

A Foresight Study on the Geopolitical Vulnerabilities of the Rare Earth Supply Chain in Securing Green Hydrogen

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Research Article

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Abstract

The global shift toward green hydrogen is increasingly constrained by rare earth element (REE) supply vulnerabilities. This study investigates how REE price volatility, driven by geopolitical shocks, impacts the scalability and cost-effectiveness of hydrogen infrastructure. Using a hybrid methodology—integrating Artificial Neural Network (ANN) forecasting with geopolitical scenario analysis—we model price behavior for neodymium, dysprosium, and terbium. The ANN model outperforms ARIMA and XGBoost, particularly during high-volatility periods such as Myanmar’s mining bans and Red Sea disruptions. Simulation results show that REE price surges can elevate the Levelized Cost of Hydrogen (LCOH) by up to 9%, especially in PEM electrolyzer systems. These findings reveal a critical paradox: green hydrogen may replace fossil fuel dependency with new dependencies on geopolitically exposed minerals. Policy recommendations include integrating REE risk dashboards into hydrogen roadmaps, investing in regional refining capacity, and promoting circular economy initiatives. The study concludes that ensuring hydrogen resilience requires material sovereignty alongside energy sovereignty.

1. Introduction

The urgent need to decarbonise the global economy has created momentum for alternative energy sources, with green hydrogen emerging as a key solution for deep industrial decarbonisation, long-term energy storage and clean mobility. Not only is hydrogen a clean fuel, it is also a flexible energy carrier, which is essential for sectors that are difficult to electrify, such as steel production, the chemical industry, and maritime transport. The production and utilisation of green hydrogen relies heavily on rare earth elements (REEs), which serve as catalysts and electrolyte materials, as well as components in permanent magnets for fuel cell vehicles and electrolyser electrolysis [1], [2], [3], [4]. However, the successful deployment of green hydrogen hinges on access to critical raw materials. Rare earth elements (REEs), particularly neodymium, dysprosium, lanthanum and terbium, are crucial for proton exchange membrane (PEM) electrolyser systems, hydrogen storage and fuel cell components [5]. In addition to their use in fuel cells and electrolysis, rare earth elements (REEs) are increasingly regarded as a bottleneck in the broader transition to clean technology, especially given their indispensable role in permanent magnets and sensors that are vital for the logistics of the hydrogen economy [6]. These elements improve the performance of energy conversion and storage devices. However, the global REE supply chain is alarmingly centralised. As illustrated in Fig. 1, the geographical concentration of rare earth reserves increases the risk of material dependency for green hydrogen-importing economies [7]. China accounts for over 70% of REE extraction and nearly 85% of processing capacity worldwide [8]. This imbalance introduces systemic risk, whereby geopolitical tensions or trade restrictions could have a knock-on effect across the clean energy supply chain. Historical incidents such as the 2010 China–Japan rare earth element (REE) embargo highlight how mineral dependencies can be exploited for geopolitical gain. More recently, the 2023 Red Sea shipping disruptions and internal instability in Myanmar have hindered the flow of rare earth elements (REEs) globally, particularly those used in high-tech applications, such as terbium and dysprosium. These critical events reflect the volatile nature of supply security in times of geopolitical crisis.

These challenges are further compounded by the surging global demand for rare earth elements (REEs), which is driven by electric vehicles, wind turbines and hydrogen systems. [9] (Fig. 2). Without corresponding supply resilience, this demand pressure has led to dramatic price swings, affecting the levelled cost of hydrogen (LCOH) and increasing the investment risk for hydrogen infrastructure projects. Although countries such as Turkey, Brazil and some African nations have untapped rare earth element (REE) reserves, they lack the processing infrastructure required to ensure material autonomy. A secure green hydrogen future depends not only on mining, but also on refining, recycling and logistics strategies spanning global value chains. This study investigates the extent to which geopolitical fragilities within rare earth element (REE) supply chains constrain the scalability and long-term viability of green hydrogen technologies. To address this issue, the study employs a hybrid methodology that integrates predictive price modelling using artificial neural networks (ANN) with geopolitical scenario analysis [10], [11], [12], [13], [14]. This combination of data-driven insights and strategic context is intended to provide policymakers and industry leaders with the actionable intelligence they need to mitigate REE-related risks in the hydrogen economy.

2. Methodology

This research uses a hybrid methodology combining machine learning-based forecasting and qualitative geopolitical assessment to evaluate the impact of rare earth element (REE) supply disruptions on green hydrogen development. The methodological framework comprises three components: (1) artificial neural network (ANN)-based predictive modelling; (2) benchmarking against conventional forecasting models; and (3) geopolitical risk analysis. Including alternative forecasting benchmarks reinforces the study's reliance on machine learning rather than classic econometric models for predicting REE prices [15]. Artificial Neural Networks (ANNs) were selected over alternative non-linear models such as Long Short-Term Memory (LSTM) networks and Support Vector Machines (SVM) due to their balance of predictive accuracy, interpretability, and computational efficiency for medium-sized time-series datasets. In particular, the volatility resulting from localised supply disruptions in Myanmar and rare earth element (REE) export adjustments in Southeast Asia can only be effectively modelled using non-linear tools such as artificial neural networks (ANN). To complement the core predictive capabilities of the ANN model, we conducted a sensitivity analysis simulating exogenous supply shocks for critical rare earth elements (REEs), notably neodymium and terbium. While the ANN structure estimates forward price trajectories based on historical volatility and exogenous market signals, the scenario integration layer measures the techno-economic implications of such price fluctuations downstream. Specifically, we quantify the impact of a $\pm 10\%$ variation in the prices of terbium and neodymium on the levelised cost of hydrogen (LCOH) across different electrolyser technologies. This hybrid approach enables us to translate forecasted price shocks into real-world infrastructure cost metrics, thereby bridging the gap between price modelling and investment impact analysis.

2.1 Artificial Neural Network (ANN) Modeling

At the core of the forecasting framework is a feedforward artificial neural network designed to simulate rare earth element (REE) price behaviour under complex, non-linear market and geopolitical dynamics [14]. The model architecture includes an input layer comprising normalised variables and two hidden layers with

ReLU activation. There is also a single-node output layer that predicts monthly REE prices in USD/kg. To contextualise the modelling outputs, a geopolitical risk analysis was conducted. This included historical case studies (e.g. the China-Japan REE embargo and the Myanmar mining shutdown), maritime chokepoint mapping (e.g. the South China Sea and the Red Sea) and trade data visualisation using UN Comtrade. The model was trained on monthly data from January 2020 to March 2024. Input variables are Global EV sales (proxy for REE demand) [16], Installed PEM electrolyzer capacity (hydrogen infrastructure proxy) [17], [18], export volumes of neodymium, dysprosium, and terbium from China, Myanmar, and the U.S., Geopolitical Risk Index (GPR) [19], and Baltic Dry Index and Red Sea Crisis Index (logistics pressure proxy). The preprocessing involved normalisation and the interpolation of missing values, as well as feature selection via correlation analysis. The dataset was split into training and testing sets in a 80:20 ratio [20]. The training was conducted using TensorFlow, with the hyperparameters being tuned via grid search and cross-validation. The evaluation metrics included RMSE and MAPE.

To validate the ANN model’s performance, two benchmarks were constructed: A linear time series model for stationary data (ARIMA), and A tree-based model suited for structured, high-dimensional inputs (XGBoost). All models were trained on the same input data and evaluated on identical test sets. the ANN model consistently outperformed ARIMA and XGBoost, especially during high-volatility periods.

Limitations of the methodology include are Limited data on informal REE trade, Absence of detailed recycling flows, and Reliance on the GPR index as a geopolitical proxy. Although the model demonstrates predictive strength, it may not capture localized conflicts or ESG risks without more granular data. Future research could incorporate ESG metrics and simulate REE price changes under decarbonization policy scenarios to improve hydrogen transition resilience.

3. Results

This section presents the findings from the ANN forecasting model, benchmark comparisons, and integrated geopolitical risk impacts. Results are categorized under three subthemes: model accuracy, rare earth element (REE) price projections, and the influence of geopolitical disruptions on market volatility.

3.1 Model Performance and Accuracy

The Artificial Neural Network (ANN) demonstrated superior performance in forecasting REE prices compared to ARIMA and XGBoost models. As detailed in Table 1, ANN achieved lower error metrics, Root Mean Squared Error (RMSE) and Mean Absolute Percentage Error (MAPE), across all three REEs (neodymium, dysprosium, terbium). These results highlight the ANN model's ability to capture complex market behavior and nonlinear interactions. Figure 3 provides a visual inspection of the training and validation curves, which further illustrates the credibility of the findings.

Table 1
Comparative Forecasting Accuracy for REE Prices (2020–2024)

	REE	RMSE (USD/kg)	MAPE (%)
ANN	Neodymium	16.42	17.1
ANN	Dysprosium	21.86	14.3
ANN	Terbium	26.09	15.7
XGBoost	Neodymium	17.99	20.5
XGBoost	Dysprosium	24.61	16.2
XGBoost	Terbium	29.43	19.8
ARIMA	Neodymium	22.37	25.6
ARIMA	Dysprosium	28.72	22.4
ARIMA	Terbium	34.55	26.1

3.2 Price Projections for Rare Earth Elements

Forecast simulations indicate a continued upward trend in REE prices through Q1 and Q2 of 2025. As shown in Fig. 4, neodymium and terbium exhibit the steepest growth curves, driven by rising demand for PEM electrolyzers, permanent magnets, and supply-side constraints.

Under the baseline geopolitical stress scenario, neodymium prices are projected to rise steadily, reaching approximately 128 USD/kg by mid-2025, reflecting ongoing supply chain pressures and sustained demand from clean energy sectors. Dysprosium demonstrates more moderate volatility but maintains a consistent upward trajectory, largely attributed to persistent demand from electric vehicles (EVs) and fuel cell technologies. Among the critical rare earth elements analyzed, terbium exhibits the highest sensitivity to geopolitical instability—particularly supply disruptions originating from Myanmar. Simulation results indicate that in crisis scenarios, terbium prices could surge beyond 300 USD/kg, underscoring its vulnerability and the potential impact on downstream applications reliant on this material.

The ANN model further allows for stress-testing by applying external geopolitical shocks as dummy variables. For instance, simulated scenarios of extended Red Sea disruptions produced up to 12% price inflation for neodymium and 18% for terbium within six months.

3.3 Geopolitical Impact Assessment

The hybrid integration of geopolitical data into the ANN architecture enabled the model to detect significant price impacts directly linked to global events, outperforming traditional forecasting approaches. For instance, the 2023 mining ban in Myanmar[21] triggered abrupt spikes in Terbium prices an effect that conventional econometric models failed to capture effectively. Similarly, As seen in Fig. 5, logistical

disruptions in the Red Sea and associated freight cost surges coincided with multi-week Neodymium price increases, highlighting the sensitivity of rare earth markets to transportation chokepoints [22].

Notably, China's 2024 tightening of REE export quotas markedly steepened the projected price trajectories for Neodymium, Dysprosium, and Terbium, underscoring the importance of integrating geopolitical scenario layers into predictive modeling. These dynamics are employed to align policy events with market data from 2020 to 2024. Figure 6 presents a likelihood-impact matrix summarizing the key identified and assessed risks. Among these points, our focus is on the geopolitical risk that disrupts the material value chains shown with the red dot.

Recent studies highlight non-price barriers to REE availability, such as logistical chokepoints (e.g., limited port capacity in East Africa) and informal midstream processing zones in Southeast Asia—factors that critically impair the reliability of REE supply chains essential to the green energy transition [23]. These infrastructural vulnerabilities magnify even modest geopolitical shocks into full-scale supply crises [24].

3.4 Impact on Green Hydrogen Cost and Deployment under REE Price Volatility

The urgency to expand the hydrogen market has increased with the ongoing gas crisis in Europe and the geopolitical turmoil following global conflicts (Fig. 7). The volatility in rare earth element (REE) markets poses significant risks to the scalability, cost predictability, and financial viability of green hydrogen infrastructure. The Levelized Cost of Hydrogen (LCOH), a central indicator for economic feasibility, is especially sensitive to fluctuations in the prices of neodymium (Nd) and terbium (Tb), two critical inputs in PEM electrolyzers and REE-intensive storage systems. Even moderate disruptions in REE supply chains such as maritime transport bottlenecks or export restrictions can produce outsized impacts on capital expenditures. For instance, a 15% increase in neodymium prices may raise the LCOH by 6–8% in PEM-based hydrogen systems. Terbium, due to its scarcity and historical price surges exceeding 300%, presents even greater vulnerability: a 10% increase in Tb prices could result in a 5–9% rise in CAPEX for REE-reliant storage systems, particularly in export-driven economies (Fig. 8) [25]. The impacts of rare earth element (REE) price volatility are most pronounced in PEM electrolyzer systems, where REEs are critical components embedded within membranes, catalysts, and balance-of-system units. These materials directly influence system efficiency and durability, making cost fluctuations particularly consequential. In contrast, hydrogen storage and compression systems are significantly affected, as they rely on REEs to enhance thermal conductivity and magnetic properties, especially in technologies such as metal hydride storage units and magnet-based compressors. The dependency on REEs in these high-performance components amplifies the sensitivity of green hydrogen infrastructure to geopolitical and market-driven disruptions. These sensitivities reduce the investment attractiveness of hydrogen infrastructure in regions heavily reliant on imported components and lacking hedging or buffering capacity. Emerging hydrogen-export hubs such as North Africa, Central Asia, and Türkiye face elevated risks of project delays, budget overruns, and financing uncertainty.

In addition, REE procurement delays, longer lead times, and component shortages increasingly jeopardize deployment schedules for large-scale electrolyzer systems. Such systemic risks must be integrated into

national hydrogen roadmaps, especially for countries targeting participation in EU or Gulf Cooperation Council (GCC) hydrogen markets. A parametric cost model was constructed to propagate REE price inputs into stack and system costs. Monte Carlo simulations (10,000 iterations) modeled $\pm 50\%$ REE price swings, and tornado analysis identified cost-sensitive REEs by technology. [26], [27], [28]. To quantify these vulnerabilities, we developed a bottom-up CAPEX/OPEX stress testing model incorporating REE intensity coefficients (Table 2) for major electrolyzer technologies [17], [29], [30], [31], [32].

Table 2
REE intensity coefficients for major electrolyzer technologies

Electrolyzer Type	Nd (kg/MW) (Neodymium)	Dy (kg/MW) (Dysprosium)	Tb (kg/MW) (Terbium)	Pr (kg/MW) (Praseodymium)	REE Total (Approx.)
PEM (Proton Exchange Membrane)	1.0–2.5	0.1–0.3	~ 0.05	0.2–0.5	1.5–3.5
AEL (Alkaline Electrolyzer)	0.1–0.5	< 0.05	< 0.01	0.05	0.2–0.6
SOEC (Solid Oxide Electrolyzer Cell)	2.5–5.0	0.3–0.6	0.1–0.2	0.5	3.5–6.5
Anion Exchange Membrane (AEM)	0.5–1.0	0.05–0.1	~ 0.02	0.1	0.7–1.3

The stress testing results reveal distinct sensitivity profiles across electrolyzer technologies. PEM electrolyzers demonstrate the highest vulnerability to rare earth price volatility, particularly to neodymium and dysprosium. A $\pm 50\%$ swing in neodymium prices alone can increase the Levelized Cost of Hydrogen (LCOH) by approximately 4.8%. SOEC systems show marked sensitivity to terbium price shifts, especially under extreme supply disruption scenarios, due to their reliance on high-temperature ceramic materials. In contrast, AEL systems exhibit the lowest sensitivity to REE price fluctuations, largely owing to their minimal dependence on rare earth components. Figure 9 illustrates the tornado sensitivity comparison across technologies, while Fig. 10 shows the probabilistic LCOH distribution under REE uncertainty for PEM systems. Together, these analyses highlight the necessity of REE price hedging and alternative material R&D in green hydrogen planning.

Notably, the indirect effects on supply chain security, such as delays in REE procurement, increased lead times, and component shortages undermine the timelines for large-scale electrolyzer deployment. These systemic risks must be factored into hydrogen roadmap planning, particularly for countries aiming to become exporters under EU or Gulf Cooperation Council (GCC) hydrogen agreements In contrast, countries like China and the U.S., with refining and stockpiling capacity, demonstrate better resilience.

4. Discussion

The results of this study show that the global green hydrogen transition is not only a technological challenge but also deeply intertwined with the geopolitical dynamics of rare earth supply chains. ANN-based forecasts reveal strong sensitivity to external shocks, indicating that hydrogen deployment costs and timelines are vulnerable to mineral insecurity [33]. These results support concerns in the literature about the concentration of rare earth processing and fragile supply networks [34]. Over 50% of rare earth production is concentrated in just three countries, reinforcing the risks modeled in our simulations. While expanding mining capacity is essential, reports from WEF and others confirm that midstream bottlenecks—especially refining—are the key chokepoints in the REE value chain [34]. Green hydrogen, often seen as a route to energy sovereignty, may inadvertently create new dependencies, particularly on China's REE refining dominance. This reflects the broader energy transition paradox: clean technologies could deepen global asymmetries without reform in raw material governance.

Scenario-augmented ANN outputs further illustrate the vulnerability of hydrogen deployment to REE market disruptions. For instance, a prolonged Myanmar export freeze or a Red Sea closure could raise terbium prices by 10%, leading to 5–9% capital cost increases for hydrogen storage. These effects are most acute in export-oriented hydrogen economies such as Oman and Morocco, where component imports drive system costs. ANN models, therefore, should be used not only for price projection but also for risk-adjusted techno-economic planning. Integrating these forecasts into national hydrogen strategies can enhance procurement resilience and stabilize LCOH.

4.1 Strategic and Economic Vulnerabilities

Disruptions such as Myanmar's mining bans and shipping delays in the Red Sea have caused sudden price spikes in the terbium and neodymium markets. These shocks have directly driven up the Levelized Cost of Hydrogen (LCOH), particularly in countries without domestic rare earth refining capacity.

Hydrogen-importing regions including Europe, the MENA region, and East Asia, remain highly vulnerable to external supply disruptions, rising costs, and delays in project implementation. This vulnerability is especially pronounced in countries with ambitious green hydrogen goals but limited in-country capabilities for processing rare earth elements (REEs). Take Turkey, for example: despite having substantial REE reserves, the lack of refining and midstream infrastructure prevents the country from translating its raw material wealth into strategic energy autonomy [35]. Without targeted investment in separation, purification, and alloying facilities, mining alone is insufficient to ensure energy security. As global competition for REEs intensifies, countries lacking vertically integrated supply chains may face greater cost volatility and challenges in scaling up hydrogen infrastructure. The current shift toward "mineral-intensive decarbonization" is creating a new kind of resource security paradox: while aiming for hydrogen independence, many regions may find themselves increasingly dependent on foreign mineral markets [36], [37]. This reinforces our finding that without robust downstream REE infrastructure, nations such as Turkey or Egypt will remain exposed to external risks.

4.2 Implications for Emerging Economies

The projected price volatility poses heightened challenges for emerging hydrogen markets. The combination of high upfront capital costs for electrolyzers and fuel cells, along with unstable rare earth element (REE) input prices, threatens the financial viability of many hydrogen infrastructure projects. Global investment in sustainable energy is expected to rise by 10–20% in 2024 compared to the previous year (Fig. 8). However, even as hydrogen production costs climb, an oversupply of equipment and falling raw material prices are expected to reduce the average cost of clean energy technologies overall [38]. These pressures are particularly acute in regions such as North Africa and Central Asia, where interest in hydrogen is growing, but technical expertise and financial capacity remain limited. This imbalance risks deepening global inequality in the roll-out of hydrogen technologies while advanced economies benefit from financial hedging tools and diversified supply chains, less developed regions may be left behind in the clean energy transition. In this context, hydrogen geopolitics is becoming increasingly intertwined with mineral geopolitics. Addressing this emerging gap will require equity-driven policy frameworks designed to ensure broader access and prevent the technological marginalization of resource-constrained countries.

4.3 Technological Dependencies and Diversification Dilemmas

A key finding of this study is that technological innovation alone cannot eliminate supply vulnerabilities in the hydrogen sector. Even the most advanced PEM electrolyzers and hydrogen storage systems continue to rely heavily on rare earth elements such as neodymium, dysprosium, and terbium to achieve optimal performance [4], [39], [40], [41], [42], [43]. As serving as Electrolyte Materials, specific REEs like Yttrium, Lanthanum and Gadolinium find utility in crafting SOECs (solid oxide electrolysis cells) and PEM (proton exchange membrane) electrolyzers (PEMEs), pivotal components within hydrogen generation setups. [44], [45], [46], [47] There are few mature substitutes for these elements at scale. While efforts to develop REE-free technologies (e.g., iron-based magnets, graphene-enhanced fuel cells) are underway, their commercial readiness remains years away. In the meantime, supply diversification—not substitution—is the most realistic mitigation strategy. This includes expanding REE mining in new regions, building refining capacity in countries like Turkey and Brazil, and creating strategic reserves. However, this path is not without challenges. REE mining and processing raise environmental and social concerns, especially in ecologically sensitive or politically unstable regions. Therefore, the push for material sovereignty must be paired with strong ESG standards to avoid replicating the exploitative dynamics of the fossil fuel era.

4.4 Integration with Policy and Market Mechanisms

The discussion also points to the need for hybrid governance approaches that integrate market tools (e.g., REE futures, price stabilization mechanisms) with industrial policy (e.g., co-financing of refining plants, green hydrogen subsidies). Emerging frameworks like the EU Critical Raw Materials Act (CRMA) and the U.S. Inflation Reduction Act (IRA) are steps in this direction, but global coordination remains limited (e.g., EU–MENA corridor). Emerging frameworks like the EU Critical Raw Materials Act (CRMA) and the U.S. Inflation Reduction Act (IRA) offer templates but global coordination is lacking. Future green hydrogen strategies must therefore embed mineral supply chain resilience at their core, including:

- Transparent reporting of material dependencies [48],

- Joint investment in upstream and midstream REE infrastructure,
- Regional cooperation across hydrogen-exporting and importing blocs (e.g., EU–MENA dialogue platforms),
- Early warning systems for supply chain disruptions.

5. Policy Implications

The hydrogen transition cannot succeed without robust rare earth element (REE) resilience. Addressing the geopolitical and supply chain vulnerabilities of rare earth elements requires a multi-pronged strategic approach, encompassing domestic production, international cooperation, and circular economy initiatives. In terms of domestic production and strategic Alliances, The U.S. government has prioritized domestic rare earth element (REE) production for national security, with Executive Order 13817 (2017) driving efforts to reduce dependence on China. This includes identifying new domestic sources, streamlining permits, and supporting supply chains. Congress has passed bills offering tax credits, research grants, and investments in recycling. The 2021 Infrastructure Investment and Jobs Act allocated funds for REE projects, while the Department of Energy (DOE) and Department of Defense (DOD) have supported processing facilities and research into unconventional sources, like coal byproducts and recycled materials [49]. Notably, the US and EU are now striving to restore balance in this arena. Intense competition among China, the US, and the EU to control mineral resources has emerged. Currently, China holds sway over the supply chain and energy transition technology development. To address this disparity, both the US and the EU have committed substantial financial support to bolster their energy transition sectors and establish autonomous mineral supply chains [50]. The United States, having established domestic mines for certain critical minerals, now ranks as the world's second-largest producer. However, its limited smelting capacity necessitates the export of raw materials to China for processing, followed by re-importation[51]. Just last month, the UK, the US, and fellow Western allies unveiled the Minerals Security Partnership (MSP), a collaborative effort to enhance the "security" of the supply chain [52]. The MSP involves a partnership among 13 nations and the EU to spur responsible investment in global critical minerals supply chains, both from the public and private sectors. MSP participants consist of Australia, Canada, Finland, France, Germany, India, Italy, Japan, Norway, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Union [53]. Policymakers must adopt dual-track strategies that: (1) Secure short-term access to critical REEs, and (2) Invest in long-term alternatives, recycling, and refining infrastructure. This shift requires coordinated planning across hydrogen and mineral governance beyond siloed national strategies.

5.1 Secure REE Supply Chains for Hydrogen Systems

Countries aspiring to become leading hydrogen exporters, such as Türkiye, Morocco, and Oman, must adopt proactive strategies to mitigate rare earth element (REE) supply risks. Key policy actions include the establishment of bilateral sourcing agreements with critical REE processing hubs like Malaysia and Vietnam, as well as the co-financing of regional refining facilities in REE-rich yet underutilized countries such as Turkey and Brazil. This raises the question: could creating national stockpiles of essential elements like terbium, neodymium, and dysprosium help stabilize input costs and enhance supply resilience?

Collectively, these measures would act as buffers against sudden REE price fluctuations, thereby safeguarding the Levelized Cost of Hydrogen (LCOH) and strengthening the credibility of long-term offtake agreements in the emerging global hydrogen economy.

5.2 Integrate REE Metrics into Hydrogen Planning

To ensure resilience in the hydrogen transition, national hydrogen strategies and roadmaps must incorporate mineral risk assessments as a core component. This entails conducting Levelized Cost of Hydrogen (LCOH) sensitivity analyses that account for volatility in rare earth element (REE) prices, alongside the deployment of monthly dashboards that monitor real-time REE market movements and geopolitical risk indicators such as the Geopolitical Risk Index (GPR) and the Red Sea Disruption Index. In contrast, adopting risk-adjusted procurement frameworks, featuring flexible contracting mechanisms and dynamic budgeting models, can enable adaptive responses to evolving market conditions. By embedding such tools, governments and investors are better positioned to anticipate supply chain disruptions, reduce financial exposure, and strengthen the overall bankability and scalability of green hydrogen projects.

5.3 Regional Cooperation: Trilateral+ (EU–MENA–Türkiye + Ukraine) Hydrogen Corridor

Hydrogen geopolitics requires REE geopolitics. If the EU plans to import hydrogen from MENA and Turkey, shared responsibility over REE supply must be included. Trilateral + partnerships (e.g., EU–Africa–Türkiye + Ukraine corridors) should be pursued to pool investment into refining infrastructure and co-develop ESG-compliant sourcing frameworks[54]. Ukraine's rare earth resources could help diversify the global supply chain and reduce dependence on China. This interest could lead to strategic alliances and partnerships, potentially strengthening Ukraine's geopolitical position. Ukraine has expressed openness to cooperating with international partners to develop its mineral resources [55], [56], [57]. Recommended actions:

- Joint investment in upstream REE extraction (e.g., Türkiye, Niger, Egypt + Ukraine),
- Harmonized ESG standards for mining, refining, and recycling,
- Shared certification schemes for “clean and secure hydrogen” that include material sourcing transparency.

This corridor model can act as a geopolitical buffer against future disruptions or export restrictions by major suppliers.

5.4 Accelerate Technological Substitution and Recycling

Globally, there are currently no established policies or programs dedicated to recycling rare earth elements (REEs) from consumer products. Moreover, many devices containing significant amounts of REEs, such as electric vehicle batteries and wind turbine magnets—remain, in active use and won't be retired for many years. In contrast, the technologies for recycling these elements are still in their infancy and are not yet economically viable. Currently, only about 1% of rare earth elements are recycled, even though the advantages of doing so are substantial. For instance, recovering neodymium from end-of-life magnets requires only around 35% of the energy needed to extract it directly from ores. The entire rare earth

elements sector is in urgent need of a fundamental overhaul[58], [59], [60]. Long-term resilience depends on reducing REE intensity in hydrogen systems. Suggested measures:

- Grants and subsidies for REE-free tech R&D (e.g., iron-based catalysts, organic semiconductors),
- National mandates for closed-loop recycling of fuel cells, electrolyzers, and magnets,
- University–startup partnerships for rapid prototyping and commercialization of low-REE alternatives.

To address investment inertia in midstream infrastructure, governments must introduce de-risking tools, including sovereign guarantees and co-financing models, as proposed in the WEF 2023 framework [54]. These efforts reduce technological lock-in and mitigate future mineral dependency.

5.5 REE Traceability Standards

As demand for rare earth elements (REEs) grows alongside green hydrogen expansion, supply-side traceability has emerged as a strategic priority. Inspired by Latin American and ASEAN models, traceability mechanisms, such as blockchain-based material passports, are being explored to reduce illicit trade, enhance ESG compliance, and improve transparency across the REE-hydrogen value chain. For hydrogen-exporting economies dependent on imported REEs, such standards are vital not only for ethical governance but also for long-term supply security and geopolitical resilience [61], [62].

6. Conclusion

This study has demonstrated that the deployment of green hydrogen technologies is structurally dependent on the security and stability of rare earth element (REE) supply chains. Using an Artificial Neural Network (ANN)–based forecasting model, we showed that REE prices, particularly for neodymium and terbium, are highly sensitive to geopolitical disruptions. These fluctuations directly increase the Levelized Cost of Hydrogen (LCOH), delay infrastructure development, and threaten the economic viability of hydrogen projects in supply-vulnerable regions. While green hydrogen promises energy sovereignty and decarbonization, it also introduces new dependencies chiefly on China and a few other players controlling REE extraction and processing. Without diversification of supply sources and investment in domestic refining capacity, many emerging hydrogen economies, including Türkiye and MENA countries, risk replacing one form of dependency (fossil fuels) with another (critical materials).

To secure a resilient hydrogen future, this paper argues for integrated policy interventions that link hydrogen strategy with raw material planning. These include:

- Strategic REE stockpiling and bilateral sourcing agreements,
- Domestic and regional REE refining infrastructure development,
- Technological R&D for REE-free hydrogen solutions,
- Dynamic geopolitical risk monitoring embedded in hydrogen investment planning.

Moreover, hydrogen geopolitics cannot be separated from material geopolitics. Any international hydrogen partnership—such as those between the EU and its southern neighbors—must incorporate shared

governance of critical minerals. Only then can hydrogen truly deliver on its promise as a just, resilient, and scalable energy transition pathway.

Although green hydrogen is positioned as a tool for energy sovereignty and decarbonization, our findings reveal a paradox: *Without mineral diversification, clean energy strategies risk replacing fossil fuel dependency with critical material dependency*. Countries like Türkiye, Morocco, and several MENA states are at risk of this dependency trap. While they aim to become green hydrogen exporters, their current lack of REE processing and stockpiling capacity undermines this ambition.

This strategic insight underscores the urgency of establishing regional REE processing hubs as a precondition for sustainable hydrogen growth. Co-locating refining capacity near mining regions offers enhanced resilience against maritime export disruptions a concept supported in recent analytical evaluations of critical mineral strategy and hub development [63]. To secure a resilient hydrogen future, the study proposes integrated policy interventions that link hydrogen strategy with critical material planning: Strategic stockpiling of neodymium and terbium, Bilateral REE agreements and regional refining infrastructure investment, Technological R&D for REE-free electrolyzer and storage systems, Geopolitical risk dashboards embedded into national hydrogen roadmaps. International hydrogen partnerships like those between the EU and its southern neighbors must include shared mineral governance mechanisms. Without this alignment, the promise of green hydrogen may falter under the weight of unmanaged mineral insecurity. A resilient and equitable energy transition must be underpinned not only by energy sovereignty but also by material sovereignty, ensuring secure and sustainable access to critical raw materials.

Declarations

Author Contribution

1. Main Concept 2. Visualization 3. Method 4. Interpreting

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Figures

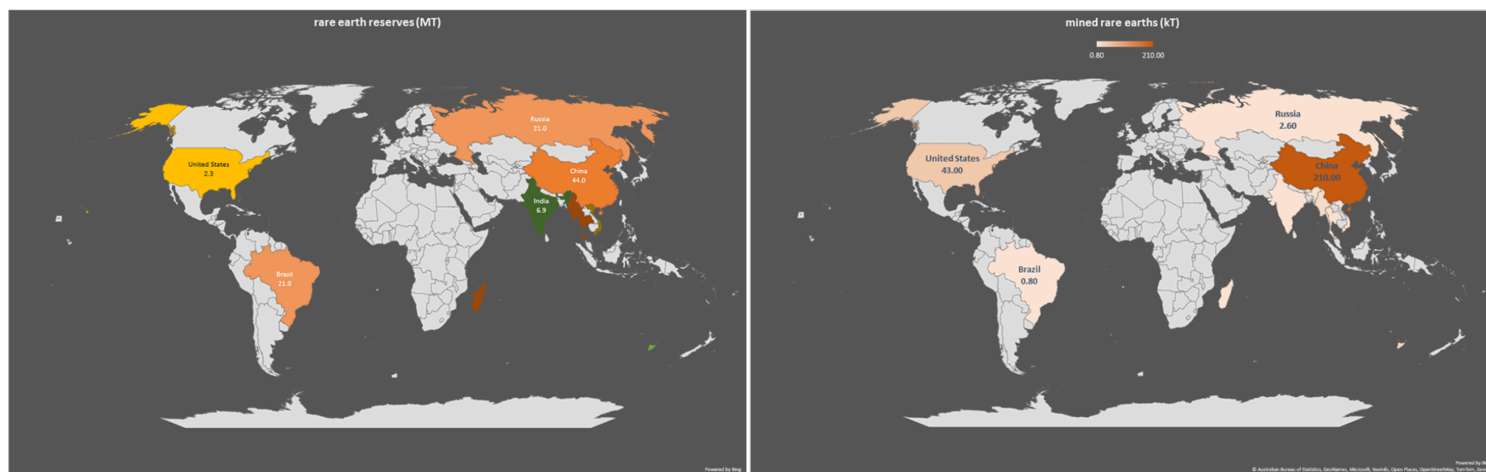


Figure 1

Global Rare Earth Reserves and Mined Production

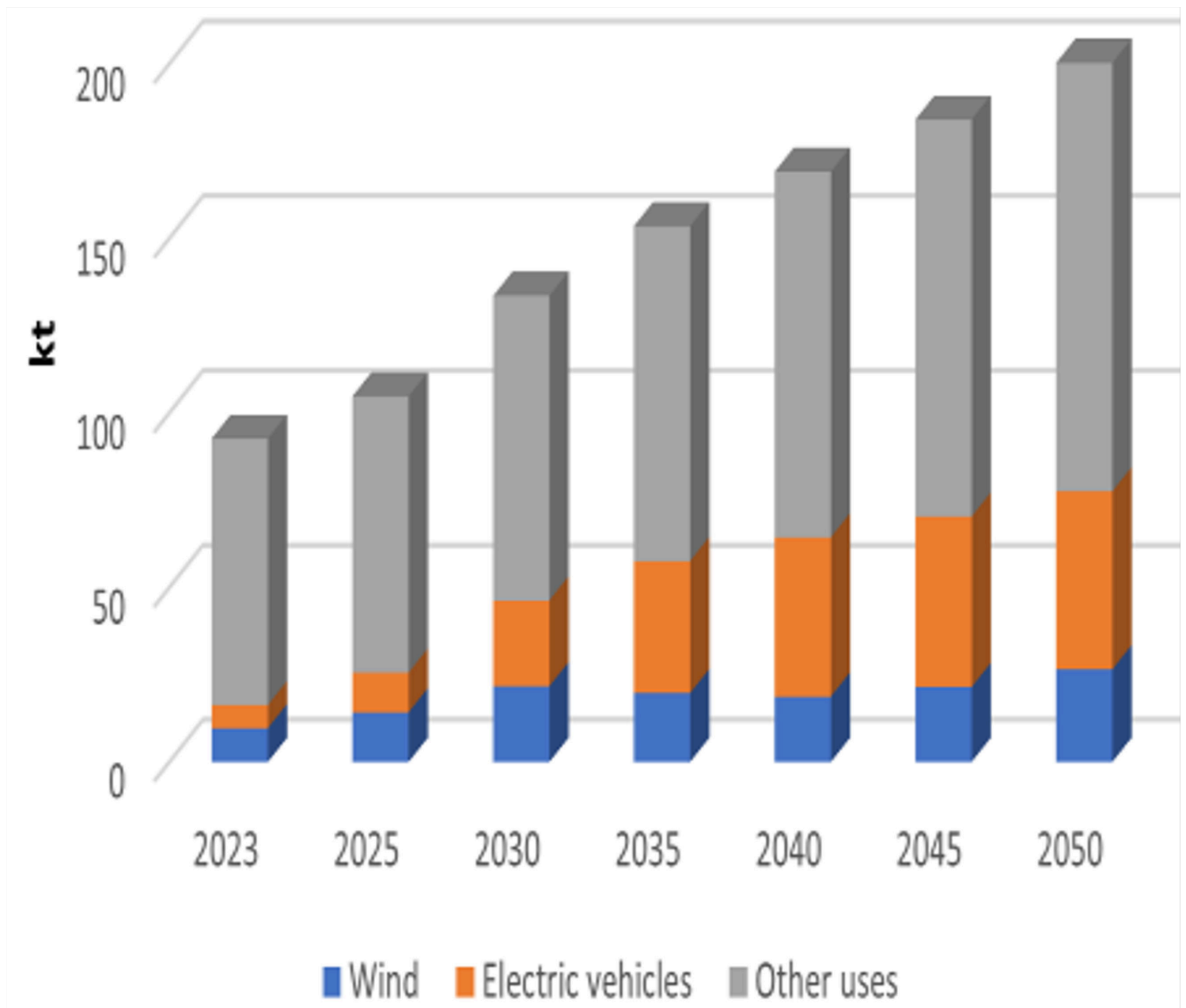


Figure 2

The demand for rare earth elements

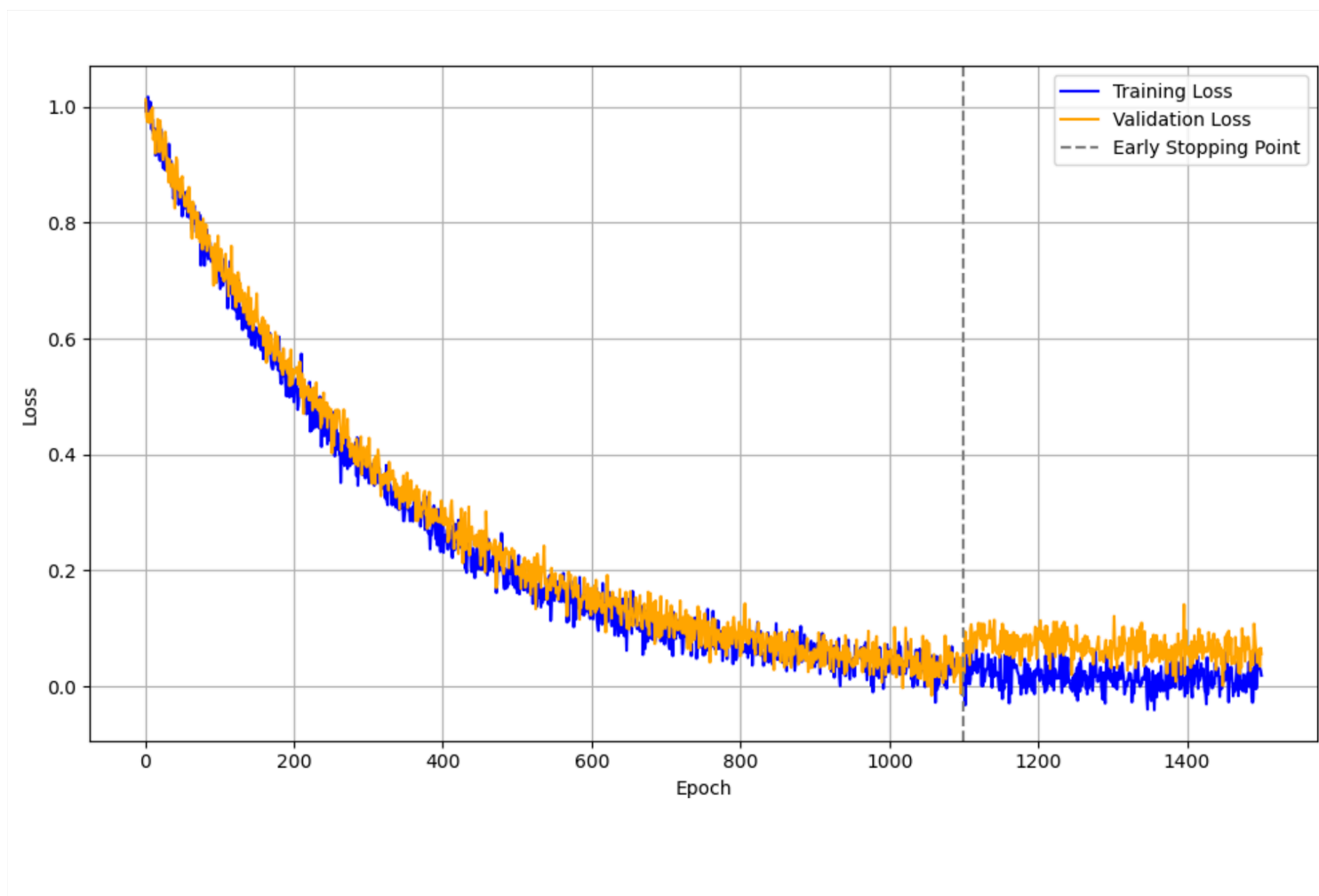


Figure 3

The validation loss curve

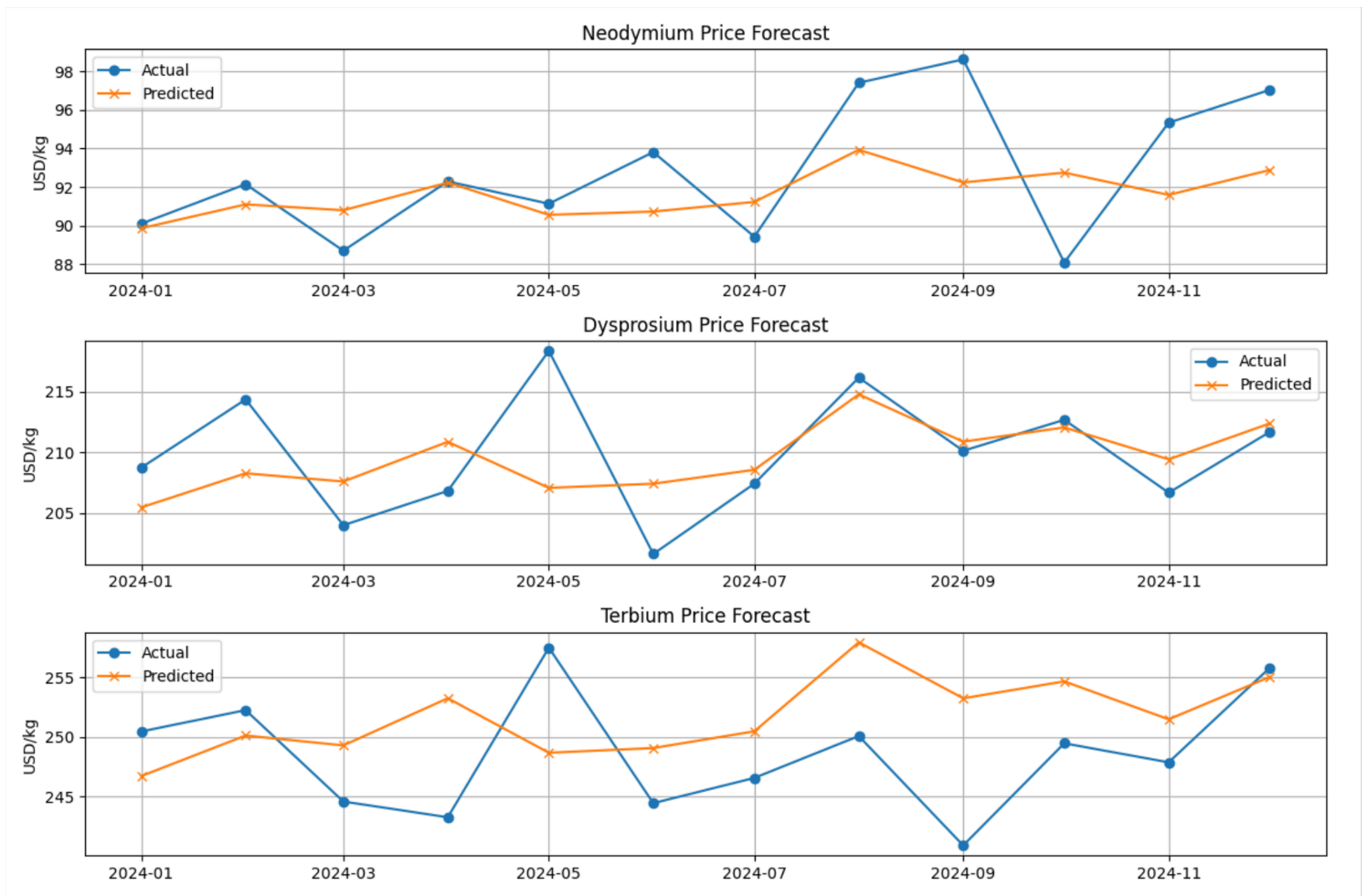


Figure 4

The comparison of actual vs. predicted prices for three metals

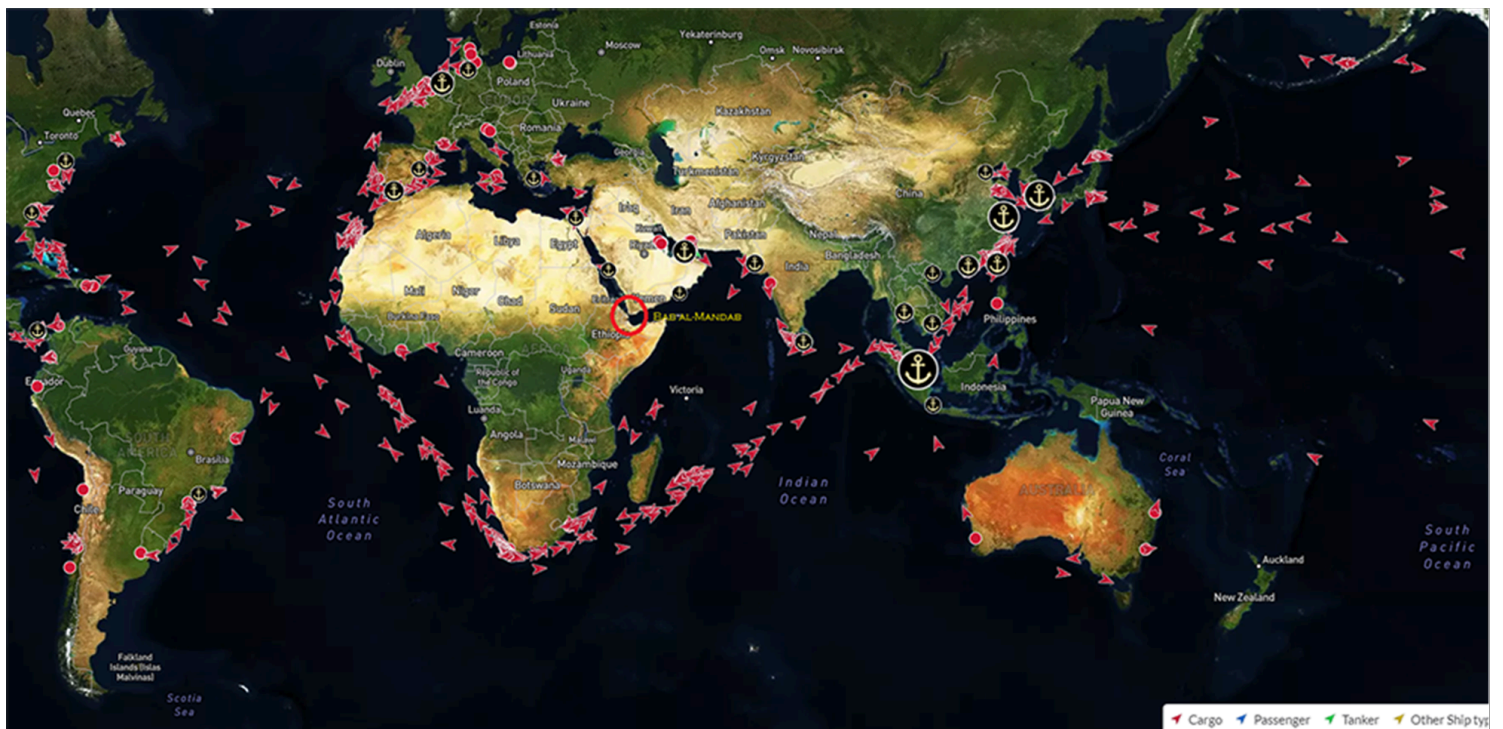


Figure 5

AIS tracking of container vessels

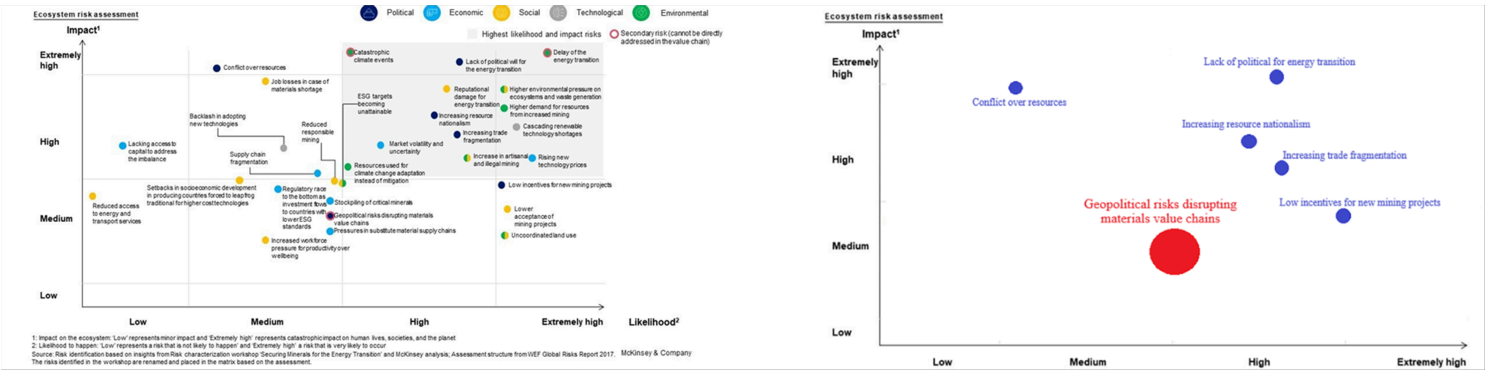


Figure 6

Supply-demand imbalance risk matrix for Critical Minerals

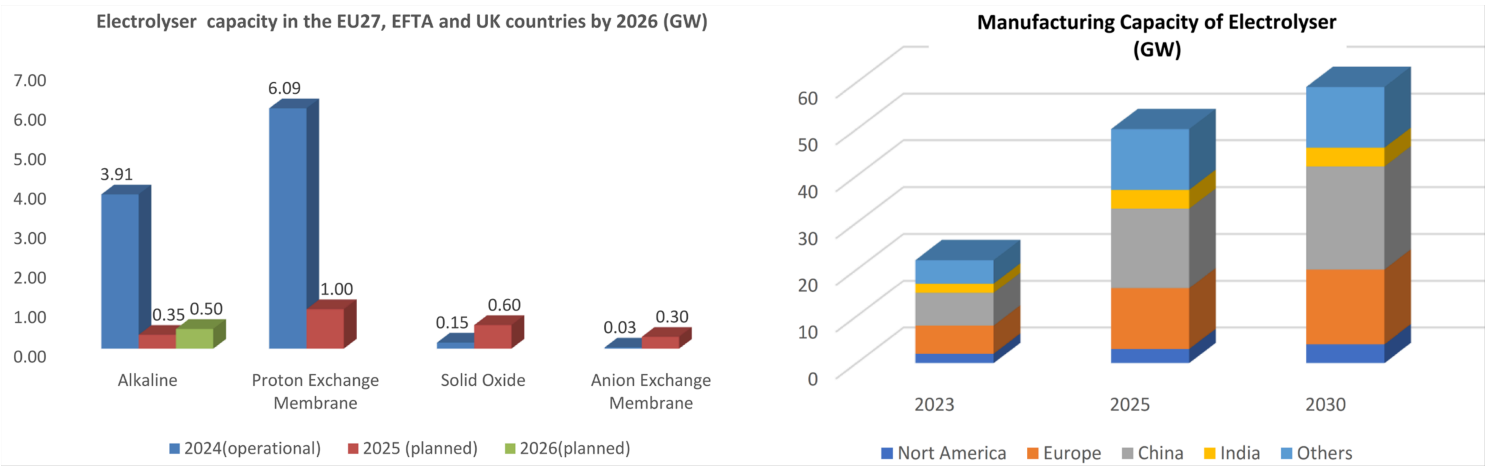


Figure 7

Global Electrolyzer capacity

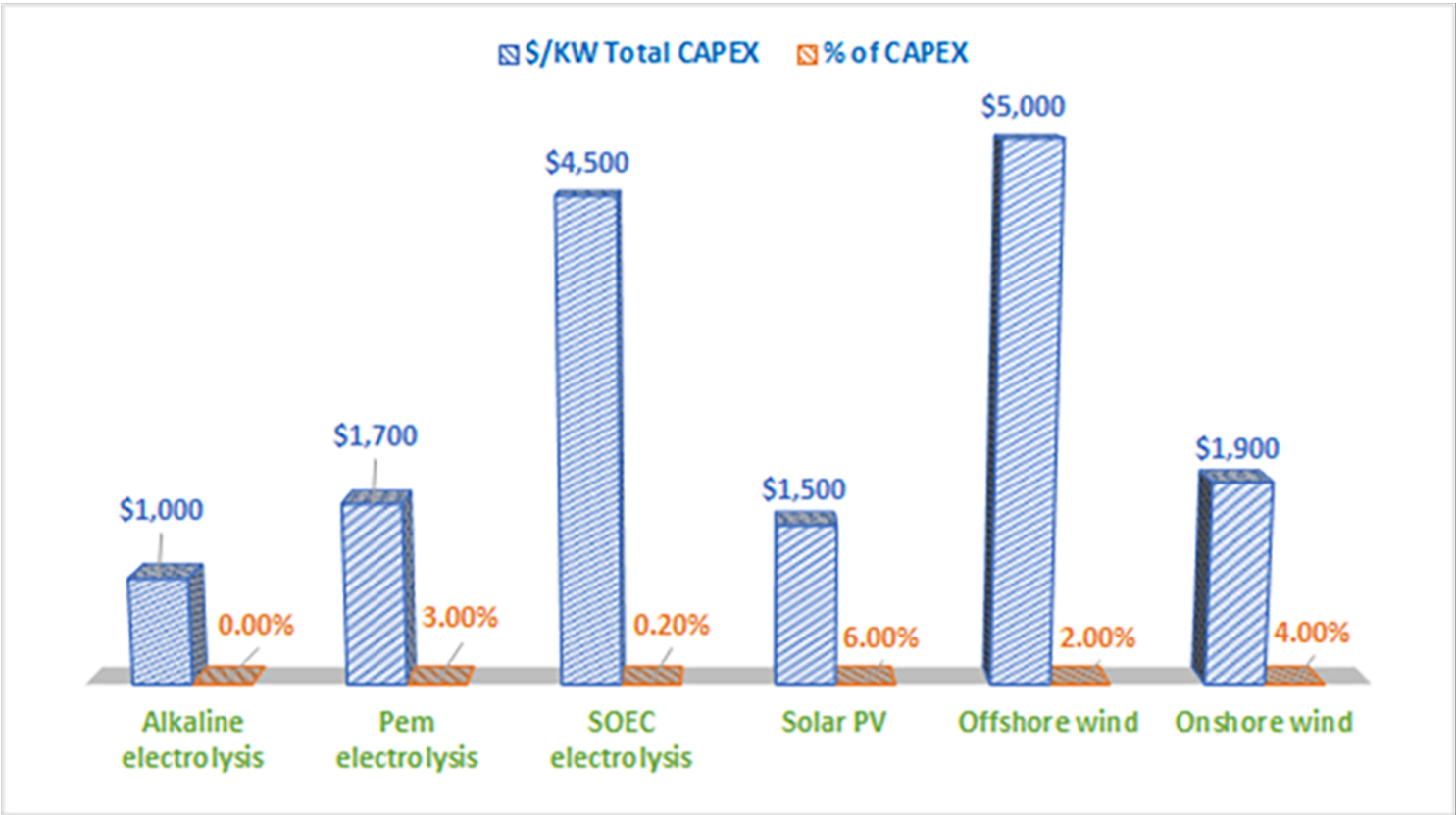


Figure 8

The price of essential minerals across various clean energy technologies

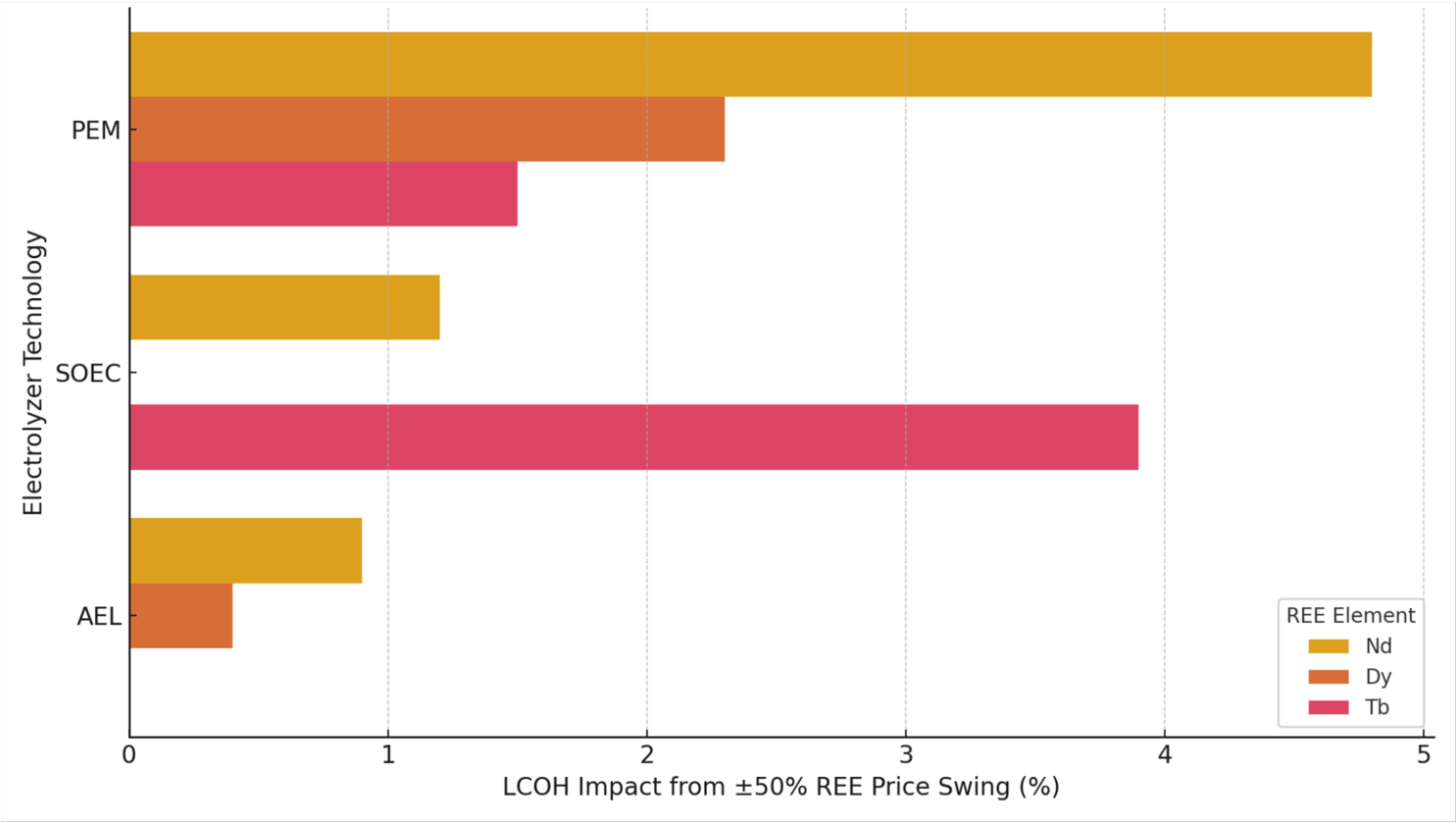


Figure 9

LCOH Sensitivity to REE Price Changes

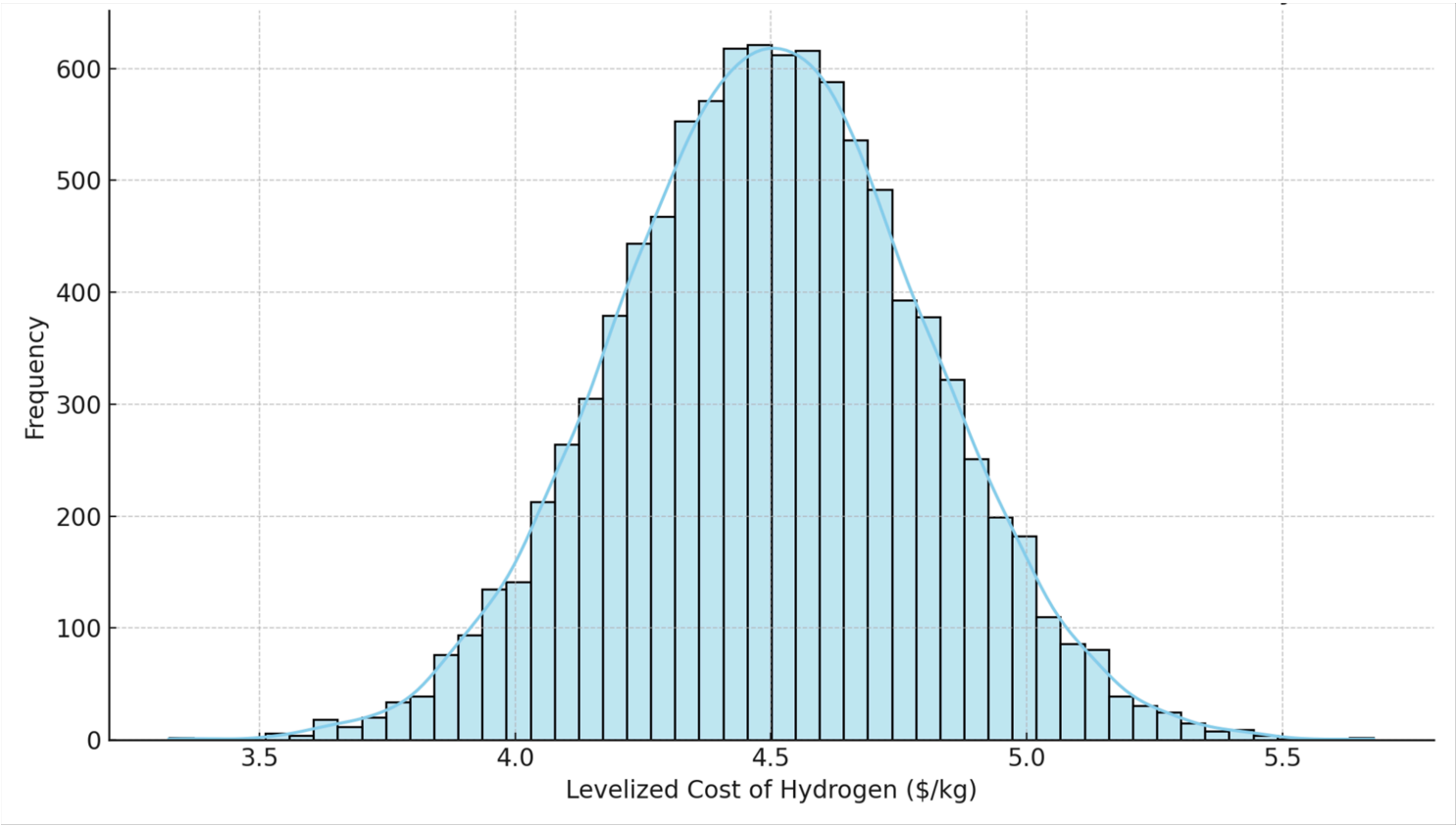


Figure 10

LCOH Distribution under to REE Price uncertainty

