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European Strategic Autonomy in the Energy Field:
Navigating Geopolitical Challenges, Policy Coordination and Innovation

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Executive Summary

- The European Union (EU) is increasingly aware of its dependence on external energy sources, highlighted by crises like COVID-19 and the Russo-Ukrainian conflict. This has exposed vulnerabilities in energy security, sustainability, and economic competitiveness, prompting a shift in focus from complete energy autonomy to building a resilient, diversified, and sustainable energy system.

- Renewable energy is crucial to reduce geopolitical vulnerabilities and tackle climate change. Advanced technologies like green hydrogen, smart grids, and storage systems are essential, but challenges like the concentration of critical raw materials and inadequate infrastructure remain.

- The EU's energy strategy must evolve with stronger coordination among member states, creating solidarity policies and financial mechanisms to support countries with less developed energy infrastructures. Governance at the EU level must also address disparities in resources, infrastructure, and technology to ensure efficient and equitable energy distribution.

- Economic investments are essential for the clean energy transition, but disparities in financial capacity among EU states require solidarity mechanisms for more inclusive progress. The EU's strategic autonomy also encompasses global competitiveness, emphasizing the importance of internal cohesion and external partnerships.

- Overall, the EU must adopt a multidimensional approach to energy security, sustainability, and innovation, which requires coordinated efforts across governance levels and member states to ensure a resilient and sustainable energy future.

Introduction

The issue of European strategic autonomy, particularly in the energy sector, has become a central priority in political, economic, and academic debates. Recent crises, such as the COVID-19 pandemic and Russia's invasion of Ukraine, have exposed the structural vulnerabilities of the European Union (EU) stemming from its dependence on external energy sources. These events have not only heightened the volatility of global energy markets but also called into question Europe's ability to balance energy security, environmental sustainability, and economic competitiveness.

The existing literature has addressed various aspects of these challenges. On the one hand, studies have focused on strategies for transitioning to a low-carbon energy system, highlighting the role of renewable energy and emerging technologies. On the other hand, a more geopolitical line of research has examined the risks associated with Europe's dependence on external suppliers, particularly Russia, and the implications for the EU's foreign policy. However, significant gaps remain in the systemic understanding of how recent energy crises are redefining the concept of strategic autonomy and influencing Europe's long-term policies. There is a lack of an integrated perspective linking the challenges of source diversification, technological innovation, and political coordination among member states.

This paper situates itself at the intersection of these issues, proposing a multidimensional approach that integrates geopolitical, environmental, and technological considerations. First, it analyzes how strategic autonomy should not merely be conceived as independence from external suppliers but as the ability to build a resilient, diversified, and sustainable energy system. In this context, the role of renewable energy becomes crucial—not only as a response to the climate crisis but also as a tool to reduce Europe's vulnerability to geopolitical pressures. Second, particular attention is given to the role of technological innovation in facilitating this transition. Technologies such as green hydrogen, smart grids, and advanced energy storage systems represent unprecedented opportunities to strengthen European energy security and promote greater sustainability. Despite the progress made in this direction, the paper highlights significant barriers that persist, including the geographic concentration of critical raw material production and challenges related to the implementation of necessary infrastructure. Finally, the study focuses on the challenges of European energy governance, analyzing the asymmetries among member states in terms of resources, technological capabilities, and financial tools. These disparities, if not adequately addressed, risk slowing the energy transition and exacerbating divisions between more advanced and lagging countries. To overcome such obstacles, the paper proposes enhanced coordination at the European level, combined with solidarity policies and targeted financial support mechanisms.

This study contributes to academic literature by offering an integrated review of the dynamics shaping European strategic autonomy in the energy sector. The findings underscore the need for a holistic approach that accounts for the interactions between environmental sustainability, energy security, and technological innovation. In doing so, the paper aims to provide valuable insights not only for future research but also for the development of more effective and inclusive public policies.

Recent Transformations in the Energy Sector

Impact of the COVID-19 Pandemic: Supply Chain Disruptions and Emerging Dynamics

In recent years, the geopolitical landscape of the global energy sector has undergone profound changes, influenced by historic events such as the COVID-19 pandemic and Russia's invasion of Ukraine. These events have had a significant impact on energy demand, supply chains, prices, and geopolitical balances, with important repercussions for the European Union.

Before the pandemic, global energy demand was steadily increasing, driven by globalization and the rapid economic development of nations like China and India. However, COVID-19 triggered an unprecedented economic crisis, causing a sharp decline in energy consumption and leaving a lasting impact on global energy systems (Paltsev, 2016). Measures adopted to contain the virus, such as lockdowns, drastically reduced mobility and economic activity, leading to the temporary or permanent closure of many businesses and contributing to a global recession that particularly affected energy demand in sectors such as natural gas, coal, and oil. The most pronounced declines were observed in Europe, China, and the United States during the first quarter of 2020.

The drop in demand further pushed down oil and gas prices, which had already been declining since 2014. A price war between Russia and Saudi Arabia exacerbated the situation, leading to significant reductions: West Texas Intermediate (WTI) and Brent crude oil prices fell by 67% and 65%, respectively, compared to 2019. Natural gas and electricity prices in Europe also plummeted, amplifying the difficulties faced by the traditional energy sector and underscoring the urgency of transitioning to more sustainable models (Kuzemko et al., 2020).

Despite the challenges, the pandemic was seen as an opportunity to accelerate the transition to low-carbon energy. However, the implementation of sustainable technologies faced significant obstacles, such as disruptions in supply chains and project delays. The solar industry was among the hardest hit: China, responsible for producing 70% of the world's solar panels, drastically reduced production during the lockdowns, negatively impacting global installation capacity. Similar difficulties affected other renewable energy sectors, such as wind power, in key countries like India, Europe, and South Africa.

The COVID-19 pandemic had a significant impact not only on the solar sector but also on related areas such as renewable energy, battery technology, heating and cooling systems, and smart grids. The closure of wind farms in regions such as North Dakota in the United States and Scotland is just one of many examples of the challenges faced by the sector. The slowed growth of Renewable Energy Technologies (RET), material shortages, temporary factory shutdowns, and rising solar product prices posed serious obstacles to global sustainable development, prompting some countries to revert to oil-based electricity production to support their economies.

Despite these setbacks, renewable energies maintained a crucial role. In 2020, they were the only energy sector to grow, accounting for 30% of global production. The pandemic thus contributed to rebalancing dependence on fossil fuels, reducing the influence of traditionally dominant countries in the global energy market, such as Russia and the Middle Eastern countries (Bahar, 2020).

The health crisis accelerated the energy transition and redefined geopolitical balances, with renewable energy emerging as a central element in global strategy. However, long-term consequences remain uncertain, as the transition presents significant challenges for oil-producing countries and the global economy. The prospect of a renewable-centric world will require coordinated efforts to ensure a sustainable and balanced transition, with a positive impact on both the environment and the economy (Hoang et al., 2021). This analysis highlights how the pandemic has not only transformed energy consumption patterns but also created opportunities and challenges for a more sustainable future.

Effects of the War in Ukraine: Energy Security and Gas Supply

With the easing of lockdown restrictions in 2021, the energy sector gradually resumed normal operations, leading to increased demand for energy carriers and, consequently, a significant rise in energy prices. That same year, growing demand in Asia and Europe contributed to a sharp increase in electricity and natural gas costs. This scenario raised concerns about the ability of European energy and climate policies to ensure energy security, especially considering the role of natural gas as a "bridge fuel" in the transition to renewable energy sources. The situation worsened further with Russia's invasion of Ukraine, which exacerbated the energy crisis and forced the European Union to confront an unprecedented supply crisis. Drastic cuts in Russian gas supplies pushed prices to record levels and strained global energy markets.

Russia's invasion of Ukraine on February 24, 2022, marked a turning point for European energy policies and the EU's international relations. Citizens and businesses faced steep increases in energy costs and the risk of rationing. This crisis tested the cohesion among EU member states, which had previously collaborated to achieve ambitious decarbonization goals. In response to the emergency, national policies shifted to prioritize securing energy supplies, driving significant changes in the Union's geopolitical relations.

Until 2021, Russia was regarded as a reliable supplier of natural gas, crucial for European domestic and industrial needs. The EU imported approximately 155 billion cubic meters of gas from Russia, accounting for 45% of its total imports, with Germany and Italy being the primary consumers. By the end of 2022, however, these imports had plummeted to around 67.6 billion cubic meters, reflecting an average weekly reduction of 55% (Figure 1).

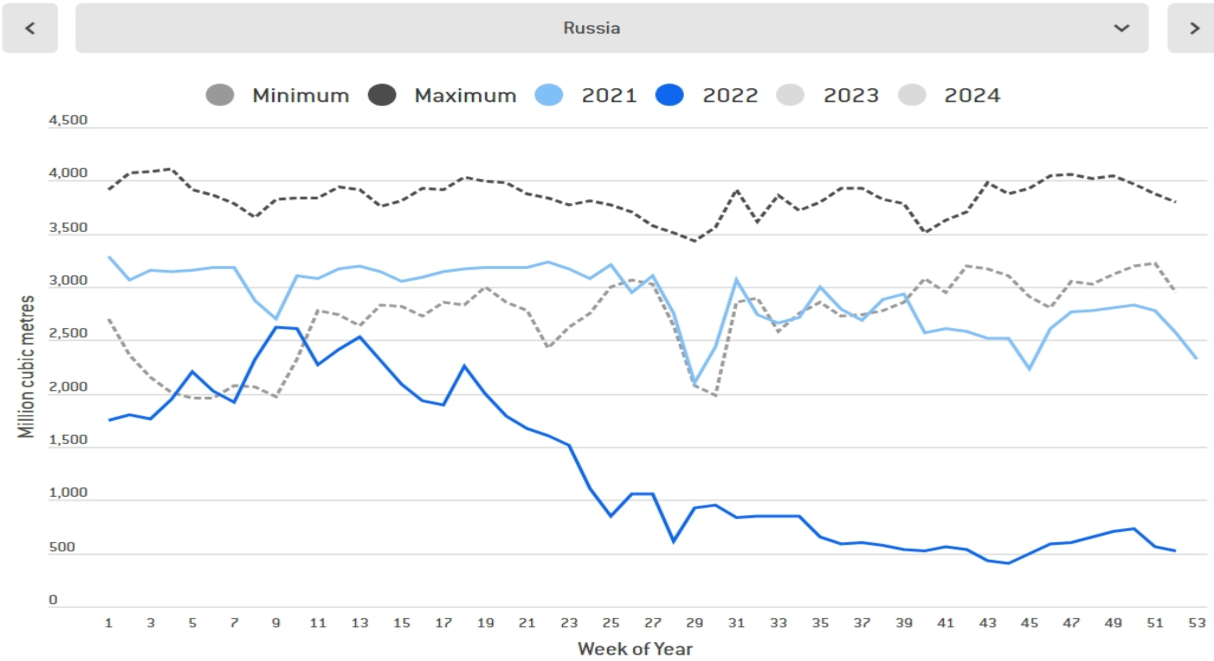

Figure 1. Impact of Russo-Ukraine Conflict on EU Gas Imports
Source: https://www.bruegel.org/dataset/european-natural-gas-imports

The crisis prompted the EU to diversify its energy supplies. In March 2022, Russia demanded payment in rubles from "hostile" countries, threatening to halt supplies otherwise. From June 2022, gas flows were progressively reduced, culminating in September with the complete shutdown of the Nord Stream I pipeline, which connects Russia to Germany via the Baltic Sea. The Yamal pipeline, traversing Belarus and Poland also experienced near-total disruption—initially due to Poland's refusal to pay in rubles and later as Warsaw terminated its contract with Gazprom, effectively halting pipeline deliveries to Europe.

The decline in Russian gas exports was accompanied by record-high price increases. Between 2015 and 2020, natural gas prices in Europe remained relatively stable, ranging between €5 and €30/MWh. However, they began to rise in 2021 with the post-pandemic economic recovery, reaching €113/MWh in December 2021. The situation worsened in March 2022 with Russia's invasion of Ukraine, pushing prices to €127/MWh. Geopolitical tensions triggered unprecedented market volatility, culminating in a historic peak of €220/MWh in August 2022. By 2023, prices returned to pre-crisis levels due to reduced demand, milder winter temperatures, and above-average storage levels (Figure 2).

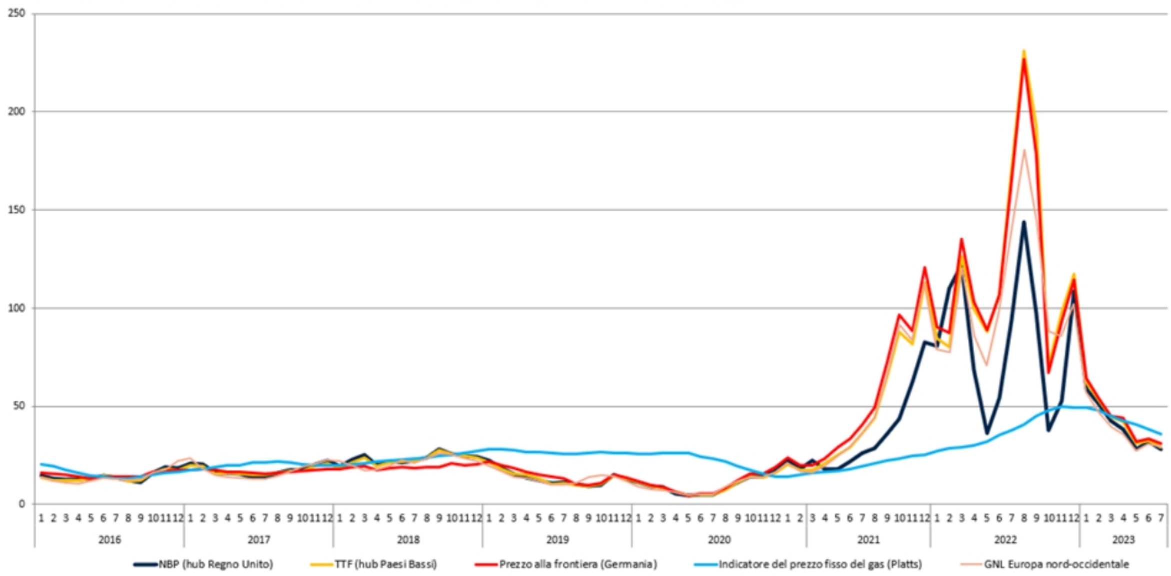

Figure 2. Some gas wholesale prices in Europe, nominal prices (EUR/MWh).
Source: Trinomics et al., sulla base dei dati S6P Platts, Energy Market Price, BAFA e Comext (Eurostat), 2023.

To reduce dependence on Russia, Europe significantly increased imports of liquefied natural gas (LNG), particularly from the United States, and enhanced pipeline supplies from Norway, the United Kingdom, and Azerbaijan. In 2022, LNG imports surged by 73% compared to the previous year, with a growing share coming from the United States, accounting for 46% of the total. That year, 21% of LNG imports came from African countries (such as Algeria, Angola, Nigeria, Egypt, Cameroon, and Equatorial Guinea), 16% from the Middle East, 14% from Russia, and the remaining 3% from various nations, including Argentina, Australia, Brazil, China, Indonesia, Jamaica, Malaysia, Norway, Peru, Singapore, South Korea, and the United Kingdom. By 2023, Norway and the United States had become Europe's primary gas suppliers, covering 30% and 19% of total imports, respectively.

Despite progress in diversification, natural gas remains essential for ensuring stability during the transition to renewables, particularly in countries heavily reliant on Russian supplies. The dependence on single suppliers and the lack of investment in new gas exploration have exposed Europe's structural vulnerabilities. Addressing these challenges requires balancing source diversification, pursuing climate goals, and managing geopolitical complexities (Péruzy and Benedettini, 2023).

Energy Security

The Centrality of Energy Security

Energy security is a central pillar in global geopolitics and economics, a concept that has progressively evolved to address changes in international dynamics and resource accessibility.

During the 20th century, oil dominated the global energy landscape, profoundly influencing geopolitical relations and fueling conflicts over resource control. With the advent of the 21st century, attention expanded to include natural gas, renewable energy sources, and the challenges posed by climate change, thereby redefining the priorities and strategies of governments and international institutions. Today, the energy security debate focuses not only on resource availability but also on their environmental sustainability, the resilience of energy infrastructure, and the need to ensure universal access to energy.

Historically, the concept of energy security has been based on three main criteria: resource availability, economic sustainability, and the resilience of energy supply systems to external shocks. These elements, which form the traditional paradigm, have evolved with technological advancements and economic innovations. In particular, the criterion of resource availability is no longer limited to fossil fuels but now includes renewable sources and energy obtained through international exchanges. Economic sustainability has expanded to incorporate a long-term perspective that considers environmental and social costs. With the increasing complexity of energy systems, the criterion of resilience has also evolved, focusing more on the ability of energy systems to withstand external crises, such as geopolitical conflicts or natural disasters.

European integration has been a fundamental step in the evolution of the concept of energy security. With the establishment of the European Coal and Steel Community (ECSC) in 1952, a supranational approach to resource management was introduced, aimed at preventing conflicts between European nations. This model laid the foundation for the current European Union (EU) and gained further significance during the oil crises of the 1970s, which strengthened energy interdependence between Europe, the Soviet Union, and later Russia, a country that became a crucial element in the European economic and geopolitical landscape (Franza et al., 2017). With the end of the Cold War and the eastward expansion of the EU in the 1990s, political and economic relations with post-communist countries and Russia intensified, leading to a growing energy interdependence.

The oil crises of the 1970s led to the creation of the “four A’s” model: availability, accessibility, economic affordability, and acceptability, a theoretical framework designed to address energy vulnerabilities. This model was adapted over time to manage the challenges posed by subsequent crises, including the reduction of OPEC’s influence and, more recently, dependence on Russian gas (LaBelle, 2023; Thaler and Hofmann, 2022).

The events of 2021 and 2022, with the unpredictable increase in gas prices and Russia’s invasion of Ukraine, revealed the fragility of European energy security. Russia reduced gas supplies, using them as a tool of political pressure, forcing the EU to rethink its strategies. The EU responded by adopting economic sanctions, accelerating the energy transition process, and launching the RePowerEU Plan, aimed at reducing dependence on Russian fossil fuels and promoting a more sustainable and independent energy system, continuing the objectives of the Fit for 55 package for a zero-emissions Europe by 2050.

The energy crisis has reinforced the importance of two fundamental pillars in European energy policy: sovereignty and solidarity. Energy sovereignty refers to the ability of member states to autonomously decide on their energy policies, while solidarity, enshrined in the European treaties, implies a mutual commitment to ensuring the security of supply. These principles are integrated into a multidimensional approach that combines soft power, such as the power of influence, and hard power, through sanctions and incentives. This approach recognizes energy security as a “threat multiplier” that affects economic, social, and political stability. The current energy crisis has redefined European geopolitical dynamics, shifting from a paradigm based on interdependence to an approach focused on greater strategic independence. This shift emphasizes the diversification of resources and the construction of a resilient and independent energy system.

The transition to a sustainable energy system requires a balanced management of energy security, sustainability, and sovereignty. However, the increasing complexity of these objectives has led to the definition of the "impossible energy trinity," according to which one of the three must be sacrificed to optimize the others. In this context, the EU has adopted strategies to strengthen energy efficiency and increase the use of renewables, maintaining a balanced approach that, rather than opposing them, integrates the dimensions of sovereignty and solidarity to enhance overall security.

The evolution of energy security in the EU reflects a continuous process of adaptation to geopolitical, economic, and climate challenges. The so-called "four A's," introduced in assessments during the 1970s and 1980s, now require revision in light of the new European energy dynamics. The current crisis and the transition to a more sustainable energy system highlight the need to redefine the relationships between the pillars of the EU system: energy security, energy sovereignty, and energy solidarity. By integrating the "three S's" with the models of the "four A's," Europe is committed to building a resilient, sustainable energy system capable of addressing future challenges. This new balance, based on technological innovation, resource diversification, and multilateral cooperation, represents the foundation of an energy-independent and sustainable Europe (LaBelle, 2024).

Energy Security in Transition: Balancing Sustainability, Diversification, and Geopolitical Stability

The International Energy Agency (IEA) defines energy security as the uninterrupted availability of energy at an affordable cost. However, beyond the economic dimension, the concept encompasses broader aspects, including sustainability, diversification of sources, and the management of geopolitical risks. Energy security is a multidimensional and often debated issue. For importing economies, it primarily involves ensuring the reliability of supply. Conversely, for exporting countries, the priority is securing stable markets for their resources—a dynamic that reflects the tension between demand security and supply security. Energy security depends on the ability to diversify supply sources and mitigate political risks associated with suppliers. According to the literature, a diversified energy portfolio, including a variety of countries and transport routes, is essential to reduce the vulnerability of energy systems. This principle, derived from financial portfolio theory, is particularly relevant for natural gas, where diversification pertains not only to supplier countries but also to transport routes, such as pipelines and liquefied natural gas (LNG) shipments. LNG, in fact, has taken on a strategic role in global energy security due to its flexibility and the growing importance of spot contracts compared to long-term agreements.

The energy transition towards renewable sources introduces new dynamics in energy security. On the one hand, renewables reduce dependence on fossil fuel imports and mitigate energy price volatility in certain markets. On the other hand, their integration presents challenges related to intermittency and the need for adequate regulatory systems. Countries like Germany have demonstrated that it is possible to manage price volatility associated with renewables through effective policies, promoting greater stability in the electricity market. Investing in renewables not only contributes to environmental sustainability but also strengthens energy security by reducing geopolitical and climate-related risks. Studies such as Azzuni et al. (2020) highlight how an entirely renewable-based electrical system can significantly enhance energy security, not only in terms of availability and costs but also in terms of environmental and health impacts.

Although energy security and energy independence are often used as synonyms, they represent distinct concepts. Energy independence focuses on reducing the share of imported energy, often by increasing domestic production of fossil fuels. However, this approach can conflict with decarbonization efforts and the goals of the Paris Agreement, slowing the transition to a green economy (Cevik, 2022). To ensure a sustainable future, it is essential to pursue energy security through investments in renewable energy and energy efficiency rather than by increasing fossil fuel production.

Geopolitical dynamics play a crucial role in energy security. Over the past two decades, coal and oil production has become more concentrated, with increasing control by major producers. The global market share of coal held by leading exporters, such as China and Indonesia, rose from 33% in 2000 to 60% in 2020. Oil production has also shown a trend toward greater concentration, with countries like the United States, Canada, and Iraq gaining shares, though the combined share of the top seven producing nations remains below 60%. In contrast, the natural gas market has not experienced significant shifts in the distribution of shares among producers. Some changes, such as increased shares by Qatar, Iran, and China, have been offset by decreases in shares from Russia and Canada (Figure 3).

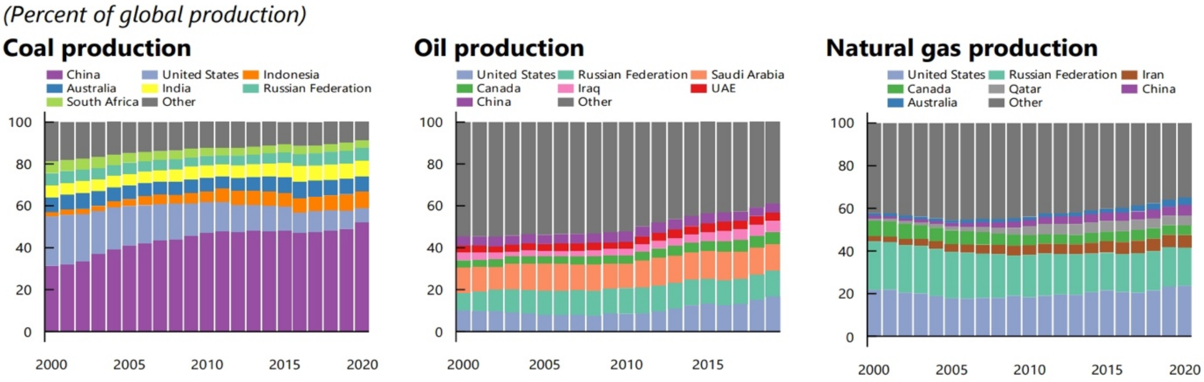

Figure 3. Composition of fossil fuel production by fuel and country.
Source: International Energy Agency, World Energy Balances; and IMF staff calculations.

Meanwhile, over the past decade, political conditions and democratic freedoms in major fossil fuel-producing countries have deteriorated. To analyze these aspects, indicators such as the Economist Intelligence Unit's Democracy Index, the political risk score provided by the PRSG group, and the Ideal Point Distance (IDP) measure, which assesses political risk in international relations, are used. The indicators show an increase in political risks for coal and natural gas, while results for oil are less consistent. Finally, the political distance between energy producers and consumers has generally decreased, but there has been an increase in geopolitical distance for natural gas since 2010. This could reflect the slowdown in globalization and the tightening of trade and financial barriers following the global economic crisis (Aiyar et al., 2023). These trends exacerbate vulnerabilities in the global energy system, highlighting the need for targeted strategies to manage geopolitical risks and market concentrations. In this context, strengthening storage infrastructure, improving interconnection between energy networks, and adopting multilateral policies for managing energy crises are essential measures (Figure 4).

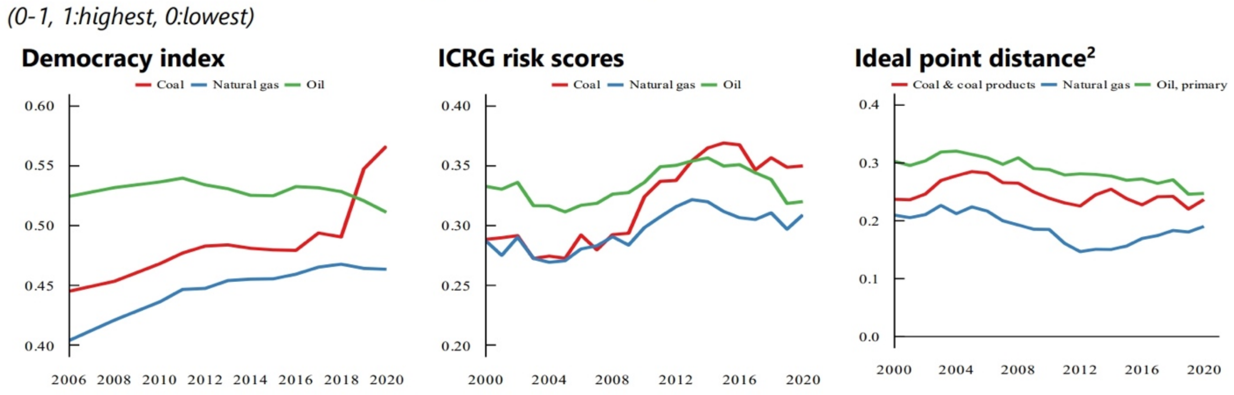

Figure 4. Political risk scores among major fossil fuel producers.
Source: International International Country Risk Guide, The PRS Group; Economist Intelligence Unit; Voeten, Strezhnev, and Bailey, 2009, United Nations General Assembly Voting Data; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculations.

Energy security is a complex goal that requires balancing sustainability, diversification of sources, and geopolitical stability. In the current context, marked by international tensions and climate change, economies must adopt an integrated approach that combines the expansion of renewable energy with supply diversification policies. Only in this way will it be possible to ensure a stable, accessible, and sustainable energy future for future generations.

Assessing Energy Security: Diversification, Political Risks, and Global Insights

Energy security is analyzed using approaches that examine various factors at both global and local levels. Globally, numerous indices have been developed to measure energy security, each with distinct methodologies, indicators, and aggregation criteria. According to Gasser (2020), there are 63 main indices, categorized into two groups: complex and simple. The former combine numerous indicators with arbitrarily defined weights, while the latter focus on a few key parameters without subjective weighting. In general, the construction of an index is based on three fundamental steps: data collection, normalization for consistent comparisons, and aggregation.

Our method favors a simple approach, avoiding the use of arbitrary weights, with a specific focus on supply security, which is particularly relevant for energy-importing countries. We use the Herfindahl-Hirschman Index (HHI), which measures market concentration, to evaluate the diversification of sources and the political risks of foreign suppliers. Although the index does not directly account for economic factors such as energy costs, supply security indirectly impacts these aspects.

Adapted to the energy sector, the HHI considers not only the concentration of sources but also political risks, geopolitical distance from suppliers, and the share of imported energy relative to total national consumption. Variations in the politically weighted HHI (DIpol) reflect three main elements: the effect of diversification, the impact of risks associated with individual suppliers, and an interaction term between diversification and risks. Figure 5 shows that in recent years, energy security risks have worsened due to reduced supply diversification, as highlighted by the rising index value since 2010.

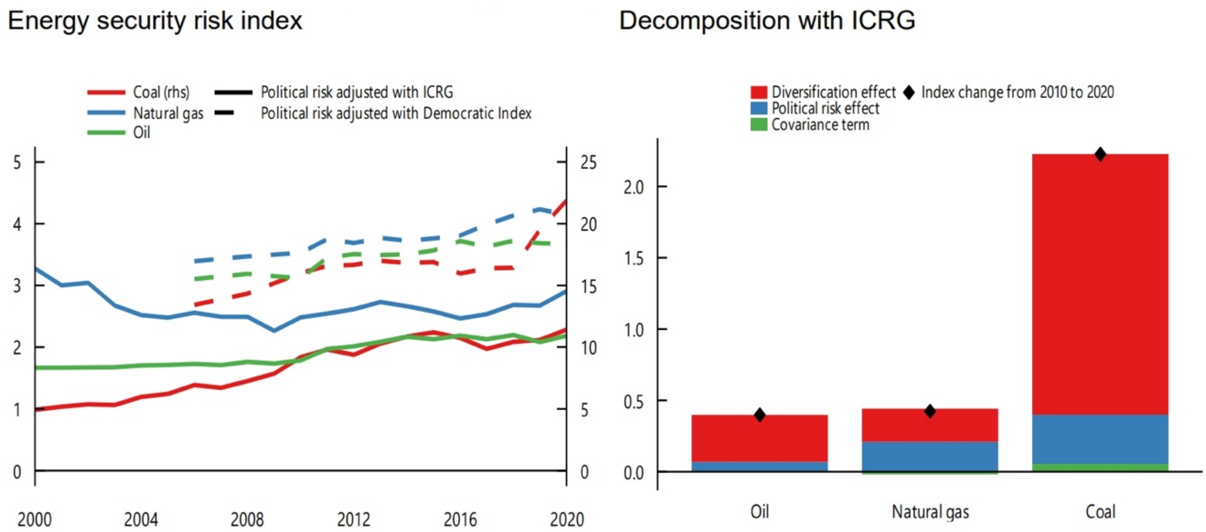

Figure 5. Decomposition of global energy security risk index for productions of individual fuels.
Source: International Country Risk Guide, The PRS Group; Economist Intelligence Unit; International Energy Agency, World Energy Balance; and IMF staff calculations.

For oil, the risk has been exacerbated by the increasing market shares of major producers like the United States, Canada, and Iraq, with political risks contributing marginally. In the case of natural gas, reduced diversification and increased political risks have had an equivalent impact, whereas for coal, the decline in diversification has been the dominant factor. Shifts in supplies across different dimensions of political risk, such as democratic freedoms and internal instability, have had varying impacts on security, with significant effects measured by the covariance term. The chart thus underscores the importance of diversification in mitigating energy security risks.

At the national level, energy security levels vary based on the type of resources used, the economic structure, and the policies adopted. Countries like the United States, thanks to their domestic production, are less vulnerable compared to nations heavily dependent on imports, such as Germany or Japan. Factors like the concentration of sources and dependence on infrastructure further influence the level of risk, while geopolitical or market fluctuations can significantly alter the situation during certain periods. For this reason, long-term analyses provide a more reliable perspective compared to short-term comparisons.

Diversification remains essential for improving energy security. A positive example is Lithuania, which reduced its dependence on Russian gas by expanding its supply sources, ensuring greater stability. Conversely, countries like Hungary, with a strong dependence on Russia, have seen their position worsen. These cases highlight the importance of strategies that diversify both supply sources and routes, mitigating risks arising from unforeseen geopolitical or economic events.

Navigating the Energy Transition: Challenges, Opportunities, and the Path to a Net-Zero Future

The transition to a net-zero emissions energy system represents a crucial shift in the fight against climate change but also involves complex challenges that require strategic solutions. This process, driven by the need to reduce greenhouse gas emissions, aims to radically transform the way we produce and use energy. One of the most evident effects is the strengthening of energy autonomy for countries, which can reduce their dependence on fossil fuel imports thanks to the increasing use of renewable energy sources. In many cases, this transition is already resulting in a decrease in natural gas and coal imports, while renewables like wind and solar power continue to grow. However, natural gas, often considered a "bridge" fuel, plays a temporary yet significant role in ensuring the stability of energy grids, as renewables, by their nature, have intermittent production. This balance is necessary to manage fluctuations in energy supply and demand but also poses the risk of increasing reliance on fossil resources during the transition phase.

Another effect of the energy transition is the reduction in global demand for fossil fuels, which inevitably leads to the exit of less competitive producers from the market. This phenomenon tends to concentrate the market in a few regions, making economies still dependent on fossil fuels more vulnerable to price fluctuations and geopolitical events. Moreover, the shift from coal to natural gas as a primary energy source increases the prominence of the latter in the energy mix, even though the overall trend is toward a decline in fossil fuel consumption. The speed at which oil will be replaced, however, depends on how quickly the transportation sector can be electrified, which is currently progressing more slowly compared to other sectors.

Climate policies, such as the introduction of a global minimum price for carbon emissions, are essential tools for accelerating the transition to renewables. These measures enhance energy autonomy but may also lead to a temporary reduction in the diversity of available fossil fuel sources, as less efficient producers are forced out of the market (Figure 6). To address these challenges without compromising energy security, it is essential to promote substantial investments in green energy, supported by clear international cooperation and long-term policies. This approach ensures sustainable growth of renewables and offsets the decline in fossil fuel production.

In addition to the implications related to fossil fuels, the energy transition brings a growing demand for critical metals, essential for renewable technologies and electric vehicles. Materials such as lithium, copper, nickel, cobalt, and rare earth elements are indispensable for manufacturing batteries, wind turbines, and solar panels. For example, an electric car requires five times more metals than a traditional vehicle. However, the production of these materials is heavily concentrated in a few regions of the world, making the system vulnerable to geopolitical crises or economic challenges. Although global reserves of these metals are sufficient to meet the estimated demand until 2060, extraction will become increasingly costly, and supply cannot be easily ramped up in the short term, as opening new mines requires years of work and investment.

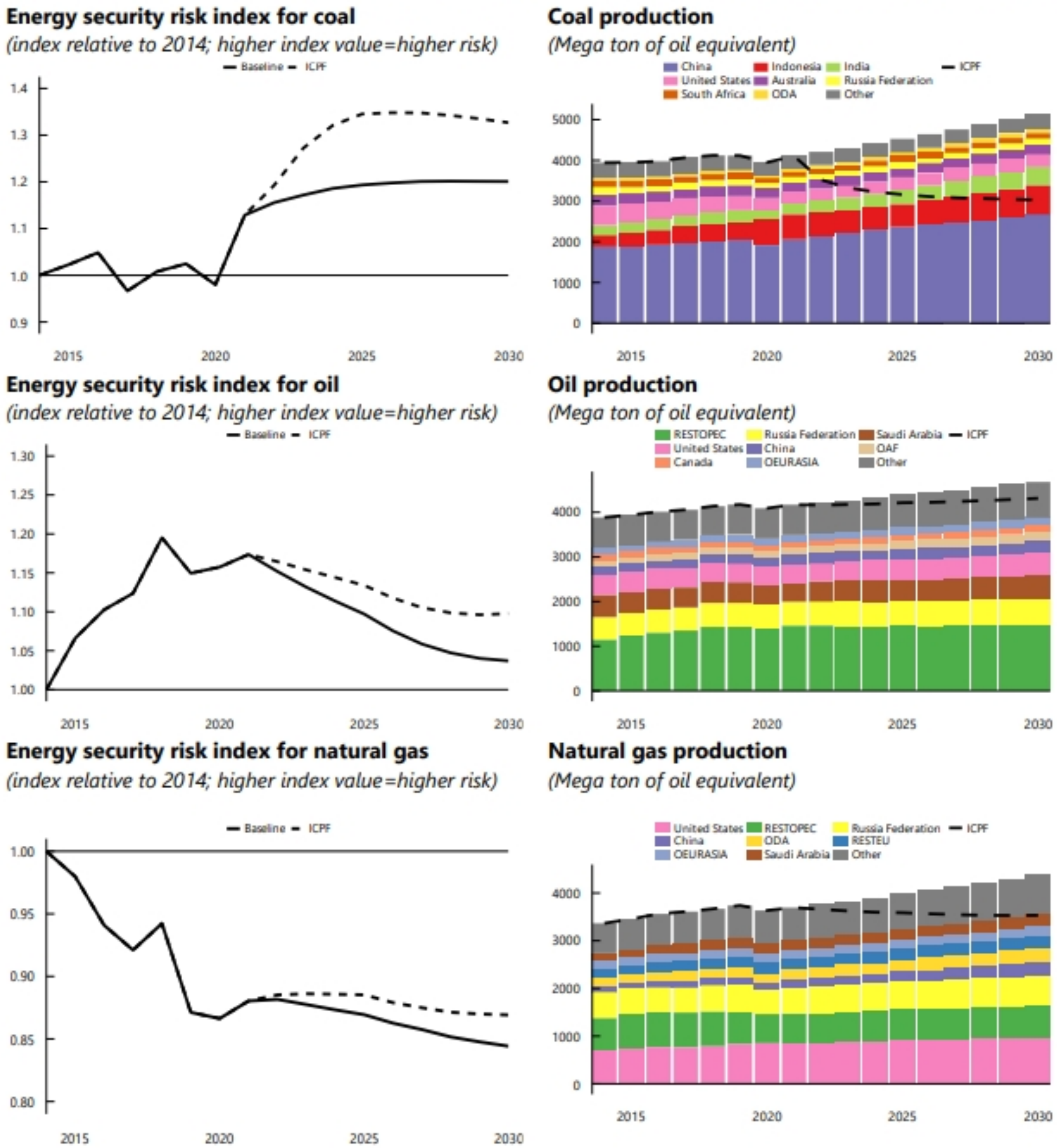

Figure 6. Global energy security in the baseline and International Carbon Price Floor (ICPF) scenarios.

Note: The graph compares global energy security under two scenarios: one baseline and one with stringent climate policies (ICPF). Although the reduction of fossil fuels temporarily increases the energy risk for individual fuels due to increased market concentration, the overall dependence on energy imports decreases due to the use of locally produced renewable energy. This improves overall energy independence and security in the long run, highlighting the importance of coordinated investments in renewables to avoid risks during the transition.

Source: PRS Group; IMF-ENV model

To address these challenges, several strategies can be implemented. Technological diversification, for example, allows the use of technologies requiring different amounts of metals, adapting to their availability. Another approach is enhancing recycling, as these metals are not destroyed during use and can be reused, reducing the pressure on primary production. Lastly, technological advancements are making it possible to use fewer metals to achieve the same results, thereby improving efficiency and reducing the system's vulnerability. Another critical aspect of the energy transition concerns the intermittency of renewable sources, such as solar and wind, which depend on weather conditions. To ensure a stable energy supply, it is necessary to adopt advanced technological and infrastructural solutions.

The expansion of electrical grids and the integration of different geographical areas can help balance energy production and demand, reducing fluctuations. Storage systems, such as batteries or pumped hydro storage, also play a crucial role by enabling the storage of excess energy for use during shortages. Another important strategy is the international trade of electricity, which facilitates energy exchange between countries and mitigates geopolitical risks associated with using energy as a political tool. In smaller countries or isolated economies, local solutions, such as increased energy storage, are essential. Additionally, flexibility on both the demand and supply sides can help balance the system: large energy consumers can adjust their usage to periods of higher availability, while gas or hydroelectric plants can complement renewables when needed. Excess energy produced by renewables can also be used to generate green hydrogen through power-to-gas technologies. This hydrogen can be stored and converted into alternative fuels for sectors that are difficult to decarbonize, such as aviation or maritime transport.

Despite its complexities, the energy transition offers significant opportunities for innovation and sustainable development. With targeted policies, international cooperation, and technological advancements, it is possible to ensure that renewables become the cornerstone of the future energy system while maintaining a high level of global energy security.

Building Resilient Energy Security: An Integrated Approach for a Sustainable Future

In conclusion, the current energy crisis highlights the need for an integrated strategy that balances short-term objectives with a long-term vision, focusing on building sustainable and resilient energy security. Dependence on imported fossil fuels, often from countries marked by political instability, represents a significant vulnerability for many economies. While domestic production of fossil fuels may temporarily mitigate these risks, it risks conflicting with climate goals, thereby compromising future energy security. It is therefore crucial to adopt policies that address both immediate and structural challenges simultaneously.

Recent market dynamics highlight how geographical concentration in the production of coal, gas, and oil can undermine energy diversification, exacerbating risks of instability. On the other hand, the adoption of ambitious climate policies can provide strategic opportunities, reducing demand for fossil fuels and promoting the expansion of renewable energy. In this context, the transition from coal to natural gas represents a relative improvement, thanks to greater diversification in the gas market, but it is merely an intermediate step toward a more sustainable energy system. However, the shift to renewables is not without challenges. The concentration in the production of critical materials for green technologies, such as rare metals and semiconductors, presents a new form of dependency. While these materials are primarily needed during the infrastructure construction phase, their scarcity could slow down the pace of the transition. These risks can be mitigated through greater diversification of sources, the development of alternative technologies, and the implementation of circular economies. Moreover, the intermittency of renewable sources like wind and solar energy requires investments in advanced infrastructure, such as interconnected power grids, energy storage systems, and tools for flexible demand and supply management.

Another crucial aspect is the physical infrastructure and the growing interdependence of energy systems between countries. International cooperation, both in resource sharing and in building resilient energy networks, will become increasingly central to ensuring stability. With the rise in renewable energy use, it will be necessary to develop new metrics to measure energy security, considering not only independence from imports but also the ability to adapt to rapidly evolving scenarios. Ultimately, the energy security of the future cannot be ensured by fragmented approaches or strategies focused solely on energy independence. An integrated approach that combines diversification, technological innovation, climate policies, and international cooperation will be essential. Only through this approach will it be possible to build a flexible, sustainable energy system capable of effectively addressing the global challenges of the 21st century (Kim et al., 2024).

Europe's Strategic Autonomy

European Strategic Autonomy: A Field in Evolution

The concept of European Inclusive Open Strategic Autonomy has evolved from a concept initially confined to security and defense into a broader vision encompassing the economy, technology, energy, and trade. This evolution reflects the urgency of responding to a rapidly changing geopolitical landscape, marked by global crises such as the COVID-19 pandemic, the war in Ukraine, and the rivalry between the United States and China. The central goal of European strategic autonomy is to strengthen the European Union's (EU) capacity to act as an independent and resilient global actor, reducing vulnerabilities linked to external dependencies while promoting internal security.

One of the key areas where this concept is most evident is energy. The war in Ukraine highlighted Europe's critical dependence on imported gas, particularly from Russia, which accounted for around 40% of Europe's supply before the conflict. This crisis has prompted the EU to diversify energy sources, promote sustainable technologies, and invest in energy security. However, the energy transition is not only a response to geopolitical emergencies but also an opportunity for Europe to lead the global transformation toward sustainability. Ensuring energy security through economic resilience and internal cohesion is essential for maintaining a central position on the global stage.

Addressing this challenge requires a strategic vision that combines competitiveness, sustainability, and inclusivity. Instruments such as issuing European sovereign debt, completing the Banking Union, and achieving a fully integrated Capital Markets Union are critical steps in equipping the EU with adequate financial resources and attracting private capital. Simultaneously, forging partnerships with emerging and strategic countries, such as India, Brazil and those in Africa, can help diversify economic relationships while fostering transparent and sustainable investments that support both local development and European supply chain security.

European strategic autonomy, however, must not be misconstrued as isolationism. On the contrary, it implies the capacity to select partners and alliances based on shared interests, striking a balance between economic openness and protecting strategic priorities. Multilateral cooperation and strengthening global institutions such as the World Trade Organization are fundamental to addressing challenges like international fragmentation, the regulation of new technologies, and environmental sustainability. In this context, the EU must integrate geopolitical considerations into its economic decision-making processes, adapting to a multipolar world where competition between the United States and China shapes global dynamics.

Internal challenges within the EU, including fragmentation among member states and divergent national priorities, remain significant obstacles. Eastern European countries focus primarily on geopolitical threats posed by Russia, while southern states are more concerned with migration and other Mediterranean issues. This diversity of perspectives necessitates enhanced internal cohesion and political leadership capable of overcoming divisions, fostering common policies, and streamlining decision-making processes.

Ultimately, European strategic autonomy is essential for ensuring Europe's economic, social, and political security in an increasingly complex world. The EU must take on a leadership role in promoting a reformed multilateral economic order and crafting a shared vision for the future. Only through an integrated approach combining technological innovation, social justice, and environmental sustainability can Europe consolidate its global role, becoming a sovereign and resilient actor equipped to address the challenges of the 21st century.

Building Energy Resilience: The EU's Strategy for Strategic Autonomy and Sustainability

The EU responded to the energy crisis with a series of measures aimed at strengthening its strategic autonomy.

Investments in Renewable Energy. Investments in renewable energy represent a key pillar of the European Union's strategy to address the energy crisis and reduce its dependence on fossil fuels, particularly Russian gas imports, which once constituted a significant portion of the European energy mix. Following Russia's invasion of Ukraine, the EU recognized the urgency of accelerating the energy transition by promoting renewable sources such as wind, solar, hydropower, and bioenergy. These sources are not only environmentally sustainable but also provide greater long-term energy security, reducing Europe's vulnerability to geopolitical fluctuations and fossil fuel price volatility.

Key initiatives such as the European Green Deal, REPowerEU, and Fit for 55 have been designed to incentivize the development and adoption of renewable energy across the continent. These policies include strong support for both public and private investment in new green infrastructure and technologies, with the goal of making renewables increasingly cost-effective and competitive against traditional fossil fuels. This includes the creation of new offshore wind energy production plants, the construction of vast solar parks, and the implementation of advanced energy storage solutions such as batteries and green hydrogen technologies, which allow for energy storage to offset the variability of renewable sources.

The support for renewable energy investments is accompanied by a strong long-term political commitment to establish a stable and favorable regulatory framework that can attract private investors. Policies like the carbon tax and the EU Emissions Trading System (ETS) are essential tools for ensuring that the cost of carbon emissions is sufficiently high to incentivize the adoption of renewables. Additionally, the increased financing capacity through the European Investment Bank (EIB) and other European funds further strengthens the availability of resources to finance the energy transition. Investments in renewable energy represent a central component of the European Union's response to the energy crisis and an opportunity to enhance its strategic autonomy. The transition to sustainable energy sources not only helps reduce dependence on external fossil fuel suppliers but also enables Europe to play a leading role in combating climate change, while improving the continent's economic and energy security. However, to fully achieve this ambitious goal, coordinated efforts among all member states and robust support at both national and EU levels will be necessary to ensure that the transition to renewables occurs rapidly, efficiently, and inclusively.

Diversification of Energy Sources. The diversification of energy sources is a crucial process to reduce dependence on a single supplier or energy source, such as Europe's reliance on Russian natural gas. This approach aims to create a broader and more resilient energy mix by integrating renewable sources, nuclear energy, and imports from various global suppliers. Recent geopolitical crises, such as the COVID-19 pandemic and Russia's invasion of Ukraine, have highlighted the vulnerabilities of the EU's energy supply chain, emphasizing the need for effective strategies to reduce dependency on imports, particularly from Russia.

Diversification is not just a safety measure but an essential element for achieving European energy independence. This goal is accomplished by spreading supply across multiple regions and energy sources. However, diversification works in synergy with the integration of European energy markets. While diversification reduces the risks associated with dependence on a single resource, market integration enables resource sharing through interconnected infrastructure, enhancing the efficiency and stability of the energy system. In a fragmented scenario, individual countries must primarily rely on their own resources or bilateral agreements, increasing the vulnerability of those less equipped. Conversely, an integrated European energy market enables an efficient exchange of resources among member states, thanks to interconnected infrastructure and strengthened political solidarity. This model minimizes supply disruptions and limits the economic impact of crises, creating a more resilient energy system capable of addressing potential emergencies (Flanagan et al., 2022).

The adoption of diversified energy sources, including solar, wind, and hydroelectric, not only reduces dependence on external suppliers but also contributes to achieving European climate goals by lowering greenhouse gas emissions. This approach represents a dual opportunity: promoting the ecological transition and enhancing energy security.

The Energy Import Diversification and Security Index (EIDS) assesses the degree of energy security in countries by measuring their dependence on imports and the variety of their energy mix. Countries with robust energy infrastructure and a diversified mix score high, demonstrating a greater ability to withstand supply shocks. Conversely, those heavily reliant on external suppliers are more vulnerable.

In conclusion, diversification of energy sources and market integration represent the fundamental pillars for ensuring the EU's energy resilience. These two approaches, working in synergy, not only reduce the risks associated with severe shortages and the negative economic impacts of supply shocks but also create a collective safety network. This integrated system enhances Europe's ability to adapt quickly and redirect energy resources in times of crisis, protecting national economies and ensuring a stable and sustainable energy future (Streimikiene et al., 2023).

Enhancement of Energy Infrastructure. The enhancement of energy infrastructure is a central measure adopted by the European Union to strengthen its strategic autonomy, particularly in response to the energy crisis triggered by Russia's invasion of Ukraine. This effort extends beyond the expansion of renewable energy production and includes the modernization of transmission and distribution networks. These infrastructures are crucial for integrating energy generated from renewable sources, such as solar and wind, into the European grid, allowing for efficient and continuous distribution despite the intermittent nature of these sources. In this context, improving the grid through the construction of new smart grids and the modernization of existing ones is essential to ensure that green energy can be utilized without interruptions, contributing to the reduction of carbon emissions.

To enhance energy security and reduce reliance on Russian fossil fuels in response to the energy crisis spurred by Russia's invasion of Ukraine, the EU has diversified import routes and developed cross-border energy networks. In this regard, the Regulation on Trans-European Networks for Energy (TEN-E) plays a pivotal role in guiding the development of cross-border interconnections to bolster the energy security of member states. A key element of this strategy is the "Projects of Common Interest" (PCIs), which aim to improve energy connections between EU countries. These projects, in addition to receiving direct funding from the Union, benefit from simplified permission procedures to accelerate their implementation. The planning and financing of such projects align with the goals of the European Green Deal and the REPowerEU plan, both aimed at promoting a transition toward a greener energy system, gradually reducing the use of fossil fuels, and increasing the adoption of renewable sources such as biomethane and green hydrogen.

However, investments in energy infrastructure are not limited to the electricity sector. Gas and oil infrastructures are also being adapted to meet new import needs and to ensure the resilience of the European energy system. The European Commission has set ambitious targets for electricity interconnection, aiming to achieve a connectivity level of 15% by 2030. This means that at least 15% of the electricity capacity of member states must be connected to neighboring countries' grids, promoting energy sharing and improving system stability. To support these objectives, the EU has allocated funds through various mechanisms, including the Connecting Europe Facility and the Recovery and Resilience Facility (European Parliament, 2023). In parallel, the EU has launched a specific Energy Networks Action Plan, which foresees an investment of €584 billion by 2030. This plan aims to improve the efficiency and flexibility of energy infrastructures, facilitating the integration of renewable energy into the grids and making the system more resilient and secure. One of the objectives is the anticipated 60% increase in electricity consumption by 2030, for which it is essential to develop more advanced networks capable of handling larger amounts of renewable energy. Key measures in the plan include simplified permission processes and specific funding for strategic projects, with a particular emphasis on promoting smart grids.

Another crucial element of the EU's energy strategy is hydrogen, which is expected to become a fundamental component of the future energy mix. The EU is planning substantial infrastructure investments to support the production and distribution of green hydrogen, seen as a solution for reducing greenhouse gas emissions and improving the sustainability of the energy system. Globally, renewable energy generation capacity is rapidly growing, with a projected 50% increase by 2023, mainly driven by photovoltaics, as highlighted in the

Renewables 2023 Report by the International Energy Agency (IEA). This trend could allow the global renewable energy capacity to triple by 2030, contributing to the achievement of international climate goals.

The European Parliament has consistently supported the importance of significant investments in cross-border energy infrastructure, recognizing that such efforts are essential to ensuring the Union's energy independence and stability. However, financing these infrastructures remains a challenge, requiring long-term planning to ensure a secure, sustainable, and resilient energy future for all European citizens.

REPowerEU: Transforming Europe's Energy Landscape for Security and Sustainability

The REPowerEU plan, launched by the European Union in 2022, represents an ambitious and strategic response to the energy crisis triggered by Russia's invasion of Ukraine. This plan marks a paradigm shift from previous energy policies, with the declared aim of ensuring energy security, eliminating dependence on Russian gas by 2030, and accelerating the transition to a sustainable and autonomous energy system. Through a combination of diversification measures, energy efficiency initiatives, and the development of renewable energy, the EU aims to transform its energy system while mitigating geopolitical and climate risks.

The central aspect of the plan is the reduction in demand for fossil gas, with a target to cut 155 billion cubic meters by 2030, equivalent to the EU's 2021 imports of Russian gas. This target will be achieved through investments of €296 billion, aimed at enhancing renewable energy infrastructure, promoting the electrification of heating and transport, and improving the energy efficiency of buildings. Incentive policies introduced between 2022 and 2023 have accelerated the adoption of technologies such as heat pumps, gradually replacing outdated gas boilers. Additionally, the European Commission has set ambitious goals for building decarbonization, supported by regulations that simplify administrative processes and promote the adoption of more sustainable energy systems.

On the supply diversification front, the EU has secured new agreements for importing liquefied natural gas (LNG) from the United States, Qatar, and other regions, reducing its exposure to Russian suppliers. However, this strategy introduces new challenges related to global competition for LNG and the security of transit routes. To address these vulnerabilities, the REPowerEU plan aims for structural transformation by increasing the share of electrified consumption and reducing overall reliance on natural gas. Nevertheless, differences persist among member states, with countries like Hungary maintaining energy ties with Russia, highlighting the complexity of achieving full political cohesion.

The energy transition outlined by REPowerEU is based on significant expansion of renewable energy, with a goal to cover 45% of gross final energy consumption by 2030. Installed solar and wind capacity is set to grow rapidly, reaching 592 GW and 510 GW, respectively, by the end of the decade. This development will drastically reduce natural gas consumption for power generation, contributing to the elimination of over two-thirds of the EU's 2021 imports of Russian gas. However, the success of this plan depends on the ability to accelerate the installation of renewable energy infrastructure, which is currently progressing at an insufficient pace.

Another layer of complexity involves the variability of renewable energy production, such as solar and wind, and seasonal energy demand, particularly high during winter months. In scenarios with adverse weather conditions, the EU might rely on natural gas reserves, leading to a significant increase in residual demand.

These factors underscore the importance of developing advanced grid management technologies and better integrating gas and electricity markets.

Figure 7 clearly illustrates the gap between the targets set in the 2019 National Energy and Climate Plan (NECP19) and the more ambitious goals of the new plan. Installed solar and wind capacity, the deployment of electric vehicles, and the adoption of heat pumps show significantly higher projections under REPowerEU. For example, solar capacity is expected to reach 592 GW by 2030, compared to the 473 GW anticipated under NECP19, while wind capacity is projected to grow to 510 GW, up from the previous estimate of 317 GW. Additionally, the number of electric vehicles is set to rise to 30 million, and the stock of heat pumps to 44 million units, highlighting the EU's commitment to a faster and more effective energy transition.

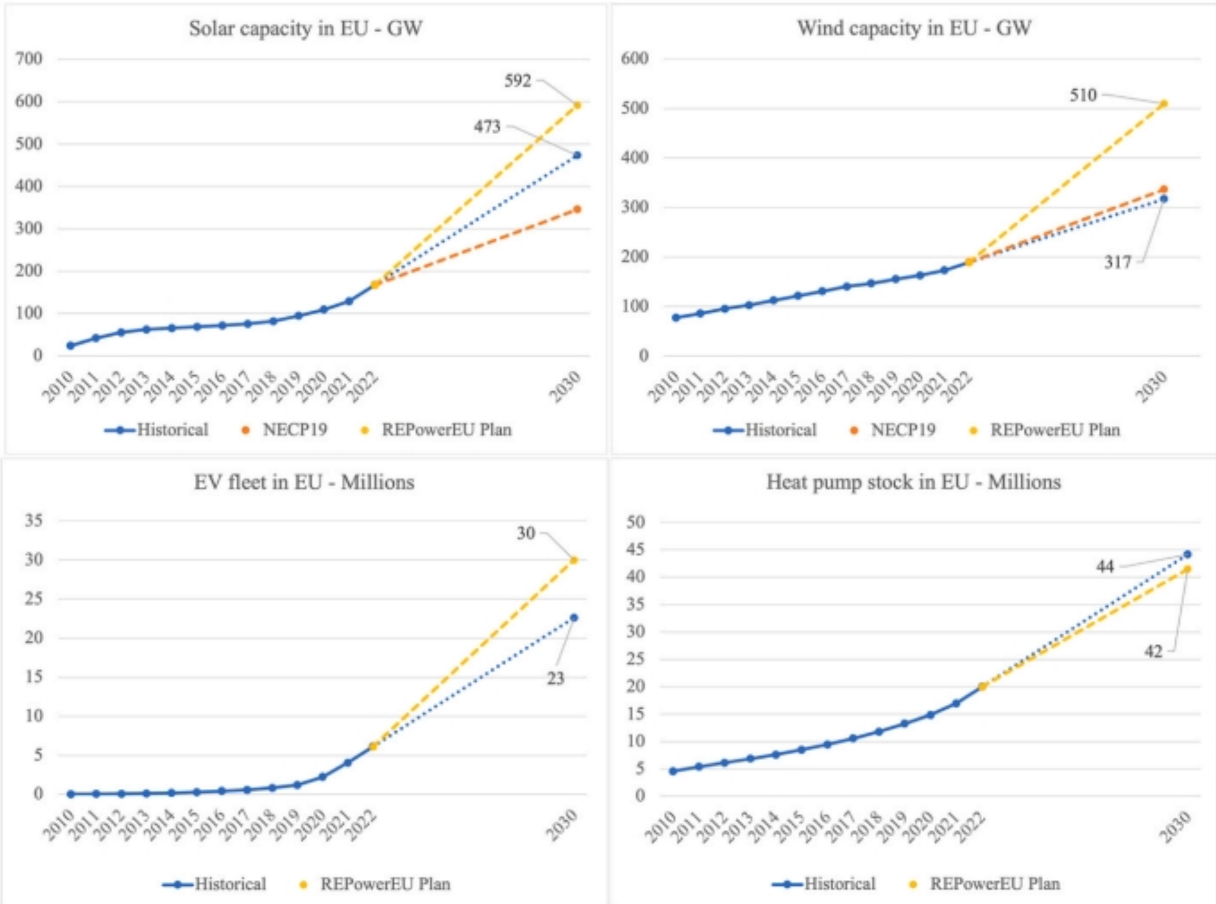

Figure 7. Comparing EU power sector trends and policy targets for 2030. Significant gap: the current installation rate is insufficient compared to the required targets. Acceleration is needed to reduce dependence on natural gas and achieve energy independence. *Source: IEA Renewables 2022, Ember, ENTSO-e.*

In conclusion, the REPowerEU plan is not only a response to the energy crisis but also a cornerstone for the EU's energy and climate future. While significant challenges remain, from internal political cohesion to supply security, the plan represents a critical step toward a more resilient, sustainable, and independent energy system.

Energy Governance in Europe

Balancing Power: The Challenges of Energy Integration and Sovereignty in the European Union

Energy represents a strategic element for the European Union, not only for its economic and industrial impact but also as a fundamental pillar of continental security and sovereignty. In recent decades, the EU has worked to build an integrated energy system aimed at addressing global challenges such as the transition to renewable energy and reducing dependence on fossil fuels. However, one of the most complex aspects of this process is the delicate balance between centralized European coordination and the implementation of energy policies at the national level. While central coordination allows for the definition of common strategies and cohesive responses to emergencies, the effective implementation of policies depends on the capacity and resources of individual member states, creating a dynamic of asymmetry that influences the overall effectiveness of European initiatives.

European energy coordination has its roots in the 1960s, with the aim of creating a common energy market. However, it is with the rise of geopolitical tensions and the pressures related to sustainability that integration has gained greater significance. Events such as the gas crisis during the conflict in Ukraine and the urgency to reduce carbon emissions have driven the EU to intensify cooperation through initiatives like the European Green Deal and the REPowerEU plan. These programs aim to promote renewable energy, decrease dependency on fossil fuels—particularly Russian gas—and strengthen the continent's energy resilience.

A centralized coordination offers significant advantages. It enables unified responses to common challenges, strengthens Europe's bargaining power in global markets, and facilitates the creation of common regulations that reduce bureaucratic barriers and promote the standardization of infrastructure. For example, the promotion of cross-border interconnections for electricity and gas has enhanced the EU's collective resilience, making the system less dependent on external suppliers. Moreover, the ability to act on a European scale allows for the mobilization of substantial financial resources through common funds, supporting regions and sectors most affected by the energy transition. However, this approach also highlights certain challenges. The diversity of economies and energy infrastructures among member states creates inequalities in policy implementation. Countries with advanced financial and technological resources, such as Germany, are able to invest quickly in renewable energy and adapt to European targets. In contrast, countries with outdated infrastructures, like Romania, face greater difficulties, slowing the transition process and creating significant disparities in outcomes.

The debate on energy governance revolves around the choice between centralization and decentralization. Centralization provides greater coordination and a cohesive response to crises but may prove rigid in addressing national specificities. Countries like France, heavily reliant on nuclear energy, may have different priorities compared to states like Spain, which are more focused on renewables. On the other hand, a decentralized approach ensures greater flexibility, allowing states to tailor policies to their own needs. However, it risks fragmenting the European energy market and hindering large-scale common projects, such as cross-border networks.

A striking example of the challenges related to the national implementation of European policies is the REPowerEU strategy, aimed at reducing dependence on fossil fuels and promoting renewables. While this strategy establishes common guidelines, its practical application varies significantly among countries, influenced by the availability of financial resources, the ability to attract investments, and local infrastructure conditions. Despite financial support from the European Commission, the primary burden of implementation falls on individual states, leading to misalignments in timelines and response capacities. Furthermore, national regulations that are not always harmonized can limit the efficiency of energy trade within the EU, hindering the creation of a truly integrated market.

In summary, the future of Europe's energy system depends on the ability to balance strategic coordination at the EU level with flexible and inclusive implementation at the national level. Only by addressing asymmetries among member states and strengthening synergies will it be possible to achieve a sustainable, resilient, and globally competitive energy system (Radtke and Wurster, 2023).

Bridging Asymmetries for a Unified Future

The asymmetries among European Union member states in the energy sector represent one of the main challenges in achieving a fair and sustainable energy transition. Each country has different natural resources, technological traditions, and economic contexts: France has established expertise in nuclear energy, Spain stands out for its focus on solar energy, while Northern European countries, such as Denmark, concentrate on wind energy. However, European directives, though flexible, do not always fully reflect these national peculiarities. Regulations promoting renewable energy, for example, prove advantageous for countries with abundant sunlight but are less applicable to those with different resources and energy priorities.

In addition to these disparities in resources, there are significant economic and technological differences. Countries like Italy and Greece, marked by prolonged economic recessions, do not have the same financial capacity as nations like the Netherlands or Sweden to invest in the infrastructure and technologies necessary for the energy transition. Furthermore, many countries face challenges with outdated or undersized electrical grids, unable to support a significant increase in energy production from renewable sources. These structural deficiencies complicate the achievement of climate goals and heighten the risk of creating a divide between advanced states and those lagging behind in the energy transition.

Among the proposed solutions to address these asymmetries is the concept of European solidarity. Mechanisms that provide economic and technological support from more advanced countries to those in difficulty can help level disparities. The Just Transition Fund is a concrete example. It supports regions heavily reliant on fossil fuels, fostering economic diversification and the development of new energy sources. Similarly, initiatives have been launched to improve the resilience and integration of the European energy system, such as the Projects of Common Interest (PCI), which enhance cross-border infrastructure, and energy corridors designed to facilitate the exchange of surplus renewable energy between countries (Gawel and Strunz, 2022). Other virtuous practices include the gas storage sharing mechanism, through which states with greater storage capacity make reserves available to less-equipped countries, improving overall energy security. Such initiatives represent significant steps toward greater cohesion but require coordination that balances centralization and flexibility. On one hand, a European governance framework is needed to respond collectively to global challenges, such as climate change and energy security; on the other, national peculiarities must be respected to ensure that each state can participate in the energy transition according to its capabilities.

The future of the European energy system will depend on the EU's ability to harmonize these two dimensions, promoting an integrated yet adaptable model. Only through effective coordination and mutual support will it be possible to overcome inequalities and build a sustainable, resilient, and united energy framework in Europe (Dekanozishvili, 2015).

Financing European Energy Autonomy

Financing mechanisms

The energy crisis triggered by Russia's invasion of Ukraine has highlighted Europe's vulnerability due to its dependence on fossil fuels. With over 80% of global energy still reliant on these resources, the need to accelerate decarbonization has become crucial not only for ensuring energy security and stability but also for achieving climate goals. According to the International Energy Agency (IEA), global investments in clean energy will need to triple by 2030, reaching $4.5 trillion annually, to achieve carbon neutrality by mid-century. These investments must focus on strategic sectors such as energy efficiency, renewable energy, infrastructure expansion, and the development of cutting-edge technologies, including floating offshore wind farms, green hydrogen, and energy storage systems (La Camera and Douglas, 2024).

The European Union has taken a leading role in the global energy transition, placing the European Green Deal at the core of its strategy to achieve climate neutrality by 2050. A key element of this vision is the REPowerEU program, designed to quickly reduce dependence on fossil fuels, particularly Russian gas, and promote the shift toward renewable energy sources. This program mobilizes significant resources to fund projects in energy efficiency, renewable energy, and innovative technologies such as green hydrogen and battery-based storage systems.

Beyond REPowerEU, the European Union employs other tools to channel funds towards the energy transition, including the European Structural and Investment Funds (ESIF), which are dedicated to supporting local projects for clean energy and energy resilience, and the InvestEU program, which aims to attract private capital through risk guarantees and innovative financial instruments. This integrated approach amplifies the impact of investments, bridging the gap between available resources and the necessary investments.

Over the past decade, the European Investment Bank (EIB) has established itself as a key player in promoting the energy transition in Europe. Since 2019, the EIB has ceased financing projects related to fossil fuels, including natural gas, focusing exclusively on decarbonization initiatives, energy efficiency, and technological innovation. Overall, the EIB has invested approximately €108 billion in the energy sector, supporting both European and international projects.

In 2023, the EIB allocated €21 billion to enhance energy efficiency, promote renewable energy, and strengthen infrastructure, with a focus on smart electricity grids and energy storage systems. Among the flagship projects is a €5 billion investment in wind energy, aimed at supporting businesses and commercial banks. This investment could generate up to €80 billion in total investments and increase Europe's wind capacity by 32 gigawatts (GW), significantly contributing to the energy transition. At the same time, the EIB launched initiatives such as the REPowerEU program, allocating €45 billion over the next five years to fund strategic projects related to clean energy and the production of net-zero technologies. This includes support for the creation of battery gigafactories and the expansion of solar and wind energy production capacity.

The European energy transition cannot rely solely on public funding. The private sector plays a crucial role in bridging financial gaps and driving technological innovation. The European Union has developed mechanisms to attract private capital, such as InvestEU and the European Fund for Strategic Investments (EFSI), which provide guarantees to reduce perceived risks for investors. Public-private partnerships (PPPs) are one of the most effective ways to combine public and private resources, enabling the development of essential infrastructure such as battery gigafactories, solar and wind energy plants, and smart grids. These partnerships help accelerate the development of strategic projects while ensuring that public goals – such as energy security and sustainability – are met. A notable example is the collaboration between governments and the private sector to build smart grids in Germany and develop green hydrogen in Norway.

The European energy transition cannot proceed without a global and inclusive approach. Beyond reducing dependence on fossil fuels, it is essential to ensure that emerging economies, particularly in Africa, can benefit from this transformation. Through investments in energy access, cost reduction, and sustainable industrial growth, Europe can contribute to a fair transition that addresses the global energy gap. Projects supported by the EIB, such as the development of 750 megawatts (MW) of renewable energy in Bangladesh and the expansion of the 3Sun solar gigafactory in Italy, demonstrate how international cooperation can be integrated into Europe's energy strategy. On a global scale, Europe aims to lead the development of clean and sustainable technologies, contributing to a resilient and carbon-neutral energy future (European Investment Bank, 2024).

The transition toward European energy autonomy requires an unprecedented mobilization of financial and human resources, accompanied by coordinated efforts between the public and private sectors. Instruments like REPowerEU, InvestEU, and the support of the EIB represent fundamental pillars to accelerate the shift to a sustainable energy system. Only through strategic investments, technological innovation, and close global collaboration can Europe achieve its ambitious climate goals while ensuring security, sustainability, and inclusivity for future generations (Feingold, 2024; Isarabhakdee, 2024).

Disparities Among Member States in Terms of Financing Capacity

The disparities among European Union member states in terms of their capacity to finance the energy transition are one of the main challenges in the continent's journey toward energy autonomy. Advanced economies, such as Germany and the Netherlands, benefit from strong financial institutions, well-developed capital markets, and easier access to innovative financial instruments like green bonds. This enables them to fund large-scale energy projects, reducing costs and accelerating the transition to renewable energy. These countries also benefit from lower interest rates and greater confidence from international investors, who see these economies as stable and secure environments for their capital (European Investment Bank, 2024). In contrast, many southern and eastern European member states, characterized by weaker economies and high public debt, struggle to mobilize the necessary resources to finance strategic energy transition projects. These countries heavily rely on European funds and public-private partnerships, given their limited access to international credit markets and difficulties in attracting private investments. Additionally, the scarcity of public resources in these states limits the possibility of direct funding for infrastructure projects, which are essential for achieving climate goals. This disparity between more and less advanced countries risks undermining the Union's overall ability to move uniformly toward decarbonization.

Globally, financial disparities are even more pronounced. A new 2023 report by the International Renewable Energy Agency (IRENA) and the Climate Policy Initiative (CPI) highlights how the flow of investments in renewable energy is concentrated primarily in developed countries, leaving emerging and developing economies behind. Although global investment in energy transition technologies reached a record $1.3 trillion in 2022, only a small fraction of these funds was directed toward developing countries. More than half of the world's population, primarily residing in these countries, received only 15% of global renewable energy investments. Sub-Saharan Africa, for example, received less than 1.5% of global investments between 2000 and 2020, highlighting a vast disparity compared to richer countries, where investments are far more substantial. In 2021, per capita investment in Europe was 41 times higher than in sub-Saharan Africa, underscoring the growing divide between different regions of the world (IRENA, 2023).

This global disparity is exacerbated by economic, political, and social conditions that hinder the ability of developing countries to attract investments. High interest rates, currency risks, and underdeveloped local financial markets make it difficult to finance large-scale energy projects, while the lack of infrastructure and limited banking experience in the renewable energy sector further discourage private investors. Public financing, which plays a crucial role in many emerging economies, is also constrained by the fiscal limitations of these governments, who rely heavily on external aid and multilateral development banks to bridge their financing gaps. Moreover, global investments are primarily focused on established technologies like solar and wind, while other less mature technologies and critical sectors for the energy transition, such as sustainable heating and cooling, receive less attention. This imbalance in the allocation of funds risks slowing down the adoption of innovative and decentralized energy solutions, which could improve energy access in poorer countries and promote more equitable development (Demertzis et al., 2024).

The situation thus calls for a substantial increase in financial flows from the Global North to the Global South, with particular attention to the needs of developing countries, which possess significant untapped renewable potential but struggle to attract investments. International cooperation must aim to create enabling policy frameworks and strengthen the development of energy infrastructure to bridge the persistent socio-economic gaps. The transition to a low-carbon economy cannot happen without an equitable distribution of financial resources and without reforming lending mechanisms to make them more accessible and favorable to developing countries (IRENA, 2023).

In conclusion, both at the European and global levels, disparities in financing capacity for the energy transition represent a significant obstacle to achieving climate goals. Only through greater collective effort, including the enhancement of public and private funds and the creation of adequate support policies, can a fair and equitable transition for all be ensured.

Economies of Scale in the Energy Sector

Economies of scale are a fundamental aspect of the development of the energy sector, particularly in the transition toward renewable energy. In the energy context, economies of scale are crucial for improving efficiency, reducing production and distribution costs, and accelerating the adoption of sustainable technologies. Their significance has become increasingly evident in recent decades with the growing demand for clean energy and the need to address global challenges such as climate change.

In the renewable energy sector, such as wind and solar, economies of scale play a vital role in enhancing economic competitiveness. Initially, the high costs of installation and management made large-scale investments difficult for both governments and private companies. However, with technological progress and the spread of large-scale installations, costs have drastically decreased. A striking example is photovoltaic solar power: over the past ten years, the cost of solar panels has dropped by more than 80% due to mass production and supply chain optimization, particularly in China, the world's largest producer of solar panels. A similar phenomenon has occurred in the wind energy sector, where the increase in turbine size has led to greater energy efficiency, reducing the cost per megawatt produced. Additionally, operational and maintenance costs decrease as the size of the plants increases, making large wind farms more competitive than smaller ones. Denmark, a pioneer in offshore wind energy, has significantly benefited from these dynamics, managing to meet a substantial portion of its energy needs with wind power. Economies of scale extend beyond energy production and also encompass distribution and storage infrastructures. With the increase in renewable energy production, modernizing electrical grids has become necessary to ensure efficient integration. Smart grids represent an example of how economies of scale can reduce management costs and increase the efficiency of the energy system.

Economies of scale in the energy sector offer significant advantages but also pose complex challenges that impact the European landscape unevenly. Countries like Germany manage to maximize the benefits of large-scale investments thanks to robust economies and modern infrastructure, while nations with weaker economies or outdated networks, particularly in Eastern Europe, struggle to develop ambitious projects. These disparities highlight the need for European coordination and solidarity tools such as the Just Transition Fund, which aims to bridge the gap between advanced states and those facing greater difficulties (Fernandez, 2018). Policies like the European Green Deal and the REPowerEU plan were designed specifically to encourage investments in large-scale projects, promoting collaboration between member states and the private sector. Projects of Common Interest (PCIs) serve as successful examples of this strategy, enabling the optimization of resources and infrastructure while reducing overall costs.

A striking example is the "North Sea Wind Power Hub," an innovative project that involves building an energy hub in the North Sea connected to offshore wind farms, significantly reducing construction and management costs and making energy more competitive. Another case is the "Viking Link", a submarine interconnection between the United Kingdom and Denmark that enhances energy security by sharing renewable energy and leveraging economies of scale in grid management. In the solar sector, initiatives such as those funded by the "Horizon 2020" project in Spain and Portugal demonstrate how increasing installed capacity can lower unit costs and accelerate the transition to a low-carbon economy.

Economies of scale are not limited to physical infrastructure but also extend to the technological and financial sectors. Large-scale production of high-capacity batteries, crucial for stabilizing renewable energy, is beginning to significantly reduce costs, as evidenced by Tesla's gigafactory in Germany. The green hydrogen sector also benefits from this approach, with innovative technologies improving efficiency and making hydrogen an increasingly accessible energy source. However, economies of scale also carry risks, such as the concentration of economic power in the hands of a few large multinational corporations, which can reduce competition and create barriers to entry for small businesses, particularly in the renewable energy market.

The future of Europe's energy transition depends on the ability to integrate national policies with common strategies, such as those outlined in the "Fit for 55" package and the REPowerEU plan. These initiatives aim to strengthen interconnections between national electricity grids, promote the distribution of renewable energy, and reduce reliance on fossil fuels. The offshore wind sector represents one of the key investment areas, with the goal of making it a primary energy source by 2050. However, it is crucial to balance large-scale investments with the development of local solutions, such as energy communities, which provide resilience and sustainability on a smaller scale but face challenges in integrating with large energy systems. In summary, economies of scale are essential for improving efficiency and reducing costs in the energy sector, particularly in the context of renewables. However, the success of Europe's energy transition will depend on the ability to combine large-scale strategic investments with localized and decentralized approaches, fostering innovation, integration, and sustainability across the continent (Sgaravatti et al., 2024).

Towards an Integrated European Energy Transition: Opportunities and Challenges

The European Union's energy transition represents not only a response to climate and geopolitical challenges but also an opportunity to build a more resilient and sustainable economic model. The current energy context is marked by geopolitical tensions, such as the crisis stemming from the war in Ukraine, which has revealed the EU's vulnerability due to its dependence on fossil fuel imports. However, the push towards renewable energy sources and innovative technologies has opened up new development possibilities for the continent.

Renewable energies have achieved significant milestones over the past decade, but their full potential remains partially untapped. With a record growth of 56 GW of new solar capacity installed in 2023 and an increase in the share of electricity generated from renewable sources to 39% of the European electricity mix, the EU has demonstrated that a rapid transition is possible. However, the need to address energy-intensive sectors such as heavy industry and transport underscores the urgency of further investing in modern and interconnected infrastructure. The simplification of permitting processes and investment plans exceeding €584 billion are crucial steps to enhance electrical grids and improve the efficiency of the energy market.

A crucial aspect is represented by the diversification of energy sources. In addition to the rapid development of solar and wind power, the EU has made significant progress in expanding interconnections among member states, increasing the resilience of the European energy system. The goal of achieving a 15% level of interconnection by 2030 will be fundamental to ensuring uniform energy distribution and reducing risks associated with regional production fluctuations.

Hydrogen as a Strategic Solution

Among emerging solutions, hydrogen occupies a central position in the European strategy. Considered a versatile energy carrier, it offers a concrete response to the challenges of decarbonization and energy security. The European plan aims to produce and import 10 million tons of green hydrogen each by 2030, with the goal of decarbonizing hard-to-electrify sectors such as steelmaking and maritime transport. The creation of the European Hydrogen Backbone, a dedicated infrastructure network for hydrogen transport and storage, is a key element in accelerating its large-scale adoption.

Hydrogen is not just an energy carrier but a catalyst for industrial innovations. In heavy sectors such as steel, ammonia, and methanol production, green hydrogen offers a solution to drastically reduce CO_2 emissions. Furthermore, in the transport sector, it is particularly promising for heavy vehicles, trains, and ships, where electric batteries are not a practical solution. Its ability to integrate with renewable energy production allows it to store excess energy, thus overcoming seasonal and intermittent challenges associated with solar and wind power.

The European hydrogen strategy is based on a phased roadmap. As of 2024, the focus is on reducing emissions from existing hydrogen use, such as in the chemical sector, and promoting new applications. The goal is to install at least 6 GW of electrolyzers to produce one million tons of renewable hydrogen annually. Between 2024 and 2030, the strategy aims for broader integration into key sectors like steel, transport, and energy storage, targeting 40 GW of electrolyzers and ten million tons of hydrogen production. By 2050, green hydrogen is expected to play a critical role in hard-to-decarbonize sectors, ensuring the completion of the energy transition.

Innovations in hydrogen storage and distribution are vital to its adoption. The European Hydrogen Backbone leverages existing natural gas pipelines and integrates new infrastructure to connect production hubs with consumption centers. Storage solutions, such as salt caverns, provide large-scale, cost-effective options for balancing supply and demand. Additionally, the development of "Hydrogen Valleys" exemplifies the EU's commitment to regional production hubs that integrate production, storage, and end-use applications.

Despite its potential, the widespread adoption of green hydrogen faces challenges. Over 95% of current hydrogen production relies on fossil fuels, resulting in high CO_2 emissions. The cost of producing green hydrogen through electrolysis remains higher than conventional methods, but ongoing innovations and investments are driving down costs. Forecasts suggest that green hydrogen could achieve economic competitiveness by 2030, supported by targeted EU funding and harmonized regulatory frameworks to stimulate private sector participation (Marhold, 2023).

Technological Innovation and New Infrastructure Solutions

Emerging technologies, such as smart grids, artificial intelligence, and advanced energy storage systems, are transforming the European energy landscape. Smart grids, already adopted in countries like Germany and the Netherlands, optimize energy distribution and improve the management of demand fluctuations. In parallel, the use of advanced data analytics and artificial intelligence enables the prediction of consumption peaks and the optimization of resource utilization. These technologies not only enhance the efficiency of energy systems but also contribute to reducing operational costs and ensuring greater grid stability.

In the energy storage sector, innovative technologies such as flywheel systems and phase-change materials (PCM) are emerging as promising solutions. Their ability to store energy sustainably and with greater operational longevity represents a step forward in the efficient management of energy resources. Additionally, the development of new hydrogen storage technologies, such as salt cavern storage, provides a cost-effective solution for managing seasonal fluctuations in energy production.

Geopolitics and International Cooperation

The EU's energy transition has inevitable geopolitical implications. The need to diversify energy sources has strengthened international cooperation, as demonstrated by numerous agreements signed with the United States, Norway, and strategic countries for LNG and hydrogen imports. The European approach combines resilience, security, and competitiveness, but its implementation requires an unprecedented level of cooperation among Member States.

The European energy strategy cannot overlook the strengthening of relations with renewable energy-producing countries. Memoranda of understanding with North African countries, such as Morocco and Tunisia, for green hydrogen imports, are key elements in ensuring stable and competitive supplies. Moreover, the implementation of the Carbon Border Adjustment Mechanism (CBAM) provides a competitive advantage for European industries, protecting them from competition from countries with less stringent environmental standards.

Challenges and Opportunities for the Future

Despite progress, the path towards a complete energy transition is not without obstacles. Energy poverty, rising costs, and infrastructure limitations continue to pose significant barriers. The financial burden of the transition, requiring hundreds of billions of euros in the coming decade, highlights the need for a centralized financing strategy. High interest rates and economic pressures make access to capital more challenging, emphasizing the necessity of coordinated European-level investments in sustainable infrastructure, such as electric grids, hydrogen refueling stations, and carbon capture systems.

Political fragmentation remains a significant challenge. Diverging national policies and priorities often hinder the harmonization of strategies required for a unified European approach. Strengthening coordination mechanisms and fostering political consensus will be crucial to overcome these barriers and ensure equitable progress among member states. The National Energy and Climate Plans (NECPs) provide a framework for aligning national efforts with European objectives, but their implementation must be enhanced to address current inefficiencies and delays. Moreover, the transition's geopolitical implications necessitate a stronger focus on energy diplomacy. Ensuring secure and sustainable supplies of renewable energy resources from global partners will require strategic alliances and robust international agreements. At the same time, the EU must reduce dependency on imports of critical materials and foster domestic production capacities to enhance resilience.

The creation of new financial tools, such as a European hydrogen bank, can bridge the gap between high upfront costs and market demand for low-carbon technologies. Leveraging the European Central Bank and other institutions to facilitate green investments will provide the financial foundation needed for rapid scaling of renewable and clean energy solutions. Such measures also have the potential to spur economic growth, create jobs, and reduce vulnerabilities in global markets.

Social acceptance is another critical factor. The energy transition must be inclusive, addressing energy poverty and ensuring that the benefits are distributed equitably across all regions and socio-economic groups. Public engagement and transparent communication about the costs and benefits of the transition are essential to build trust and foster collective support for ambitious climate and energy goals.

The energy transition represents a unique opportunity for Europe to redefine its global role. With an integrated approach combining technological innovation, strategic investments, and international cooperation, the EU has the potential to become a world leader in combating climate change, promoting sustainable and inclusive economic growth. The key to success lies in overcoming political and social barriers, and building a consensus that unites European citizens around a common vision of a sustainable energy future.

Conclusion

The pursuit of European strategic autonomy in the energy sector is a complex challenge intertwining sustainability, security, and innovation. Recent events, such as the COVID-19 pandemic and the Russo-Ukrainian conflict, have highlighted the vulnerabilities of a system overly reliant on external energy sources and imported fossil fuels. These events have catalyzed changes in energy policies, accelerating the transition toward a diversified, resilient, and sustainable system based on the integration of renewable energy and technological innovation, such as green hydrogen and smart grids.

Initiatives like the European Green Deal and the REPowerEU plan mark significant steps toward a more secure and sustainable energy future. However, significant challenges remain. Disparities among member states in terms of infrastructure, financial capacity, and natural resources present critical obstacles. Addressing these issues requires a multi-level approach that balances climate ambitions with economic and social realism, reduces the fragmentation of national policies, and fosters greater integration of European energy markets.

The 2024 Draghi Report highlights the need to tackle these challenges through a combination of coordinated policies and concrete actions. In particular, the report emphasizes the importance of reducing the fragmentation of national policies, strengthening market integration, and improving cooperation among member states. It also underscores the crucial role of diversifying supply sources and building new global partnerships, with a focus on emerging economies in Africa and Asia, as well as on the United States. According to the report, these actions are indispensable for ensuring European energy security and supporting a fair and sustainable transition. Furthermore, it calls on Europe to combine internal resources with opportunities offered by emerging technologies to maximize efficiency and energy autonomy.

The future of Europe's energy sector will depend on its ability to integrate common strategies, targeted investments, and technological innovations within a flexible yet cohesive political framework. Solidarity mechanisms aimed at reducing internal disparities among member states and promoting strategic international partnerships will be essential. Only through a long-term vision that addresses geopolitical, economic, and climate challenges in a coordinated manner can Europe achieve energy autonomy and establish itself as a global leader in combating climate change.

In summary, Europe must adopt an integrated approach that combines internal resources, emerging technologies, and international relations to transform its vulnerabilities into opportunities. Such an energy model will not only ensure energy security and sustainability but also strengthen Europe's role as a paradigm of equitable and sustainable development for the rest of the world.

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