency (IEA) projects that global oil demand will plateau by the mid-2030s, with renewable energy sources expected to account for nearly 90% of total electricity growth by 2040 (IEA, 2020). This trend signals a potential shift in global energy geopolitics, where the dominance of oil-exporting nations could be undermined by the expansion of renewable energy markets (Goldthau & Sovacool, 2016).

At the same time, new sources of influence are emerging, particularly for countries that control the supply chains for renewable energy technologies. China, for example, dominates the production of solar photovoltaic panels and electric vehicle batteries, and its strategic investments in the renewable energy sector have positioned it as a leader in the global energy transition (Zhang et al., 2020). This new form of energy geopolitics, driven by control over clean energy technologies and critical minerals like lithium and cobalt, is shifting the balance of power towards countries with strong technological capabilities (Meckling et al., 2019).

3.4.3. New Energy Trade Networks and Alliances

The emergence of renewable energy is also reshaping global trade networks. Unlike fossil fuels, which require complex international logistics for extraction, refining, and distribution, renewable energy technologies are often traded as manufactured goods, such as wind turbines, solar panels, and batteries (IRENA, 2019). This has led to the creation of new trade partnerships focused on clean energy technologies, as countries seek to secure access to the materials and technologies needed for their energy transitions.

In addition, cross-border energy infrastructures are evolving to accommodate renewable energy trade. Transnational electricity grids and hydrogen pipelines allow countries to export surplus renewable energy to neighboring regions, fostering new forms of energy interdependence (IRENA, 2020). Projects like the European Union’s plans to import renewable hydrogen from North Africa illustrate how renewable energy is creating new geopolitical connections and dependencies (Kucharski et al., 2021).

3.4.4. Effects on Traditional Fossil Fuel Importing Countries

For traditional fossil fuel importing countries, the shift towards renewable energy offers numerous benefits, particularly in terms of reducing dependency on volatile fossil fuel markets. Countries like Japan, which rely heavily on imported energy, are investing in renewables as a way to enhance energy security and reduce exposure to geopolitical risks (Stevens, 2019). By reducing fossil fuel imports, countries can also improve their trade balances and invest more in domestic energy infrastructure. The development of renewable energy industries has the potential to create new jobs and stimulate economic growth, further enhancing the economic resilience of fossil fuel importing nations (IRENA, 2018). Furthermore, the transition to renewable energy is reshaping foreign policy, as countries realign their alliances based on clean energy cooperation rather than fossil fuel trade (Mikheeva & Sovacool, 2020). In contrast, traditional fossil fuel exporting countries face significant challenges as the world transitions towards renewable energy. Many of these countries, such as Saudi Arabia, Russia, and Venezuela, are highly dependent on oil and gas revenues, and the decline in global demand for fossil fuels threatens their economic stability (BP, 2021). This has prompted several of these nations to pursue economic diversification strategies aimed at reducing their reliance on oil exports.

Saudi Arabia’s Vision 2030 is a prime example of a fossil fuel exporting country attempting to shift its economy towards sectors like tourism, finance, and renewable energy (Al-Sarihi, 2021). Similarly, the United Arab Emirates has invested heavily in renewable energy projects such as Masdar City, a planned city aimed to become a hub for clean technology innovation (Ulrichsen, 2020). These efforts reflect the growing recognition that the future of energy lies in diversification away from fossil fuels.

However, for many fossil fuel-exporting countries, the transition to renewable energy remains fraught with challenges, particularly in terms of maintaining political and economic stability. Countries with limited institutional capacity to manage the transition may face internal unrest and economic crises as oil revenues decline (Ross, 2012). Sovereign wealth funds, like Norway’s Government Pension Fund, have been used by some countries to invest in renewable energy and other sectors, providing a financial buffer to help navigate through the transition (Næss-Schmidt et al., 2018).

4. Case Studies

This chapter examines case studies of six countries -Germany, China, the United States, Brazil, Morocco, and Norway- that have adopted diverse renewable energy strategies with implications for energy security, economic development, and geopolitical influence. Each case study analyzes both the unique and common approaches and outcomes of these transitions, focusing on how different renewable energy sources affect energy security resilience, economic growth, and global positioning. The chapter offers insights into the successes, challenges, and future prospects of renewable energy, highlighting how these countries' renewable energy initiatives shape their energy independence, grid stability, and role in the evolving global energy landscape.

4.1 Germany's Energiewende and Its Impact on Energy Security

Germany's Energiewende represents one of the most ambitious national energy transitions in the world, marked by a comprehensive shift toward renewable energy and a commitment to reducing reliance on fossil fuels. Initiated in the early 2000s and further solidified in response to the 2011 Fukushima nuclear disaster, the Energiewende has transformed Germany's energy policy framework and raised the nation as a leader in renewable energy deployment (Westphal, 2018). It has been a cornerstone of Germany’s climate and energy policy, but it also represents a significant transformation of its energy security landscape. This case study explores both the successes and limitations of the Energiewende, focusing on its impact on energy security, with particular attention to challenges related to energy reliability, affordability, diversification, and geopolitical implications.

4.1.1. Objectives of the Energiewende

The primary objectives of Germany's Energiewende include reducing greenhouse gas emissions, phasing out nuclear energy, increasing the share of renewable energy in the energy mix, and improving energy efficiency. Specifically, the Energiewende aims to cut greenhouse gas emissions by 80-95% by 2050 compared to 1990 levels (Schiffer & Trüby, 2018). Additionally, Germany seeks to achieve a renewable energy share of at least 80% in electricity consumption by 2050 and reduce primary energy consumption by 50% relative to 2008 levels by the same year (Matthes, 2017).

4.1.2. Policy Mechanisms and Regulatory Framework

Feed-in Tariffs (FiTs)[17] were one of the earliest mechanisms implemented under the Energiewende. This policy provided long-term contracts and fixed prices for renewable energy producers, significantly reducing financial risks and promoting investment in renewables, particularly in solar and wind power (Matthes, 2017).

The Renewable Energy Sources Act, or Erneuerbare-Energien-Gesetz (EEG), enacted in 2000, has been pivotal to Germany's renewable energy expansion. The EEG mandated priority access for renewable electricity to the grid, ensuring that all renewable energy generated would be purchased and distributed, thus guaranteeing a stable revenue stream for renewable energy producers (Schiffer & Trüby, 2018).

In recent years, Germany has shifted from the FiT model to an auction-based system, aiming to control costs and promote market competition. The auction model has enabled Germany to keep renewable energy prices more competitive, aligning with its economic goals while promoting sustainable energy growth (Westphal, 2018).

Germany has participated in the European Union's Emissions Trading System (EU ETS)[18] and, more recently, introduced a national carbon pricing system for sectors not covered by the EU ETS, including transportation and heating. Carbon pricing is designed to incentivize emissions reductions by assigning a monetary value to carbon emissions, thereby encouraging a shift to cleaner energy alternatives (Matthes, 2017).

4.1.3. Progress and Achievements

The Energiewende has substantially increased Germany's renewable energy capacity. In 2022, renewables accounted for approximately 40% of the country's electricity generation, up from just 6% in 2000 (Kendziorski et al., 2022). This growth has been primarily driven by wind and solar energy, with wind turbines concentrated in northern Germany and solar photovoltaic (PV) installations widely adopted across the country (Schiffer & Trüby, 2018).

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[17] Guaranteed payments to renewable energy producers to encourage investment.

[18] A carbon emissions allowances trading mechanism that incentivizes emissions reductions in the EU.

Germany's energy transition has relied on citizens playing an active role in renewable energy investments. Approximately 46% of installed renewable energy capacity is owned by individual citizens or energy cooperatives, demonstrating a high level of civic engagement and decentralized ownership in the energy transition (Kratzenberg et al., 2021).

The shift toward renewable energy has resulted in a more decentralized grid, where smaller-scale, local renewable installations contribute to overall generation and grid resilience. This decentralized model provides energy security and reduces reliance on centralized power plants, although it requires more sophisticated grid management (Westphal, 2018).

4.1.4. Impact on Energy Security

The variable nature of RES, particularly wind and solar, poses significant challenges. These sources are dependent on weather conditions, and their intermittent output contrasts sharply with the stable, predictable output from conventional energy sources like coal, nuclear, and natural gas. As Germany phases out coal and nuclear plants, ensuring a reliable energy supply with a growing share of renewables has become a central concern (Fraunhofer ISE, 2023). Wind generation fluctuates based on wind speeds, while solar energy depends on sunlight availability, both of which are unpredictable and often do not align with peak electricity demand (IEA, 2022). During periods of low wind and solar output, such as windless winter nights, renewable generation can fall significantly short of demand, necessitating backup from other sources (Richter et al., 2022).

Studies indicate that Germany's renewable generation often produces excess power during windy or sunny periods, leading to curtailment of renewable output. Conversely, during low-output periods, Germany relies heavily on imports and fossil fuel-based backup plants to meet demand (Hirth & Ziegenhagen, 2021). This reliance on imports, particularly from neighboring countries like France and Poland, raises concerns about energy sovereignty and the ability to ensure stable energy supply in cases of regional supply shortages (Agora Energiewende, 2022).

To counter the intermittency of renewables, Germany has invested in energy storage solutions and demand response mechanisms. Battery storage, pumped hydro storage, and green hydrogen[19] are emerging technologies that can store excess renewable energy for later use. However, these technologies are still in development and currently lack the capacity required to fully stabilize Germany's grid (BMWK, 2023).

Pumped hydro storage is Germany's most developed storage technology, but its capacity remains limited. Battery storage, while expanding, is expensive and has a limited energy storage duration, typically providing power for only a few hours. Green hydrogen, which can store energy over longer periods, holds promise for balancing seasonal fluctuations in renewable generation, but the technology is not yet commercially viable on a large scale (Fraunhofer ISE, 2023).

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[19] Hydrogen produced using renewable energy, considered essential for decarbonizing sectors like transportation and heavy industry.

Renewable sources like wind and solar lack the inertia that conventional power plants provide, making it more challenging to maintain grid frequency and stability. Traditional coal, gas, and nuclear plants generate synchronous electricity, stabilizing the grid by providing inertia to absorb fluctuations in demand and supply (BMWi, 2022). Renewable sources, however, do not contribute to grid inertia, making the grid more susceptible to imbalances that can lead to power outages or frequency instability (Sioshansi, 2022).

Germany has addressed these issues by implementing advanced grid management technologies, such as real-time frequency regulation and flexible load management. Additionally, Germany is interconnected with the European grid, allowing for cross-border electricity flows that help stabilize the system. This interconnection provides a buffer, but it also makes Germany partially dependent on the stability of neighboring grids, posing risks if those systems face concurrent supply issues (Hirth & Ziegenhagen, 2021).

The rapid increase in renewable energy generation has necessitated significant investment in Germany's transmission and distribution infrastructure. Much of Germany's wind energy is generated in the north, while demand centers are located in the industrialized south. This geographical imbalance requires extensive transmission lines to transport electricity across the country. However, the development of these transmission lines has faced delays due to regulatory, financial, and public opposition issues (Agora Energiewende, 2022).

In response, Germany has accelerated grid expansion projects and implemented high-voltage direct current (HVDC)[20] lines to improve the efficiency of electricity transmission over long distances. Despite these efforts, delays and underfunding continue to create bottlenecks in renewable energy distribution, which limits the system's reliability (BMWK, 2023).

Germany has pursued flexible energy solutions to enhance the reliability of renewable energy, including flexible natural gas plants, smart grids, and demand response initiatives.

German energy policy has increasingly relied on natural gas as a backup to balance renewable variability. Gas-fired plants, which are more flexible than coal or nuclear, can ramp up or down quickly, providing the necessary stability during periods of renewable shortfalls. However, this strategy has faced criticism, as it prolongs Germany's dependency on fossil fuels, potentially conflicting with its long-term decarbonization goals (IEA, 2022). The geopolitical tensions surrounding gas imports, especially from Russia, have further underscored the need for a self-sufficient and renewable-based energy system for Germany (Bundesnetzagentur, 2023). Smart grids and demand response programs are essential components of Germany's strategy to enhance reliability in a renewable-dominant system. Smart grids allow for real-time monitoring and adjustment of electricity flows, enabling grid operators to respond quickly to fluctuations in renewable generation. Demand response programs, where consumers reduce or shift their electricity usage during peak periods, help manage demand and reduce strain on the grid during periods of low renewable output (BMWK, 2023).

Germany has introduced incentive programs for industrial and residential consumers to participate in demand response, allowing the system to balance loads more effectively. These

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[20] Transmission lines that efficiently transport electricity over long distances, crucial for connecting renewable energy projects to demand centers.

programs have shown promise in improving reliability but require further development and consumer participation to have a significant impact on the grid (Huenteler et al., 2022).

4.1.5. Affordability of Energy

The cost of the Energiewende has been a significant issue, particularly concerning electricity prices. Germany's renewable energy expansion has been financed mainly through surcharges on electricity bills, the EEG surcharge. This mechanism has led to rising electricity prices for households and small businesses, which by 2020, had some of the highest electricity prices in Europe (Agora Energiewende, 2020). Between 2000 and 2020, household electricity prices increased by approximately 50%, driven largely by surcharges to finance renewable energy subsidies (BDEW, 2020). This rise in energy costs presents challenges to energy affordability and can impact industrial competitiveness. To mitigate these issues, the German government has implemented subsidies for low-income households and energy-intensive industries (IEA, 2021). Moreover, the cost of renewable energy technologies, particularly wind and solar power, has fallen dramatically over the past decade. In fact, the levelized cost of electricity (LCOE)[21] for solar photovoltaic (PV) and onshore wind has reached parity with, or fallen below, that of fossil fuels in many parts of the world (IRENA, 2020). In the long term, the decreasing costs of renewable energy are expected to reduce the financial burden on consumers. Germany has also implemented compensation mechanisms to mitigate the impact of rising energy costs on energy-intensive industries which are often the most affected. Large industrial consumers are often exempt from paying the full EEG surcharge, allowing them to remain competitive in the global market (BMWi, 2021). However, this has shifted more of the cost burden onto households, fueling concerns about social equity in the cost distribution of the Energiewende.

4.1.6. Diversification of Energy Supply

One of the primary objectives of the Energiewende was to reduce Germany's reliance on imported fossil fuels, predominantly from geopolitically risky regions such as Russia and the Middle East. However, natural gas is considered a "bridge fuel" in Germany's energy transition, given its lower carbon intensity compared to coal. More than 55% of Germany's natural gas was imported from Russia prior to 2022, creating potential vulnerabilities in the context of geopolitical tensions (IEA, 2021). However, according to the International Energy Agency (IEA), Germany's dependence on imports for primary energy has decreased, enhancing its energy autonomy (IEA, 2020). With the onset of the Ukraine crisis, Germany faced the urgent task of finding new, reliable gas sources. U.S. LNG provided an immediate solution to replace Russian pipeline gas, diversifying Germany's natural gas sources and reducing dependency on any single supplier (IEA, 2022). By securing American LNG,

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[21] The total cost of building and operating a power-generating asset divided by its total electricity output over its lifetime.

Germany not only alleviated short-term energy shortages but also enhanced its energy security, supporting the longer-term goals of Energiewende by allowing more flexibility in the transition to renewables (IEA, 2023).

4.1.7. Energy Security vs. Sustainability Trade-offs

With the import of American LNG, Germany faced a challenge in balancing energy security with its sustainability targets. The 2022 energy crisis led to an unavoidable increase in fossil fuel imports, which is at odds with Energiewende's goal of reducing reliance on fossil fuels and achieving carbon neutrality[22] by 2045 (Bundesregierung, 2022). Although LNG burns cleaner than coal, it is still a fossil fuel that emits greenhouse gases (GHGs), contributing to climate change. American LNG, in particular, often involves a process of extraction (fracking) and liquefaction that emits substantial CO_2 and methane, adding to Germany's carbon footprint (Fraunhofer ISE, 2023).

The rapid development of LNG import infrastructure, such as new floating LNG terminals and planned permanent LNG terminals, represents a significant financial commitment. The German government invested billions of euros to fast-track these projects, ensuring immediate energy security but potentially creating a "lock-in" effect that could hinder the future shift away from natural gas (BDEW, 2023). These LNG facilities have long operational lifespans, often 20-30 years, and maintaining them will require continuous LNG imports.

This infrastructure, while necessary in the short term, raises concerns that Germany may be inadvertently reinforcing a dependency on fossil fuels, as these terminals may still require utilization for decades to recoup investment costs (IEA, 2022). Critics argue that resources could instead be allocated directly to renewable energy infrastructure or energy storage systems, accelerating the shift toward a carbon-neutral energy system without the added emissions from LNG.

4.1.8. Challenges and Future Prospects

The Energiewende represents a bold vision for a sustainable energy future, but it also faces several ongoing challenges. These challenges include ensuring the reliability of supply as coal and nuclear are phased out, managing the rising costs of the transition, and addressing geopolitical vulnerabilities related to natural gas imports. To ensure a reliable energy supply, Germany will need to scale up investments in energy storage technologies, such as batteries and hydrogen, while efforts for electricity grid modernization continue. Managing the costs of the Energiewende, particularly for households and the German industry, while ensuring that the transition remains socially seems very difficult. Finally, Germany will need to address its reliance on Russian natural gas, both by diversifying its gas supply and

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[22] Achieving a balance between emitting carbon and absorbing it from the atmosphere through natural or artificial means.

accelerating its shift to renewables. The success of these efforts will have broader implications for Europe's energy security overall.

4.1.9. Summary

Germany's Energiewende has had profound implications for Germany's energy security, reducing its reliance on coal and nuclear power and positioning it as a global leader in climate action. However, the transition has also introduced new challenges, particularly regarding energy affordability, grid stability, and geopolitical vulnerabilities related to natural gas imports.

From a geopolitical perspective, the Energiewende has reshaped Germany's role in Europe and the world. While it has strengthened Germany's leadership in climate policy, it has also exposed vulnerabilities in terms of energy security, particularly its energy imports reliance. As the Energiewende continues, Germany will need to address these challenges to ensure that the integration of renewable energy strengthens, rather than undermines, its long-term energy security.

4.2. China's Renewable Energy Deployment and Its Geopolitical Impact on Energy Security

As the world's largest energy consumer, China faces a range of energy security challenges, including heavy reliance on imported fossil fuels and environmental degradation due to extensive coal use. Over the past two decades, China has dramatically expanded its renewable energy capacity, driven by both environmental imperatives and concerns over energy security (Chen, 2022). In this case study, we explore China's renewable energy deployment, with a particular focus on how it strengthens the country's energy security and its broader geopolitical implications. The analysis highlights China's strategic shift toward energy independence, its leadership in the global renewable energy supply chain, and the emerging challenges it faces as it seeks to balance energy needs with global geopolitical dynamics.

4.2.1. China's Energy Security Context

Energy security has long been a priority for China, as rapid industrialization and urbanization have driven surging energy demand. Traditionally, China has relied heavily on coal, accounting for approximately 60% of its energy consumption in 2020 (IEA, 2021). However, air pollution, carbon emissions, and geopolitical vulnerabilities tied to energy imports, particularly oil and natural gas, have compelled China to explore renewable energy as a key component of its energy security strategy (Zhang & Andrews-Speed, 2021). By 2022, China imported over 70% of its oil, much of which came from politically unstable regions in the Middle East and Africa (Chen, 2022). Similarly, about 40% of China's natural gas demand was met through imports, primarily from countries like Russia, Turkmenistan, and Australia

(Li et al., 2021). These dependencies exposed China to both market fluctuations and geopolitical risks, as global supply chains could be disrupted by regional conflicts, trade wars, or sanctions (Li & Xu, 2021). Renewable energy thus offered a pathway to reducing reliance on volatile global energy markets while mitigating environmental damage.

4.2.2. Policy Framework for Renewable Energy Development

China's transition to renewable energy has been guided by robust policy support, with the government enacting laws and regulations that incentivize the development of clean energy sources. The Renewable Energy Law of 2005 was a major milestone, establishing feed-in tariffs (FITs), subsidies, and tax incentives to promote the uptake of solar, wind, and hydropower (IEA, 2021). This legal framework has been periodically updated to reflect the country's evolving renewable energy goals.

The 13th and 14th Five-Year Plans (2016-2020, 2021-2025) set ambitious targets for renewable energy deployment, aiming to decarbonize the economy and reduce fossil fuel dependence (NDRC, 2020). In 2020, China's President Xi Jinping announced that the country would aim to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (State Council, 2021). This announcement further accelerated investment in renewables, reinforcing China's commitment to transitioning toward a low-carbon energy system and enhancing its energy security.

In addition, China's National Energy Administration (NEA) oversees the deployment of renewable energy projects, while the National Development and Reform Commission (NDRC) coordinates the country's energy transition policies, including energy efficiency and promotion of green technology (Huang & Li, 2022).

4.2.3. Growth of Renewable Energy Capacity

China's renewable energy deployment has been exceptional in terms of both scale and speed. As of 2023, China leads the world in installed renewable energy capacity, with over 1,200 gigawatts (GW) of solar, wind, and hydropower (REN21, 2023).

China's installed solar capacity surpassed 400 GW in 2023, accounting for more than one-third of the global total. The country dominates the global photovoltaic (PV) market, producing over 70% of the world's solar panels (IEA, 2021). Wind energy capacity reached over 400 GW by the end of 2023, making China the world's largest wind power market. The expansion of offshore wind farms along China's eastern coastline has been particularly rapid, with substantial growth projected over the next decade (Global Wind Energy Council [GWEC], 2023).

Hydropower remains a key component of China's renewable energy strategy, with over 370 GW of installed capacity. The Three Gorges Dam, the world's largest hydropower project, continues to play a central role in balancing the national grid (World Energy Council, 2022).

While not renewable, nuclear power and energy storage are vital for balancing the intermittent nature of renewables. China has invested heavily in grid-scale storage solutions, such as pumped hydro and battery storage systems, to support renewable integration (He et al., 2022).

4.2.4. Reducing Dependence on Imported Fossil Fuels

The expansion of renewable energy has enabled China to reduce its dependence on imported fossil fuels, particularly oil and natural gas. Solar and wind energy, which are abundant within China's borders, offer a domestic solution to energy security risks. In particular, China's extensive solar capacity has been instrumental in decreasing the need for imported natural gas used for power generation during peak demand periods (Chen, 2022).

According to Li et al. (2021), the diversification of energy sources has reduced China's vulnerability to geopolitical tensions in oil-producing regions, such as the Middle East, and to trade disputes, such as the U.S.-China tariff war that affected energy markets. By shifting towards renewable energy, China has insulated its economy from the volatility of global energy markets, thereby enhancing its energy security (Cui et al., 2021).

4.2.5. Enhanced Grid Resilience and Decentralization

Renewable energy, particularly solar and wind, has fostered a more decentralized energy system in China. In contrast with traditional fossil fuel plants, their centralized nature and consequent vulnerabilities, renewable energy projects tend to be geographically dispersed, reducing the impact of localized disruptions on the national energy supply (Li & Xu, 2021). Moreover, China's investment in ultra-high voltage (UHV) transmission lines has facilitated the efficient transport of renewable energy from resource-rich regions, such as Inner Mongolia (wind) and Qinghai (solar), to the heavily populated eastern provinces (Li et al., 2021). This infrastructure development not only strengthens China's domestic energy supply but also enhances the resilience of the national grid, thereby improving overall energy security (He et al., 2022).

4.2.6. Technological Leadership and Global Supply Chains

China's dominance in renewable energy technology manufacturing has had profound implications for its energy security and geopolitical standing. As the leading producer of solar PV panels and wind turbine components, China controls critical supply chains for the global renewable energy transition. This technological leadership not only strengthens China's own energy independence but also provides it with significant geopolitical leverage, as countries around the world look to expand their renewable energy sectors (Kong, 2022).

China's renewable energy companies, such as BYD, Trina Solar, and Goldwind, have become global leaders, and China's position in the critical minerals supply chain (e.g., rare earth elements, lithium, and cobalt) further cements its influence over global energy markets (Zhao & Liu, 2023). The country has also invested in overseas mining operations in Africa, South America, and Central Asia to secure access to these minerals, which are essential for the production of renewable technologies and energy storage systems (Zhao & Liu, 2023).

4.2.7. Energy Diplomacy and Global Influence

China's renewable energy leadership has had significant geopolitical implications. By positioning itself as a key player in the global renewable energy transition, China has expanded its influence through energy diplomacy. This is particularly evident in its Belt and Road Initiative (BRI)[23], which includes significant investments in renewable energy projects in developing countries (Chen, 2022). Through these investments, China is exporting its renewable energy technologies and expertise, while simultaneously gaining access to new markets and strengthening political ties with energy-importing countries (Zhang & Andrews-Speed, 2021).

Moreover, China's ability to provide financing and infrastructure for renewable energy projects in countries across Africa, Asia, and Latin America has elevated its geopolitical influence, particularly in regions where Western powers have traditionally been dominant (Kong, 2022). This shift in influence challenges traditional energy alliances, reshaping global energy geopolitics.

4.2.8. Competition with Other Major Powers

China's renewable energy dominance has also created tensions with other major powers, particularly the United States and the European Union (Zhao & Liu, 2023). Both regions are seeking to reduce their reliance on Chinese-manufactured renewable technologies, fearing that overdependence on Chinese supply chains could create new energy security vulnerabilities. The U.S. and the EU have introduced policies aimed at promoting domestic manufacturing of solar panels, wind turbines, and batteries to counter China's dominance (Kong, 2022).

Trade disputes, such as the imposition of tariffs on Chinese solar panels by the U.S. and Europe, have further complicated global renewable energy markets. These tensions reflect broader geopolitical competition, as renewable energy technology becomes an increasingly strategic sector in global energy security (Zhao & Liu, 2023).

4.2.9. Challenges to China's Energy Security in the Renewable Transition

Despite the rapid growth of renewable energy, challenges remain in integrating intermittent sources like solar and wind into China's grid. The variability of these sources, particularly in regions that are far from population centers, creates difficulties in maintaining a stable and reliable energy supply. China has addressed this issue by investing in energy storage technologies and UHV[24] transmission networks, but further advancements are needed to ensure grid stability (He et al., 2022).

Moreover, large-scale hydropower projects, such as the Three Gorges Dam[25], have raised concerns about their environmental and social impacts. These projects can lead to the displacement of local populations, changes in water ecosystems, and increased seismic activity (World Energy Council, 2022). As China continues to expand its renewable energy capacity, managing environmental and social costs of such projects will be critical to ensuring a sustainable energy transition.

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[23] China's global infrastructure and investment strategy, which includes renewable energy projects to enhance its geopolitical influence.

[24] China's advanced grid infrastructure for efficiently transmitting renewable energy from resource-rich areas to population centers.

[25] The world's largest hydropower project, crucial for China's renewable energy strategy but controversial for its environmental impacts (World Energy Council, 2022).

4.2.10. Summary

China’s renewable energy deployment has had a profound impact on both its domestic energy security and the global geopolitical landscape. By diversifying its energy mix and becoming a global leader in renewable technology manufacturing, China has strengthened its energy security and enhanced its geopolitical influence. However, challenges remain in managing the intermittency of renewable sources, securing critical minerals, and addressing environmental concerns. As China continues to lead the global renewable energy transition, its policies and strategies will have far-reaching implications for both global energy security and the future of international relations.

4.3. The Case of USA’s Renewable Energy Sources and Energy Security

The United States, one of the largest energy consumers globally, has taken significant strides toward increasing its share of renewable energy sources, driven by policy initiatives, market dynamics, and technological advancements. This case study presents the United States’ renewable energy integration, examining how renewable energy has contributed to diversifying the U.S. energy mix, impacting energy independence, economic and environmental security, while also addressing the challenges posed by intermittency, supply chain constraints, and infrastructure needs. Furthermore, it evaluates whether the increase in renewable energy sources in the total energy mix towards renewables has altered geopolitical relationships, particularly with major fossil fuel exporters and key suppliers of critical minerals.

4.3.1. Renewable Energy Deployment in the USA

The United States has experienced significant growth in renewable energy deployment over the last two decades. Renewables, including wind, solar, biomass, and hydropower, accounted for 23% of the country’s electricity generation as of 2023 (U.S. Energy Information Administration [EIA], 2023). This growth has been driven by both market forces, such as falling costs of solar photovoltaic (PV) cells and wind turbines, and supportive government policies, including tax incentives, renewable portfolio standards (RPS), and federal investment in clean energy technologies (Sivaram, 2018).

Wind energy has become a major player in the U.S. electricity market, accounting for 10% of total electricity generation in 2023 (AWEA, 2022). Wind energy capacity is particularly concentrated in the Midwest and Great Plains states, with Texas, Iowa, and Oklahoma leading in production. Technological advancements have driven cost reductions in wind power, while the federal Production Tax Credit (PTC) has provided significant financial support to the industry (Wiser et al., 2022). Wind energy has been pivotal in reducing reliance on natural gas and coal in states like Iowa, where over 50% of electricity now comes from wind power (NREL, 2022).

Solar power has also seen exponential growth, with total installed capacity reaching over 130 gigawatts (GW) by 2023, contributing around 4% of the nation's electricity generation (EIA, 2023). Utility-scale solar farms and distributed generation, particularly rooftop solar, have expanded rapidly, particularly in sun-rich states such as California, Arizona, and Nevada. The Solar Investment Tax Credit (ITC), which offers a 26% tax credit for solar system installation costs, has been instrumental in driving the growth of solar energy

(Sivaram, 2018). The continued decline in the cost of solar modules has made solar power more competitive with fossil fuels, encouraging greater adoption across residential, commercial, and industrial sectors.

Hydropower remains a critical component of the U.S. renewable energy portfolio, contributing around 6.3% of total electricity generation in 2023 (EIA, 2023). While most of the large hydropower plants were built in the mid-20th century, the sector still plays a vital role in providing baseload renewable energy. Biomass, which includes biofuels, wood, and waste, accounted for a smaller share but remains significant, especially in industries like pulp and paper where waste by-products are used for energy generation (EIA, 2023).

4.3.2. Impact on U.S. Energy Security

The United States' increase in share of renewable energy has had profound impacts on the nation's energy security. Energy security is typically defined as the uninterrupted availability of energy at an affordable price, and the diversification of energy sources provided by renewables has strengthened the U.S. energy system by reducing reliance on imports and stabilizing supply chains.

One of the most significant impacts of renewable energy deployment has been the diversification of the U.S. energy mix. Historically, the U.S. has been heavily reliant on imported oil, particularly from politically unstable regions such as the Middle East (Jaffe & Soligo, 2021). The increasing share of wind, solar, and other renewable energy sources has reduced this reliance, enhancing energy independence. The U.S. no longer depends as heavily on global oil markets for its energy needs, particularly in the electricity sector, where renewables have substantially replaced coal and gas (Nye, 2022).

The domestic production of renewable energy particularly in regions like the Midwest and West Coast, coupled with the American shale gas revolution, reduces the vulnerability of the energy system to geopolitical events such as oil supply disruptions or price shocks (Awerbuch & Yang, 2020). As a result, the U.S. has become more resilient to fluctuations in global energy markets.

Addressing intermittency related with renewable energy requires investment in grid modernization and energy storage technologies (DOE, 2022). The U.S. Department of Energy's Grid Modernization Initiative has sought to enhance grid resilience by integrating advanced sensors, smart grid technologies, and automated controls that improve the management of variable renewable energy (DOE, 2020).

Battery storage has emerged as a critical component of grid reliability, enabling the storage of excess electricity generated by renewables during periods of low demand and its subsequent deployment during peak periods or when renewable generation is low (California Energy Commission, 2021). States like California, which have a high penetration of solar power, have led in deploying large-scale battery storage systems to balance supply and demand, ensuring that the grid remains stable and reliable (NREL, 2022).

The renewable energy sector has been a significant driver of job creation in the U.S. economy. According to the U.S. Department of Energy (2022), the clean energy sector employed over 3.4 million people, with jobs in solar and wind growing faster than traditional fossil fuel industries. This economic growth has provided resilience to regional economies, particularly in states that have become renewable energy hubs (Brown & Sovacool, 2021).

The development of local renewable energy industries also reduces vulnerability to energy price volatility, as domestic resources such as wind and solar are not subject to the same market forces as imported oil or gas (Jaffe & Soligo, 2021).

4.3.3. Geopolitical Impacts of the U.S. Renewable Energy Transition

The transition to renewable energy in the U.S. has far-reaching geopolitical implications, reshaping international energy relationships, altering trade dynamics, and shifting the balance of power among global energy exporters and importers.

Historically, U.S. foreign policy has been heavily influenced by the need to secure reliable access to oil, particularly from the Middle East. The increasing share of domestically produced renewable energy, further reduces the strategic importance of maintaining such relationships (Nye, 2022). For instance, the U.S. involvement in the Gulf region has often been motivated by the need to protect oil supplies from geopolitical risks such as conflicts, embargoes, and terrorism (Klare, 2019). As renewable energy assists in reducing the U.S. reliance on foreign oil, the strategic rationale for maintaining military and diplomatic involvement in these regions diminishes (Evans & Mitchel, 2021).

There has also been a shift in terms of the U.S. relations with major fossil fuel exporters, particularly countries like Saudi Arabia, Russia, and Venezuela. These countries have long supplied the U.S. with oil and natural gas, and the reduction in demand for these imports weakens their leverage over U.S. energy security (Jaffe & Soligo, 2021).

While renewable energy reduces reliance on oil and gas imports, it creates new dependencies on the supply chains for critical minerals used in renewable energy technologies. Lithium, cobalt, nickel, and rare earth elements are essential for the production of solar panels, wind turbines, and battery storage systems (Kavlak, McNerney, & Trancik, 2020). Many of these materials are concentrated in a small number of countries, including China as analyzed previously, which dominates the production and processing of rare earth elements (Evans & Mitchel, 2021).

This dependency highlights for the U.S. as a global superpower, the limit of the role renewable energy has to play long-term. The geopolitical risks associated with the supply of critical minerals are particularly concerning given the increasing global competition for these materials as more countries transition to renewable energy (Kavlak et al., 2020). The U.S. has taken steps to secure its supply of critical minerals, including domestic mining initiatives and strategic partnerships with countries like Australia and Canada, but the concentration of supply chains in geopolitically sensitive regions remains a challenge (DOE, 2022).

In other words, the U.S. would never fully commit in a “game” where China is the dominant player. However, through investments in clean technology research and development (R&D), the U.S. can leverage its technological power to influence global energy markets and promote the deployment of renewable energy in developing countries (Brown & Sovacool, 2021). Initiatives such as the U.S. Climate Alliance and international partnerships like the Paris Agreement enhance the U.S.’s ability to shape global energy policy, while also contributing to domestic energy security (Klare, 2019).

4.3.4. Challenges to U.S. Energy Security

Despite the progress made in renewable energy deployment, several challenges remain for the U.S. in terms of energy security. The intermittency of renewable energy sources, constitutes an equally significant problem as it does in any other country. While energy storage technologies and grid modernization efforts are helping to address this issue, large-scale deployment of renewables will require further investments in storage solutions, demand response systems, and enhanced grid flexibility (Milligan et al., 2019). Ensuring reliable electricity supply during periods of low renewable generation remains a priority for

U.S. energy planners. As discussed earlier, the deployment of renewable energy introduces new dependencies on the global supply chains for critical minerals. The U.S. must continue to invest in domestic production and processing capacity for these materials, while also diversifying its supply chains through international partnerships to support the participation of renewables in the energy mix (Kavlak et al., 2020). The U.S. energy infrastructure, much of which was built in the mid-20th century, is ill-equipped to handle the rapid expansion of renewable energy. Upgrading and expanding transmission lines, building new energy storage facilities, and modernizing the grid to accommodate variable renewable energy generation will require significant investments (DOE, 2022). While federal initiatives like the Infrastructure Investment and Jobs Act (2021) and the Inflation Reduction Act (2022) have provided substantial funding for these efforts, regulatory and permitting delays remain significant barriers to progress (U.S. Congress, 2022).

4.3.5. Summary

The deployment of renewable energy in the United States has brought about substantial improvements in energy security by diversifying the energy mix, reducing reliance on fossil fuel imports, and creating new economic opportunities. However, this transition also presents challenges, particularly regarding the intermittency of renewable energy, critical mineral supply chains, and aging infrastructure. Geopolitically, the integration of renewables has impacted the U.S.'s relationships with traditional fossil fuel exporters while introducing new dependencies on countries that control critical mineral supplies. Finally, especially after President Trump's second withdrawal of the U.S. from the Paris Agreement, the clash of priorities in the national agendas are rendered obvious. Global superpowers such as the U.S. cannot and will not undermine their national economic security and development in favor of environmental concerns when in the playing field of the latter, that being the control over critical minerals and technologies essential for renewables, a rival superpower like China dominates.

4.4. Brazil's Renewable Energy Deployment: Impacts on Energy Security and Geopolitics

Brazil is recognized as one of the leading nations in renewable energy deployment, driven by its vast natural resources, strategic policies, and efforts to enhance both energy security and geopolitical influence. This case study examines Brazil's renewable energy landscape, focusing on its key energy sources -hydropower, bioenergy, wind, and solar power- and the implications of these resources for energy security and Brazil's geopolitical standing.

4.4.1. Renewable Energy Mix in Brazil

Brazil's energy mix is overwhelmingly reliant on renewable sources, which accounted for approximately 82% of its electricity generation in 2020 (Ministry of Mines and Energy, 2021). Hydropower remains the dominant source, constituting around 60% of Brazil's electricity. However, the country has made significant strides in diversifying its energy mix through the development of wind, solar, and bioenergy sectors.

Hydropower has traditionally been the backbone of Brazil's electricity generation due to the country's rich water resources. The massive potential of Brazil's river systems led to the construction of large-scale hydropower plants, such as the Itaipu Dam, which is one of the largest in the world. However, the heavy reliance on hydropower has also created vulnerabilities, particularly during periods of drought, which can significantly reduce energy output. This challenge became evident during the droughts of 2014 and 2021, where low water levels forced Brazil to rely more on thermoelectric power generation, increasing the cost and carbon intensity of electricity (Almeida & Nunes, 2022).

To mitigate these risks, Brazil has expanded its investment in other renewable energy sources. Wind energy, particularly in the Northeast region, has experienced exponential growth, with installed capacity surpassing 19 GW in 2020, up from just 1 GW in 2010 (ABEEólica, 2021). The solar energy sector, though still in its early stages, has also grown rapidly, benefiting from declining costs and favorable government policies, such as the Regulatory Framework for Distributed Generation, which incentivizes small-scale solar installations (Energy Research Office, 2020).

Brazil's bioenergy sector, primarily based on bioethanol from sugarcane and biodiesel, plays a crucial role in the country's renewable energy strategy. The Proálcool Program, launched in the 1970s, significantly expanded Brazil's bioethanol production, positioning the country as a global leader in biofuels. Today, Brazil is the second-largest producer of bioethanol globally, after the United States, and flex-fuel vehicles, capable of running on bioethanol or gasoline, account for more than 75% of vehicles on Brazilian roads (Ministry of Mines and Energy, 2021).

4.4.2. Energy Security and Renewable Energy in Brazil

Brazil's renewable energy strategy is closely tied to its pursuit of energy security. By expanding its use of domestic renewable resources, Brazil has reduced its dependency on imported fossil fuels and mitigated the risks associated with fluctuations in global oil prices. The National Energy Plan 2030 emphasizes the importance of maintaining energy independence and ensuring a reliable, affordable, and sustainable energy supply (Energy Research Office, 2020). Although hydropower is Brazil's most abundant renewable resource, its susceptibility to climate variability poses a significant energy security risk. Severe droughts have periodically affected the water levels in Brazil's reservoirs, reducing hydropower generation and forcing the country to rely on more expensive and polluting energy sources. For instance, the 2021 drought led to a sharp increase in thermoelectric generation, which raised electricity prices and underscored the need for diversification (IEA, 2022).

To address the limitations of hydropower, Brazil has turned to wind and solar energy as complementary solutions. The Northeast region of Brazil has become a wind energy hub, with its unique wind patterns allowing for generation throughout the year. Brazil's wind potential is estimated at around 880 GW, far exceeding current demand (ABEEólica, 2021). Solar energy, while smaller in scale, also has significant potential, with Brazil's total solar capacity reaching 13 GW in 2021 (Energy Research Office, 2020). These developments enhance Brazil's energy security by providing a more diversified and resilient energy mix.

Brazil's bioenergy sector also contributes to its energy security. The National Biodiesel Program and the expansion of ethanol production have reduced the country's dependence on imported diesel and gasoline, respectively. By promoting the use of biofuels, Brazil has created an alternative energy supply that can be rapidly scaled up in response to international oil price fluctuations or supply disruptions (Goldemberg et al., 2018).

4.4.3. Geopolitical Implications of Brazil's Renewable Energy Strategy

Brazil's renewable energy leadership has important geopolitical implications, both within South America and globally. As a major exporter of biofuels and renewable energy technology, Brazil has strengthened its diplomatic and trade relationships, particularly with key markets such as the United States, European Union, and China.

Brazil has leveraged its expertise in bioenergy and through partnerships with African and Latin American nations, Brazil has facilitated technology transfer and capacity building in bioenergy and renewable electricity generation. This cooperation has enhanced Brazil's geopolitical influence in the Global South and promoted its leadership in international energy forums (Furtado et al., 2020).

Brazil's interconnected electricity grid, known as the National Interconnected System (SIN), plays a key role in its regional energy strategy. Brazil exports renewable electricity to neighboring countries such as Argentina, Uruguay, and Paraguay, reinforcing its position as a regional energy leader. This energy integration strengthens regional cooperation and enhances Brazil's influence in South America (Burke & Stephens, 2018).

Brazil's biofuels sector also plays a vital role in global energy markets. As countries worldwide seek to decarbonize their energy systems, demand for sustainable biofuels is expected to grow. Brazil's ability to export bioethanol and biodiesel enhances its position in global trade and strengthens its ties with major energy-consuming nations (Goldemberg et al., 2018).

4.4.4. Challenges and Future Prospects

Despite Brazil's success in deploying renewable energy, several challenges remain. The ongoing reliance on hydropower exposes Brazil to the risks of climate change, particularly increased drought frequency. Political instability and changes in government policies could also impact investment in renewable energy infrastructure. Furthermore, the expansion of bioenergy, particularly sugarcane cultivation, has raised concerns about deforestation, land-use conflicts, and food security (Tollefson, 2021).

Looking forward, Brazil's vast wind and solar potential, combined with continued technological advances and declining costs, suggest that renewable energy will remain an integral part of the country's energy strategy. Brazil's commitment to international climate agreements, such as the Paris Agreement, also underscores its long-term dedication to reducing greenhouse gas emissions and transitioning to a low-carbon economy (IEA, 2022).

4.4.5. Summary

Brazil's renewable energy deployment is a cornerstone of its strategy to enhance energy security and assert geopolitical influence. The country's diverse energy mix, dominated by hydropower, wind, solar, and bioenergy, has significantly reduced its dependence on fossil fuels and enhanced its resilience to external energy shocks. However, challenges related to climate variability, political uncertainty, and environmental impacts remain. Nevertheless, Brazil's leadership in renewable energy is likely to continue, particularly as the world moves towards decarbonization, offering both domestic and international opportunities.

4.5. Morocco's Renewable Energy Deployment and Energy Security

In recent years, Morocco has emerged as a global leader in renewable energy deployment, driven by concerns over energy security, economic development, and climate change. The Kingdom's efforts to diversify its energy mix through solar, wind, and hydropower projects have not only mitigated its reliance on imported fossil fuels but also positioned it as a key player in regional energy geopolitics. Morocco's case study serves as insight for the African continent with its renewable energy strategy. Below we examine how its deployment has contributed to enhancing energy security, the geopolitical implications of its renewable energy initiatives, and the associated challenges. This study underscores Morocco's transition as a model for emerging economies looking to balance energy security with sustainability.

4.5.1. Morocco's Energy Landscape

Historically, Morocco has been heavily reliant on imported fossil fuels, with over 90% of its energy needs met through imports, particularly oil and coal (IEA, 2019). This dependency exposed the country to global energy price fluctuations, adversely affecting its economic stability and energy security. Recognizing the unsustainability of said reliance, Morocco's government launched a comprehensive National Energy Strategy in 2009, which placed renewable energy at the core of its vision to reduce fossil fuel imports, diversify the energy mix, and enhance energy sovereignty (El-Katiri, 2014).

One of the pillars of Morocco's renewable energy strategy is solar energy. With abundant sunlight averaging 3,000 hours of sunshine per year, Morocco has the natural resources necessary to harness solar power. The Noor Solar Complex, located near Ouarzazate, represents the flagship of Morocco's solar initiatives. The complex is one of the world's largest concentrated solar power (CSP) facilities and is a critical part of the country's plan to reach 52% of installed energy capacity from renewables by 2030 (World Bank, 2020).

The Noor Complex uses advanced CSP technology, allowing it to store energy for use during cloudy periods or at night. This feature enhances grid stability and offers significant advantages for energy security, as it reduces the intermittency issues (Reiche & Bechberger, 2019). By generating up to 580 MW of electricity, the Noor plant is expected to supply power to over one million Moroccan households (World Bank, 2020). This project demonstrates the importance of investing in large-scale renewable energy infrastructure and how such projects can contribute to national energy security by decreasing dependence on volatile energy imports.

In addition to solar energy, Morocco has made significant strides in harnessing wind energy. The country's geographic location along the Atlantic coastline provides favorable conditions for wind power generation, with wind speeds averaging 7.5 to 9.5 meters per second in key locations (García-Ruiz & Garcés de los Fayos, 2020). Morocco's wind energy potential has been realized through the development of large-scale wind farms, such as the Tarfaya Wind Farm, which has an installed capacity of 300 MW and is one of the largest in Africa (IEA, 2019).

Wind energy projects play a critical role in Morocco's energy security by complementing solar energy production. Wind farms tend to generate electricity in the evening and during overcast days, balancing the energy supply when solar power is less available. This diversified energy mix is essential for maintaining grid stability and reducing the need for fossil fuel-based backup power plants (Hafner et al., 2018).

Moreover, Morocco's wind energy sector has attracted significant foreign investment and technological partnerships, particularly with European companies. For example, Siemens Gamesa, a major player in wind turbine technology, has established production facilities in Morocco, contributing to local job creation and technological expertise (Siemens Gamesa, 2021). These partnerships not only benefit Morocco economically but also enhance its geopolitical standing as a regional leader in renewable energy.

While Morocco's focus has been on expanding solar and wind energy, hydropower remains an important, albeit limited, component of its energy mix. Morocco has a long history of utilizing hydropower, but the availability of water resources is variable, and the growing demands of agriculture and urbanization have limited its expansion (Bouzekri et al., 2020). Nevertheless, existing hydropower plants contribute to energy security by providing a stable and reliable source of electricity.

In addition to traditional hydropower plants, Morocco is exploring the potential of pumped storage hydropower. Pumped storage offers a means of energy storage that is particularly valuable in a grid dominated by intermittent renewable energy sources. It allows excess electricity generated during periods of high solar and wind production to be stored and later used during peak demand periods (Bouzekri et al., 2020). This technology is an important part of Morocco's strategy to integrate renewables more fully into the national grid and ensure a steady and reliable energy supply.

4.5.2. Geopolitical Implications of Morocco's Renewable Energy Strategy

Morocco's renewable energy initiatives have implications that extend beyond domestic energy security, impacting the country's regional and international geopolitical standing. First, Morocco's leadership in renewable energy has enhanced its diplomatic influence in Africa. Through initiatives such as the Morocco-Africa Solar Plan, the Kingdom is providing technical and financial assistance to sub-Saharan African countries to develop their own renewable energy sectors (Kousksou et al., 2015). This energy diplomacy has strengthened Morocco's political ties across the continent, solidifying its role as a regional power.

Furthermore, Morocco's renewable energy strategy has strengthened its relationship with the European Union (EU), particularly in the context of European energy diversification efforts. As the EU continues efforts to diversify its energy imports away from Russian natural gas, Morocco's renewable energy potential presents an attractive alternative (Reiche & Bechberger, 2019). Projects such as the "Desertec" initiative, which envisions large-scale solar energy exports from North Africa to Europe, highlight Morocco's potential to become a key energy supplier to the EU. This enhances Morocco's geopolitical leverage and economic prospects, particularly as Europe accelerates its transition to clean energy.

Finally, Morocco's renewable energy strategy aligns with global climate goals. By reducing its greenhouse gas emissions and transitioning to a low-carbon economy, Morocco has gained recognition as a leader in the fight against climate change, further enhancing its international standing (Kousksou et al., 2015).

4.5.3. Challenges to Morocco’s Renewable Energy Deployment

Despite its successes, Morocco faces several challenges in its renewable energy transition. Financing large-scale renewable projects remains a significant hurdle. While the Noor Solar Complex and other projects have attracted international funding, continued investment is required to meet the country’s ambitious 2030 targets. The reliance on foreign financing introduces vulnerabilities related to global economic conditions and exchange rate fluctuations (El-Katiri, 2014).

Another challenge is the technical complexity of integrating large shares of intermittent renewable energy into the national grid. Morocco has made progress in addressing the issue of variable renewable energy production through investments in energy storage technologies, but further developments are needed to ensure a reliable energy supply (Hafner et al., 2018).

Moreover, geopolitical tensions surrounding the Western Sahara region present a potential obstacle to Morocco’s renewable energy ambitions. The region, which is rich in renewable energy potential, particularly wind power, is subject to international disputes. This has raised concerns among foreign investors and international bodies, which could potentially limit investment in projects located in the contested area (García-Ruiz & Garcés de los Fayos, 2020).

4.5.4. Summary

Morocco’s renewable energy deployment has been transformative in terms of enhancing energy security, promoting economic development, and positioning the country as a regional and leader in renewable energy generation. Solar and wind power, supported by hydropower and energy storage technologies, have reduced Morocco’s dependence on fossil fuel imports, stabilized its energy supply, and opened new opportunities for regional cooperation and international diplomacy. However, the country must continue to address financial, technical, and geopolitical challenges to realize the full potential of its renewable energy strategy. If successful, Morocco’s experience could serve as a model for other emerging economies seeking to enhance their energy security through the development of renewable energy sources.

4.6 The Case of Norway’s Renewable Energy

Norway stands as a global leader in renewable energy, with its vast natural resources playing a pivotal role in shaping its energy landscape. The country has utilized its topographical advantages, particularly its abundance of water resources, to generate electricity predominantly from hydropower. In recent years, Norway has increasingly focused on green hydrogen as part of its broader strategy for energy diversification and security. Below we attempt to examine Norway’s renewable energy sector, particularly hydropower and green hydrogen, and assess their impact on the nation’s energy security.

4.6.1. Norway's Hydropower

Hydropower has been the dominant source of electricity generation in Norway for over a century. As of 2020, more than 90% of Norway’s electricity came from hydropower, making the country the largest hydropower producer in Europe and the sixth-largest globally (Norwegian Water Resources and Energy Directorate [NVE], 2020). This reliance on hydropower has provided Norway with substantial energy security benefits, enabling the country to meet its domestic electricity needs without relying on imported fossil fuels.

Norway's hydropower system is particularly well-suited for energy security due to its large reservoir capacity, which allows for the storage of excess water during times of high precipitation. These reservoirs enable flexible power generation that can respond to variations in electricity demand. According to the Norwegian Ministry of Petroleum and Energy (2020), the country has an installed hydropower capacity of around 33 GW, with a total potential of approximately 45 GW, meaning there is room for further development and optimization of this renewable resource.

Norway's hydropower contributes significantly to its energy security in several ways. First, the renewable and domestic nature of hydropower eliminates dependence on foreign energy imports, which is a critical factor in reducing vulnerability to global energy market fluctuations (IEA, 2021). Second, hydropower plants equipped with reservoirs can provide stable and reliable electricity during periods of low water inflow, enhancing grid stability. Finally, hydropower serves as a valuable export commodity, with Norway exporting excess electricity to neighboring countries such as Sweden, Denmark, Germany, and the United Kingdom, reinforcing its role as a key player in regional energy security.

However, the future sustainability of Norway's hydropower sector faces challenges, particularly from climate change. Research conducted by The Norwegian University of Science and Technology (NTNU*)* indicates that changing precipitation patterns may impact hydropower production, with more intense rainfall in winter and drier conditions in summer potentially affecting water availability. Despite these challenges, the Norwegian government continues to invest in maintaining and upgrading hydropower infrastructure to ensure its long-term viability as the backbone of the country's energy system (Ministry of Petroleum and Energy, 2020).

4.6.2. Green Hydrogen: Norway's Emerging Energy Sector

While hydropower remains central to Norway's energy security, the country is increasingly turning to green hydrogen as a complementary renewable energy source. Green hydrogen is produced by using renewable electricity, such as hydropower or wind, to electrolyze water, separating it into hydrogen and oxygen. Norway's government has identified green hydrogen as a strategic priority for meeting its long-term energy security and climate goals (Ministry of Petroleum and Energy, 2021).

Green hydrogen presents several opportunities for Norway. It offers a versatile energy carrier that can be used in various sectors, including heavy industry, shipping, and aviation, which are difficult to decarbonize through electrification alone. Additionally, green hydrogen can serve as a storage solution for excess renewable electricity, helping to mitigate the intermittency challenges of renewable energy sources (IEA, 2021). Norway's abundant renewable energy resources position it to become a major producer of green hydrogen, both for domestic use and for export to Europe, where demand for clean hydrogen is expected to grow significantly in the coming decades.

4.6.3. Norway’s Energy Security: Hydropower and Green Hydrogen

From an energy security perspective, Norway’s hydropower offers several critical benefits. Hydropower allows Norway to generate most of its electricity from a domestic, renewable source, reducing reliance on imported energy and shielding the country from global energy market disruptions (NVE, 2020).

Hydropower reservoirs provide Norway with a unique ability to store energy, enabling the country to manage supply and demand fluctuations more effectively than many other countries with renewable energy systems based solely on intermittent sources (IEA, 2021).

Norway’s ability to export surplus electricity, particularly through interconnectors with neighboring countries, strengthens the energy security of the broader European region. For example, Norway plays a critical role in balancing the electricity grid in Denmark, which relies heavily on wind power, by supplying hydropower during periods of low wind (Statnett, 2020).

The development of a green hydrogen economy in Norway is seen as an essential component of the country’s future energy security strategy. By adding green hydrogen to its energy mix, Norway can further diversify its energy sources, reducing its vulnerability to supply disruptions in any single energy resource. This is particularly important as the country aims to reduce its reliance on natural gas for industrial and domestic use (Ministry of Petroleum and Energy, 2021).

Hydrogen can be stored and transported more easily than electricity, providing a solution to the intermittency issues associated with renewable energy sources. It can be produced using excess renewable electricity and stored for use when demand is higher or when renewable generation is low (Norwegian Hydrogen Strategy, 2020). Norway has the potential to become a major exporter of green hydrogen to Europe, contributing to the continent’s decarbonization efforts and enhancing regional energy security. This aligns with the European Union’s hydrogen strategy, which envisions importing significant amounts of hydrogen from neighboring countries (European Commission, 2020).

Despite its potential, there are significant challenges associated with the development of a green hydrogen economy in Norway. One of the primary challenges is the high cost of producing green hydrogen compared to hydrogen derived from fossil fuels (known as blue hydrogen). However, as the costs of electrolysis technology decrease and carbon pricing mechanisms are strengthened, green hydrogen is expected to become more cost-competitive (IEA, 2021). Additionally, the development of the necessary infrastructure, including pipelines, storage facilities, and refueling stations, will require substantial investment from both the public and private sectors (Norwegian Hydrogen Roadmap, 2021).

4.6.4. Norway’s Role in European and Global Energy Security

Norway has long been a reliable exporter of energy to Europe, primarily in the form of natural gas and electricity from hydropower. As Europe focuses on a low-carbon energy system, Norway’s renewable energy resources will become increasingly important for regional energy security. Hydropower exports via interconnectors contribute to stabilizing European electricity grids, while green hydrogen offers a potential future export market that could help Europe meet its decarbonization targets while reducing dependence on imported fossil fuels from countries like Russia and the Middle East (IEA, 2021).

The geopolitical implications of Norway’s green hydrogen ambitions are also significant. By positioning itself as a leader in green hydrogen production, Norway could enhance its geopolitical influence within Europe. As the European Union seeks to reduce its reliance on Russian natural gas, green hydrogen imports from Norway could play a vital role in securing Europe’s energy future (European Commission, 2020). Furthermore, the development of a green hydrogen export market could strengthen Norway’s economic and political ties with key European partners such as Germany, the Netherlands, and the United Kingdom (Ministry of Petroleum and Energy, 2021).

4.6.5. Summary

Norway’s renewable energy sources, particularly hydropower and green hydrogen, are central to its energy security strategy. Hydropower has provided the country with a stable, reliable, and domestic source of electricity for over a century, reducing dependence on fossil fuel imports and contributing to grid stability. As the country moves towards a more diversified energy system, green hydrogen presents an emerging opportunity to enhance both national and regional energy security. By investing in green hydrogen infrastructure and production, Norway can further solidify its position as a leader in the global energy transition, providing valuable renewable energy exports to Europe while ensuring its own long-term energy independence.

5. Conclusions

The deployment of renewable energy sources has emerged as a crucial strategy in redefining energy security for the 21st century. By reducing reliance exclusively on fossil fuels, renewable energy contributes to greater autonomy and resilience in energy systems, mitigating the geopolitical risks associated with fuel imports (Goldthau & Sovacool, 2016). Solar, wind, and other RES offer sustainable alternatives that can address energy demand while reducing greenhouse gas emissions, aligning with global climate goals such as the Paris Agreement (Osička & Černoch, 2022). These benefits underscore the dual role of renewables in enhancing energy security and addressing environmental imperatives.

Despite their potential, integrating RES into existing systems presents challenges, particularly regarding intermittency and resource distribution. Solar and wind energy depend on weather conditions, leading to variability that complicates supply reliability (Lund et al., 2015). Advances in energy storage technologies and grid modernization, including smart grids, are necessary to overcome these challenges and ensure stable energy supplies (IEA, 2022). Additionally, the deployment of renewable energy sources raises critical questions about equity, as developing regions often lack the financial and technical capacity to adopt large-scale renewable technologies (Sovacool & Saunders, 2014).

Another significant issue lies in the environmental and social impacts of extracting critical materials required for renewable technologies, such as lithium and cobalt. Sustainable supply chain management is imperative to avoid replicating the ecological and social harms associated with fossil fuel extraction (Bazilian, 2018). In addition, the dominant position China has secured in terms of controlling the supply chain of rare earth elements required for the development of renewable energy technologies and infrastructure poses many challenges for countries willing to invest in renewables, as new dependencies emerge on that end. An example that stands out is the case of the U.S. as a global superpower, which although having increased the share of renewable in energy in the total energy mix, cannot and will not undermine neither its economic development -thanks to the benefits of the American shale gas revolution- nor its geopolitical status by full-committing in renewables, dominated by China. The case of Germany also serves as a cautionary tale. Despite the many achievements of the ambitious Energiewende, the costs incurred by households and the German industry, as a result of the aggressive shift to renewable energy post the Russian-Ukraine conflict, delivered profound economic blows for Germany.

On the other hand, there are the cases of Brazil, Morocco and Norway, all countries which integrate renewables in ways which not only enhance their domestic energy landscape but also better their diplomatic position in their respective regions by pioneering in terms of both renewable energy generation and potential.

In conclusion, renewable energy deployment comes with both benefits and challenges. It presents a path of opportunities for states' energy security, independence, resilience and more climate friendly energy generation. The challenges, on the other hand, such as the intermittent nature of renewables, the technological and supply chain dominance of a superpower like China, the delay in advancement and scaling of necessary technologies, as well as both economic and opportunity costs of integrating renewables in traditional energy grids, seem to establish clear-cut limits of renewable energy deployment for states. In view of climate change, there is most definitely a role for renewables to play, as a complementary energy source in states' energy mixes, backed with the necessary policies and the establishment of well-regulated markets, to ensure renewables are contributing to the benefits of the environment while enhancing energy security, rather than further undermining it.

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