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Energy security in the transition to a green economy: challenges and strategies

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Abstract ;

Decarbonizing the energy sector improves public health, environment, and climate goals, but raises concerns about energy security due to reliance on renewable sources and vital minerals. Analyzing the green transition's effect on energy security—especially availability, affordability, and sustainability—highlights essential strategies. This transition introduces challenges like mineral dependence, supply variability, investment needs, regulatory alignment, and geopolitical risks. Key measures include diversifying technologies, strengthening infrastructure, ensuring market stability, and encouraging global cooperation. While conflicts between climate goals and energy security may exist, they can be resolved by developing adaptable security measures in a low-carbon framework, focusing on coordinated policies to lessen greenhouse gas emissions.
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1. *Introduction*

The ongoing transition towards a green economy is widely acknowledged as one of the major challenges of the twenty-first century, implying a systemic move from fossil fuels to greener energy sources. This shift raises concerns about energy security—a universal and enduring issue. According to Labandeira and Manzano, energy security is defined as the uninterrupted availability of energy sources at an affordable price . Consequently, it is important to assess the present energy security levels of Spanish energy vectors and technologies, as well as the implications of a decarbonisation pathway projected to 2050.

The dual process of decarbonisation and commitment to the UN Sustainable Development Goals continues to motivate public and private investment in renewable energy. An accelerated electrification process of the economy is being dated and semantically qualified as a "green transition" towards the generation and use of zero-carbon energy carriers. However, it is important to ensure that the structure of energy supply and the overall quality provided remain resilient enough to fulfil other energy security benchmarks, namely availability, affordability, and sustainability.

Research question: What are the main challenges to energy security in the transition to a green economy, and what strategies can be implemented to address them?

1. Conceptual framework

Energy security is the accessibility of supply and the resilience of infrastructure and system to diverse, evolving threats. The green transition aims for decarbonization of supply and end-use technologies and for economic, social, and environmental opportunities that build on decarbonization. The green transition frequently serves as a vehicle for resilience, where security, resilience, and reliability mean the same thing. The present analysis develops recommendations for sectors and systems in a decarbonized future. It examines the resilience of the system under diverse transmission configurations and the expected residual unserved and curtailed generation under contemporary arrangements. Deployment costs imply further trade-offs between energy security, climate, and economy that complement transitional technology considerations. The analysis also explores multi-pronged strategies comprising operational and architectural solutions for climate-modernized systems (A. Brown et al., 2011).

Resilience encompasses freedom from rapid, irreversible transitions that compromise the capacity to revisit critical decisions. It is jeopardized by key dependencies across low-carbon

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technologies. System layouts are evaluated on their ability to mitigate renewables-based electricity outages as investments in electricity backup, storage, and user flexibility alone fall short of requirements for intermittent resources with low capacity factors. The related theme of critical minerals appears alongside advanced systems that have yet to transition to market valuing the multidimensional nature of the secure supply concept (Li, 2012). The focus on security is emerging already for hydropower, advanced nuclear, and electricity applications.

2. Drivers of energy security in a green transition

Energy security has traditionally been a concept linked to security of fossil fuel supply in the determinants of supply. To assist further supply with additional domestic production capacities national energy security has moved towards reduced reliance on foreign sources to redress markets and develop renewable based energy sources. The focus is now on clear and coherent policy measures to diversify technological options. All countries can similarly reduce the proportion of fossil energy in their energy mix according to their specific circumstances. National energy security also encourages attention to domestic energy endowments and alternative indigenous energy technologies that decrease fuel reliance (Li, 2012).

2.1. Diversification of energy supply

Ongoing global efforts to achieve climate-neutral economies make energy security an increasingly salient policy issue. The Paris Agreement has enhanced momentum for a major transition from fossil fuels to renewable sources, yet energy insecurity remains a serious impediment to economic growth and human well-being. Investments in low-carbon technologies, energy efficiency, and renewable energy can be counterproductive unless energy-security implications are considered alongside decarbonization goals. Across multiple dimensions, climate-neutral systems will assume energy-security importance outside the fossil-fuel domain (Chalvatzis & Ioannidis, 2017)

2.2. Resilience of energy infrastructure

The resilience of energy infrastructure involves understanding social and technical aspects of energy systems in transition. Resilience can be conceptualized using two core attributes: diversity and connectivity. Diversity includes properties such as variety, balance, and disparity, while connectivity involves measures like path length, centrality, and modularity. Maintaining resilience is crucial for the transition to renewable and decentralized energy systems, ensuring that the system can withstand external and internal shocks and disruptions throughout the process. Both technical properties and social connections

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across different transition phases must be considered to support resilient energy infrastructure (R. Binder et al., 2017).

Energy management becomes more challenging with renewable integration, which is predominantly based on distributed sources, altering traditional roles and relations in the energy market. The large-scale deployment of building-integrated photovoltaic technology can transform consumers into prosumers who both produce and use energy. This changes the energy flow from a one-way radial flow, requiring system design and grid adaptations. Infrastructure is also influenced by transformations in the transportation sector, responsible for 15% of carbon dioxide emissions, and the building sector, which increases demand and peaks with urban density. Electrification of transport and integrated infrastructure for heating and cooling enable decarbonization but pose major operational challenges. Malfunctions can affect the entire grid, especially during extreme climate events. Energy storage at the domestic level, such as community-scale systems, mitigates demand fluctuations and boosts system resilience by enabling autonomous operation and facilitating distributed energy management (M Nik et al., 2020).

2.3. Market stability and affordability

The market stability and affordability of energy supply—primarily through reliability, decarbonization, and cost-effectiveness—depend on demand and price signaling, as well as on investments in a diversified energy portfolio (Egenhofer & Legge, 2001). The degree and pace of renewable energy investment must consider the capacity of technologies to meet demand and the level of technology needed to address intermittence, variability, and flexibility. In the absence of public action across multiple sectors and borders, significant investment and financial blocking points remain. Such investing efforts must also consider public concerns that may impact market strategy. (Verbruggen et al., 2015)

3. Challenges to energy security in the green economy

The green economy presents prominent challenges to energy security, given the central role of productive resources in ensuring socio-economic well-being and development options. Historic analyses of energy transitions suggest that the most advanced economies have used diverse energy technologies to support an ever-rising Living Standards Index . Electricity consumption—driven mainly by industrial activity—listed as a priority energy security goal. A better focus of critical resources related to electrification is still required to steer the transition towards a Green LSI Addressing this lack of focus naturally entails awareness of international development goals (Li, 2020). Ongoing conflicts under the disruptive narrative of

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the climate emergency generation expand the affordability constraints of national-level resource mobilization (Labandeira & Manzano, 2012).

Green-energy development is severely crippled by the risk concentration of critical minerals (e.g., lithium, cobalt, graphite, nickel) and interdependence across supply chains . Thus, the energy history of nations that would wish to emulate the European model draws heavily from the prism of nuclear energy, decommissioned plans in the European Union, and similar pre-decommissioned plans in the United States . Installation of renewable generation capacity has materially disappointed; renewables have lower capacity to deliver available resources than historically installed capacities of electrical plants. Low deliverability rates accompanied the Clean Dark Spread, leading its level structure towards higher profitability than contemporary precharged investments remain (Li, 2012). Policy dependence on delivering industry-wide supported experimental projects determines the industry pre-investment complicate systematic de-risk-matching needs on presumed Clean Renewal Technology across the European Union.

3.1. Dependence on critical minerals and supply chains

The green economy transition demands worldwide capacity of lithium-ion batteries of 4,147 GWh by 2030; to meet demand, strategic mineral supply chains need urgent action from state and industry. Worldwide, the quest for minerals is intensifying. The green economy transition requires urgent action to build mineral supply chains for lithium-ion batteries to meet projected demand of 4,147 GWh in 2030 (Kilinc-Ata et al., 2023). A clean-energy transition may decrease fossil fuels but sharply increase demand for non-fuel essential minerals, creating dependency and scarcity problems. In the EU, fourteen technologies are classified as critical for the low-carbon economy, ranging from minerals to metals, achieved through more than one hundred individual supply chains (T. Nassar et al., 2020). In the USA, the Department of Energy monitors twelve basic minerals such as cobalt, lithium, manganese, rare-earth elements, nickel, and silicon needed for electric vehicles, solar panels, and wind turbines.

Policies to mitigate supply risk should implement diversified sourcing, circular logistics, redundancy, or stockpiling (H. Ali et al., 2018). The EU proposal to classify ten mineral commodities—bauxite, copper, graphite, indium, lithium, magnesium, nickel, platinum-group metals, rare-earth elements, and silicon—as critical for clean energy illustrates the challenges ahead.

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3.2. Intermittency and variability of renewable resources

The reliance on renewable energy sources such as solar PV and wind raises important concerns related to intermittency and variability. Both technologies have very low capacity factors and large variations in power output, and feed-in tariffs may induce the use of unbalanced and inefficient generation systems due to their long-term contracts on commercially unviable energy technologies. This raises questions on how to move from a fossil fuel-dominated system to a green energy-dominated system without compromising energy security. The characteristics of renewables, enabling technologies, and approaches to enhance security need to be examined (Noussan et al., 2018).

Wind and solar energy are the most rapidly increasing sources of primary energy and fossil fuel substitutes, but their high intermittency generates technical concerns. The typical capacity factor of wind in China is 25 to 30 percent in most locations and considerably lower in Northwest China. In contrast, CSP with thermal storage and hydro power generation have capacity factors higher than 60 percent and are commercially available (Avramidis & Takis-Defteraios, 2021).

3.3. Investment and financing gaps

Globally, achieving national Long-term Climate Strategies (LTCS) to reach net-zero emissions by 2050 or soon thereafter in line with the Paris Agreement objectives will require an unprecedented scale-up of investment and financing in energy supply infrastructure (Simister et al., 2014). Moreover, many LTCS require associated energy efficiency investments to achieve deep demand-side cuts in final energy consumption and emissions by 2050. Early in the energy transition, risk-return profiles of energy supply projects are shifting under progressive substitution of fossil fuels with zero-carbon energy sources. Increasing risk premia attached to major fossil fuels are contrasting sharply with strong and still growing public sector demand for investment that can catalyse start-up of incremental capacity of next-generation energy technologies (Mahrous, 2016). This means that the affordability of financing for infrastructure supply that still relies on fossil fuel primary energy sources is deteriorating in many countries . Because public (treated broadly) expenditure continues to devote a larger proportion of overall capital expenditure to national infrastructure projects, the share of expenditure which is still earmarked for retrofitting existing fossil-fuel capacity (and/or for associated supply-chain development) is falling.

3.4. Policy coherence and regulatory risk

Climate policy integration across sectors and technologies is limited. Water and biodiversity policies rarely consider their interactions with low carbon energy transitions. Trade and other economic

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policies have an equally lack of coherence. The energy security risk associated with critical minerals, for example, remains largely divorced from broader industry, trade policy and development discussions. International policy co-ordination around mutually reinforcing objectives to stimulate demand for green technologies is similarly absent in line with broader economic development objectives.

Long timelines for reducing emissions of current energy systems and extensive technology portfolios raise regulatory risks in uncertain transition environments. The low-carbon transition scene continues to evolve; energy systems, supplier profiles, and crucial minerals will differ significantly over the next two to three decades. Long timelines for reducing emissions of current systems encourage commissioning state-of-the-art technologies with low operating costs and extended lifespans. Hasty deployment of assets without consideration for anticipated future shifts in line with transitional policy frameworks locks economies into carbon intensive lock-ins. Economic actors also seek to safeguard capital and dampen exposure to shifting technological paradigms, straddling pre- and post-transition systems, over the medium term. Although considerable literature documents the broad significance of transitional risk across capital-intensive sectors, few analytical frameworks isolate its specific dimensions and interdependencies in shaping energy security.

Transition arrangements may necessitate adjustments to international treaties, develop new treaties, or devise complementary arrangements either with partners at similar transition phases or specific to relevant regimes (Pastukhova & Westphal, 2020).

3.5. Geopolitical considerations

The geopolitical landscape is changing under the pressure of climate change and the urgency of adopting technologies that help decarbonise economies faster, in a world that is also engaged in a larger transition to a circular economy. Renewables-based energy systems require larger volumes and diversification of supply chains for critical minerals and metallic goods; they entail stronger interdependences across regions; and they reshape the temporalities governing the remuneration of technologies, the conversion of energy vectors and the long-term investment horizon.

The geopolitical implications of these changes are better understood when confined to the strategic commodities – rarely regarded as commodities throughout the 20th century – and regions. The understanding that the transition will require extremely diverse portfolios encompassing multiple sources of energy and migration pathways is further refined. Transition mineral commodities also

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express the decay of some energy flows with the prospective demise of oil and coal transitions, while geoenergy remains scarce, leading to increased hierarchisation of supply concerns, as do technologies replacing an energy vector such as solid to liquid energy carriers (Orhun Altiparmak, 2022).

4. Strategies to enhance energy security

Ensuring energy security during the transition to a green economy requires focusing on strategies aligned with existing decarbonization objectives and initiatives. Six strategies can enhance energy security in the transition to a green economy and parallel the deployment of clean energy technologies:

• Strategic diversification of supplies: Employing a mixed technology portfolio capable of supporting each other across regions could mitigate electricity shortages during the transition to a renewable energy system. Moreover, promoting diversity among energy supplies, including fuels, generation technologies, carriers, and delivery systems, further supports resilience. Consequently, redundant assets and backup options provide flexibility in the event of failure.

• Modernizing and enhancing grid flexibility: High shares of variable renewable energy impose greater demands on the electricity grid. Continuing to develop smart grids, expand the transmission network, improve demand-side management, enhance forecasting capabilities, and bolster regional interconnections facilitates the management, distribution, and integration of fluctuating renewable generation and electric loads.

• Establishing strategic reserves and complementary policy tools: Governments can support energy security through stockpiling technology-specific supplies and offering or co-developing hedging instruments, procurement strategies, and price governance initiatives.

• Aligning the electrification of end-use sectors with the decarbonization of supply: The pace of electrification should match the concurrent decarbonization of the industrial, transport, and building heating sectors. Synchronizing these transitions minimizes reliance on non-renewable resources. (Varghese & M Pai, 2016)

• Encouraging international cooperation and resilient value chains: The cross-border exchange of materials, technologies, and services strengthens the overall decarbonization and energy transition, while interconnections, common standards, joint procurement, and collaborative research on decarbonized fuels distribute shortfalls and reduce supply-chain vulnerabilities.

• Fostering domestic innovation, research, and capabilities: Supporting R&D by firms and research institutions, localizing supply chains where feasible, and facilitating

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technical training and workforce development cultivates greater expertise, creativity, and problem-solving capabilities in the energy domain (Ramagoma & Adendorff, 2016) .

4.1. Strategic diversification and diversification of technologies

A complementary approach to enhancing energy security in low-carbon systems is strategic diversification. Resilience is strengthened by employing a mix of energy technologies within a diversified supply portfolio, balancing local, regional, and international opportunities to maximize choices for demand. Reliable energy can be secured with back-up generation and storage. Portfolio breadth and regional specialization foster technology diversity and access to distinct supply sources, minimizing exposure to high-impact risks. Redundant assets, including back-up generation, help ensure a stable supply. The shift toward renewable energy, despite backup or storage, may increase susceptibility to disruptions. In electricity-reliant systems, flexibility to switch fuels can enhance security. Transitioning to low-carbon fuels allows continued technological advancement while cutting greenhouse gas emissions. Policies focused on diversification decrease the necessity for back-up generation and storage under low reliability. Regions can specialize in variable-renewable options with minimal backup, optimizing technology considerations and reducing operational-expenditure risks. (Udo Schroeder, 2008)

4.2. Grid modernization and flexibility

Enhancing grid modernization and flexibility promotes better electricity management and security in low-carbon systems, aligning with the green transition. Expanding income opportunities from energy flexibility stimulates investment in both generation capacity and demand-side technology, broadening the market's scope for flexibility solutions. Diversifying supply across the grid makes greater integration of renewables achievable and improves the overall security of the energy system. Prioritizing regulatory investments in renewable generation on-site, grid supply near critical demand, and energy flexibility solutions enables the transition.

Modernizing the grid to optimize electricity flows is a central element of the energy transition, enabling more efficient use of existing renewables while easing the management of the inevitable remaining fossil fuel supply. The next generation of digital technologies and smart service solutions spans the entire energy ecosystem, offering demand-side management (DSM) alternatives to conventional expansion of generation capacity and the construction of new assets (Avramidis & Takis-Defteraios, 2021).

In many markets, the shift from fossil to renewable energy, increasing electrification of end-uses, and the growing

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significance of DSM alternatives jointly demand a new focus on security of the grid. Establishing storage options and making energy-flexibility investments drastically reduce the volume of backup capacity required in a predominantly fossil fuel system, decreasing the criticality of fossil fuel supply.

4.3. Strategic reserves and policy instruments

In containment of future price surges and security risks associated with market concentration, the establishment of stockpiles or buffer reserves represents a potential line of defence. Public buffer stocks can be effective in addressing short-term calls for emergency procurement at reasonable prices, especially when private companies engage in speculation. They can also trigger a contingent or automatic release of supply in relation to extraordinary price hikes. Various procurement options merit consideration, such as a direct specification of temperature thresholds for residential heating or cooling at which triggering takes place.

Hedging instruments help deal with future price developments. Options an energy supplier purchases on electricity or on fossil fuels can buffer against unwanted future price increases. A government can offer such a (subsidised) facility on behalf of consumers. Procurement strategies complement hedging tools in striking longer-term deals, though uncertainty about future technologies may limit benefits. The combination of procurement mandates, hedging options, and supply-buffering rules can restrain acute price surges, threat perception, and excess risk premiums related to decarbonisation technologies.

Governance of price developments is especially relevant in loss-of-gas scenarios that cannot be prevented through supply diversification. Despite gradual market changes since unbundling, long-standing contracts still dominate the market. Price linkage to arbitrage levels for domestic resources or between interconnections constitutes the core principle in remaining arrangements. Exploration and production at an adequate pace are necessary before pricing rules can be amended. Prior establishment of an effective framework for a transition-free zero-gas system is key, along with ongoing investments to keep services attractive into multiple carbon-free avenues towards zooming in on remaining economic players. (Egenhofer & Legge, 2001)

4.4. International cooperation and resilient value chains

The path to a green economy requires international cooperation to ensure resilient supply chains that enhance energy security. Strong manufacturing bases together with industrial policies and standards provide the foundation for

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market development and global cooperation. Supply chain resilience underpins energy security and climate goals (Garlick, 2019). Cooperation to ensure clean energy objectives fosters trade and investment, lowers costs, and supports the development of regional and global markets. Such international approaches safeguard against interconnected geopolitical threats and ensure that energy security and net-zero commitments advance together (Egenhofer & Legge, 2001).

Cross-border interconnections, standards, and joint procurement agreements strengthen supply chain resilience, enhance energy security, and promote the green transition across countries. Interconnected grids and regulated wholesale electricity markets expand the share of renewables. Trading platforms and common standards stimulate low-carbon hydrogen and the circular economy. Joint technology and innovation programmes, workshops, and supply chain monitoring encourage coordination while strengthening regional and global value chains.

4.5. Innovation, research, and domestic capability building

Securing domestic capabilities across the green economy is essential to maintain the national supply of critical minerals, implement large-scale renewables, and foster local technological innovation and adoption of green solutions by businesses and households (R. Heard et al., 2022). The development of such capabilities can also be actively promoted through targeted funding and knowledge-sharing investments in technologies and end-use applications (P Tomain, 2012). Building these along global supply chains ensures continued access to strategic components necessary for the country to progress through the transition while retaining the opportunity to both partake in and adapt the technological approaches and solutions to specific domestic needs beyond individual sectors.

5. Policy design and implementation considerations

Effective policy design and implementation underpin energy security within a green transition. Supply- and governance-related conditions are necessary to materialize policy strategies that enhance energy security (Benson et al., 2023).

1. Regulatory certainty and investment signals Stable regulatory rules, transparent planning timelines, and predictable permitting processes send unambiguous investment signals and thus foster energy security in a green transition. Initiatives promoting energy security at a significant scale typically involve multiple years of lead time before rewards materialize, necessitating the early signalling of governmental intent. Such initiatives are especially critical when portfolios

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comprise technologies with uncertain timing.

2. Social equity and affordability Affordability and equitable access to energy services figure prominently in operational bills of rights across advanced economies. Energy conservation or efficiency measures, universal-service obligations, or social tariffs can reinforce access to electricity or essential-use fuels without impairing energy security. Timely reforms that ensure asset and product-market pricing align with energy system costs enable fresh infrastructure investments and demand-side services, thus enhancing security. Portfolio approaches can bolster this alignment across different fuels or energy carriers.

5.1. Regulatory certainty and investment signals

Since 2010, large international declines in oil and gas prices have created substantial economic benefits for most oil and gas importing countries. The present study shows that Saudi Arabia has been losing significant revenues and market shares to US, Russian, and other oil producers while prices remain low and the outlook for future prices remains subdued (Verbruggen et al., 2015). Thus, considerable uncertainties exist regarding the hydro-carbon-rich Kingdom's budget, foreign political activities and positions, and potential responses to temporary new oil and gas price spikes. The economies of several oil and gas exporting countries have been severely hit by the unexpected and dramatic drops of the otherwise internationally interconnected prices of crude oil and natural gas since the middle of 2014. In spite of a steady decline in their performance in the inter-media situation due to the drop of oil and gas prices, many OPEC countries can be expected to keep their current production rates relatively high.

The concern is that an even more substantial external change may eventually lead to dramatic fiyat and quantity bordertankärenı 없는 refinery, ban since the üst peder and second hanation levels have been achieved by several such countries. Although the long-standing Dutch Disease problem remains in certain quarters of the world, the general picture may be that most oil and gas-exporting countries have suffered major losses by a drastic decline in the international crude oil and natural prices, price stability is no longer guaranteed and oil-producing countries have been separated from gas suppliers.

5.2. Social equity and affordability

The socio-economic impacts of the energy transition lie within a historical and structural socio-spatial context that continues to shape contemporary development. The transition towards a low-carbon energy system is therefore contingent on seeking active pathways for

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a socially just transition to take effect based on wider social, economic and governance arrangements (E H Jenkins & Martiskainen, 2018). Undoubtedly, these proposed pathways influence the employment or emergence of socio-political and spatial strategies considered to deliver a socially just transition. Consequently, prior investigations focused both explicit proposed pathways towards a low-carbon system and how system transitions are socio-spatially contextualized and how policies are crafted. The socio-economic consequences of imminent energy system transitions addresses multiple interrelated geographies.

5.3. Risk management and contingency planning

Modern energy systems face threats from many interconnected events or trends that could disrupt supply, reduce the affordability of energy services, or increase the need to rely on imports. Such disruption events can be sudden and demand a rapid response (so-called 'acute' risks), or occur slowly over years or decades, and their effects may not reach the society or economy for years (or even decades) after their commencement (so-called 'slow-burn' risks). Tracking supply, infrastructure, technological, and climate change considerations can help to identify the risks associated with highly postponed, gradual trends.

Five dimensions of energy supply risk for the period 2000–2020 have been assessed (Avramidis & Takis-Defteraios, 2021). A first dimension focuses on the share of supply provided by electricity networks as well as other physical energy infrastructures and assets (including oil pipelines) using the share of electricity capacity provided by the top 20+% of generation units (which are more exposed to political interference, technical failures, and climate change events) and indicators reflecting pipeline infrastructure and diversity. A second dimension assesses climate evolution, linking average temperature over landmass with cumulative green-house gas emissions. A third dimension aims to capture high-frequency supply fluctuations in the system—indicative of short-term investments needs and investment conditions—via the share of climate-sensitive energy supply. A fourth dimension measures the exposure to geopolitical-driven supply disruptions, with focus on oil and gas pipelines while a final dimension tracks the degree of exposure to energy price volatility.

5.4. Monitoring, reporting, and governance

There is a growing consensus that effective monitoring and reporting systems are critical for enhancing the governance and accountability of all energy security strategies (Pastukhova & Westphal, 2020). They can help to build a common

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understanding of evolving energy security risk profiles and stakeholder needs along the green transition, thus easing policy trade-offs among the various dimensions of security, decarbonization, and affordability. To this end, mechanisms such as dashboards and independent reviews that communicate progress in a clear and transparent manner can foster stakeholder confidence and strengthen the government's accountability to citizens and to the private sector.

6. Case studies and empirical evidence

Countries are heavily investing to diversify mineral supply chains and develop local resource stocks. Governments seek to enhance supply resilience, reduce reliance on imports, and lower vulnerability to price fluctuations. The integration of variable renewables brings challenges with intermittency, necessitating significant investments in energy storage and balancing services for reliability. These costs must be measured against the benefits of green transition investments. Pathways to a green economy present opportunities for interconnected decarbonization strategies that mitigate impacts and boost energy security. Rising demand for critical metals and market concentration raise urgent resource security concerns. Meeting environmental goals requires a shift towards technologies using lower-impact materials.

6.1. Case study A: grid integration in high-renewables regions

Excessive generation from renewable electricity sources, exceeding local demand and far exceeding the limits of electricity trading with neighbouring regions, opens up the technical option to curtail generation but may also allow the use of other instruments designed to maintain security of supply.

This situation can arise when a high penetration of variable renewable energy production, in particular wind and solar either one of them or both together—for instance, in a sprint scenario where substantial additions of renewable supply are realised before reaching the wholesale objective set by the European Union of 2030—coincides with situations of low demand surge as extensively demonstrated by the implementation of the model in for example Central Europe. Regional supply and demand trajectories emerge together with incidentally covering redundant generation triggered by the 2050 net-zero drivers such as Synapse, BeSmart!, PEP, Free and ACRE yet implying very different service and forward manifestations of the security of supply operators' traditional and updated approaches, ranging from expected electricity imports and curtailments to alternatives that may come as an afterthought and that served typically as standby options under conventional configurations e.g., cross-sector coupling, stock relays, storage, active demand-side

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management measures (Sasse & Trutnevyte, 2020).

Generation curtailment is one approach that explicitly may be triggered on a day-ahead base typically driven by sustained low market price risks, however it is not an exclusive strategy nor a preferred option substitute hence the distribution of minimum residual generation available with respect to curtailment—assuming that curtailment enables meeting each modelling countries' individual secure supply requirement even if these are generically speculative—illustrates the need for the concurrent consideration also of all the mentioned alternatives under not only high renewables but in permanent need for aggregate candidate supplies at all times (Avramidis & Takis-Defteraios, 2021).

6.2. Case study B: mineral supply chain resilience

Low-emission technology requires abundant quantities of minerals such as cobalt, lithium, nickel, copper, rare earth elements, and others as a prerequisite for safe-mobility cars, batteries, construction, solar cells, and wind turbines. The ability of renewable energy technology to achieve zero carbon emissions for many countries hinges on securing the material supply to deploy the technology at a principle or practical scale (H. Ali et al., 2018).

Dependencies on these critical minerals exist due to a narrow domestic supply capacity coupled with heavy reliance on imports from small numbers of countries. For example, fifteen African states provided over 90% of cobalt in 2021 where the global market is totally dominated by two countries such as China remains high. Energy security concerns arise from mere increase in prices triggered by geopolitical events (Kilinc-Ata et al., 2023).

6.3. Case study C: regional cooperation frameworks

The green transition is an unprecedented challenge for the energy architecture in Southeast Europe (SEE). The existing institutional and infrastructural arrangements for energy cooperation and investment could be further improved, even though important steps have been taken in the past decade to reinforce regional cooperation in SEE and to accelerate the accession of Western Balkan economies to the European Union. Collaborative energy planning at the regional level could establish a long-term perspective for the development of national plans, support coordinated investments in infrastructure for energy transport, and align regulatory frameworks to ensure coherent decarbonisation strategies, even when the economies and the actual climatic and technological starting points differ widely.

Jandarov (2021) identified a regional approach to public financing of investments as a fundamental condition for

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the implementation of the green transition. Shared infrastructure and enhanced cross-border interconnections would facilitate renewable energy exchanges and hydropower cooperation; importantly, joint procurement of renewable capacity and joint agreements on the socalled "green eligibility" of projects under the EU's Green Taxonomy could limit excessive competition for public support and accelerate the deployment of critical solutions (Egenhofer et al., 2015).

Conclusion

The transition to a green economy implies a number of severe challenges for energy security. Dependence on critical minerals and supply chains, intermittency and variability of renewable resources, investment and financing gaps, policy coherence and regulatory risk, and geopolitical considerations all impose significant and complex constraints. Nevertheless, a range of strategies can enhance energy security, including strategic diversification of technologies, grid modernization and flexibility, establishment of strategic reserves and policy instruments, alignment of electrification with the decarbonization of end-use sectors, international cooperation and resilient value chains, and support for innovation, research, and domestic capability building.

The design and implementation of accompanying policies require careful attention to regulatory certainty and investment signals, social equity and affordability, risk management and contingency planning, and monitoring, reporting, and governance. Empirical evidence from various contexts underscores that energy security concerns are not incompatible with the green transition, provided that public authorities design and implement appropriate measures

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