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Global uranium market dynamics: analysis and future implications

Sa'd Shannak[a], Logan Cochrane[b] and Daria Bobarykina[b]

[a]Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, Doha, Qatar; [b]College of Public Policy, Hamad Bin Khalifa University, Doha, Qatar

ABSTRACT

This paper analyzes the global uranium market and assesses whether future supply can meet growing demand through 2050, focusing on market and geopolitical drivers. A dual approach was used, combining econometric analysis and uranium supply curve modeling. The econometric analysis examines the long-term relationship between prices and production volumes, using multiple methods to ensure robustness. Supply curve modeling shows how uranium availability changes with price, which helps gauge market resilience under various conditions. The main finding is a significant gap between projected uranium supply and demand, particularly in medium and high-demand scenarios, with a potential shortage emerging as early as 2035. By 2050, Kazakhstan and Canada are expected to dominate the uranium export market. Political and energy security concerns may lead to new global alliances and trade routes to meet the growing demand for nuclear energy. The study also highlights the International Atomic Energy Agency's outlook, emphasizing that primary mining will remain the dominant source of uranium, despite contributions from secondary sources. For policymakers, the study stresses the need for strategic interventions, including re-evaluating production and export policies in uranium-rich nations and developing effective strategies to secure supply. Findings offer key insights into market dynamics and ensure nuclear energy's sustainability.

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Introduction

At the 2024 United Nations Climate Change Conference (COP29) in Azerbaijan, nuclear power (re)emerged as a key area of focus for the next energy transition in achieving global decarbonisation targets by 2050 (IAEA 2024). In the previous COP28 summit, more than 20 countries pledged to triple their nuclear energy capacity by 2050. Six more did so at COP29. Alongside nuclear power plants, Small Modular Reactors (SMRs) were presented as a flexible option that is cost-effective and capable of meeting the demand of several markets, including urban, suburban, and remote areas, with projections that they could comprise 25% of new nuclear capacity by 2050 (IAEA 2024). However, while these announcements were made, the United States approved legislation to ban uranium imports from Russia (Bloomberg 2023) and Russia restricted enriched uranium exports to the United States (Reuters 2024). Earlier in 2023, a coup d'etat in Niger drew (additional) attention to its important role in providing uranium to France (Tharoor 2023; Volberding and

CONTACT Sa'd Shannak saedshannak2002@gmail.com

Warner 2018). As a result of supply constraints, increasing demand and geopolitics, throughout 2023 the spot price of uranium continued to rise, starting the year below US$50 and ending above US$90. Given these significant changes to the supply, demand and supply chain dynamics of uranium, this paper provides an updated forecast scenario and considers the role that geopolitics may play in influencing this market. To do this, this article builds on existing studies (e.g. Grancea, Hanly, and Organisation for Economic Co-Operation and Development 2018; Mirkhusanov, Semenova, and Kharitonov 2024; Pedregal 2020) by analysing aspects of uranium reserves, production, enrichment, trade, and nuclear energy plans, providing a multi-dimensional perspective. Additionally, the paper explores the governance and policy directions that different stakeholders (producers, such as Kazakhstan and Canada; consumers, such as the USA, China and France) might consider given the future scenarios.

This paper begins with a geopolitical review of uranium, drawing on a review of existing evidence. The reason this section focuses upon geopolitics is because the geopolitical aspects have the potential to continue to be disruptive to the global supply chain. This has also been done because the data regarding the supply chain itself (reserves, production, consumption) are detailed in a later section, which helps to contextualise the supply chain. Following the geopolitical background, the paper presents an empirical analysis of production and consumption of uranium, upon which future scenarios are developed. The paper then outlines the implications of the results, combining both the geopolitical context and the empirical data, providing insight into the governance and policy directions for stakeholders. While the uranium market has been studied, and geopolitical aspects of that market have also been analysed, this paper presents an updated assessment given the significant changes that occurred in 2023 and 2024, particularly the COP28 decision to triple nuclear energy by 22 countries, which was expanded at COP29 to include an additional 6 countries, as well as the significant geopolitical tensions.

Despite previous research on uranium and its global supply, there is still a significant vacuum in understanding how contemporary geopolitical dynamics and the global energy shift will impact uranium supply chains and market stability. This study aims at filling that gap by investigating the current relevance of uranium in light of nuclear power's potential as a low-carbon energy source. Understanding uranium's significance as a major baseload energy source is essential for both researchers and policy makers as the world decarbonises the energy system and experiences increasing demand for energy (e.g. computing power for data centres and artificial intelligence). While previous studies have looked at the uranium market's dynamics, these insufficiently address how geopolitical conflicts, such as those between Russia and the U.S. and bifurcated markets more broadly, may affect global supply networks. This study seeks to close that gap by examining the possible effects of geopolitical instability on uranium supply chains, offering insights for policy makers and researchers. This study finds a divergence between supply and demand widening in the medium term. The geopolitical analysis highlights how major supplying countries (e.g. Canada, Kazakhstan) may face increasing political pressure (e.g. with limits on Russian exports), highlighting the critical role of geopolitics in global supply chains as nuclear expands as a cleaner baseload energy source. This paper suggests strategies for policy makers to mitigate risks amidst the global energy transition.

Uranium in context

The role of uranium in geopolitics extends beyond traditional energy supply concerns because it includes debates about the role of nuclear power in the global energy transition, especially in the context of nuclear power as a low-carbon energy source. Amidst the global push toward decarbonisation and efforts to reduce fossil fuel use, uranium's significance as a key component in nuclear reactors positions it as a key baseload energy supply in the transition towards cleaner energy alternatives. Nuclear power, fuelled by uranium, may be a promising avenue for meeting growing energy demands while mitigating greenhouse gas emissions. This section situates uranium as a commodity, its global supply chain, and its geopolitical dimensions, which are returned to in the analysis of the paper.

The uranium market, integral to the nuclear energy sector, is characterised by its unique dynamics shaped by a concentrated pool of major producers and a diverse array of global consumers. Kazakhstan leads the world in uranium production, leveraging its vast resources to dominate the market. Close behind are Canada, Namibia and Australia, countries with rich deposits and extensive mining operations (El Obeid 2021). Niger is also a key player, contributing substantial quantities from their mining activities (Volberding and Warner 2018), but has faced significant disruptions and political instability. Russia, straddling the line between producer and consumer, plays a pivotal role in the broader nuclear fuel cycle, providing enrichment services to the global market (World Nuclear Association 2023).

Uranium is a dense and radioactive metal that is not uncommon in the Earth's crust but is unevenly distributed in quantities that are economically viable for extraction. Table 1 shows uranium reserves and production trends across major countries. Australia has the largest uranium reserves, with almost 28% of the world's total. Kazakhstan follows, with 13%, and then Canada with 10%. Production of those resources, via economically viable mining operations differs from these reserves. Production data for 2021 and 2022 show Kazakhstan leading global production, followed by Canada and Namibia (Table 1). These natural, mined resources provide 57% of the global demand for uranium used in nuclear energy, while alternative sources, such as stocks of highly enriched weapons-grade uranium resulting from the implementation of the START-1 and START-2 accords as well as fuel recycling, account for the remaining 43% (Torebayeva 2021). The ability to create low enriched uranium (LEU) from highly enriched uranium (HEU) has reduced the market's reliance on natural uranium (Chernykh 2020).

While Table 1 highlights current production, a historical perspective shows that the United States previously had significant production capacity (Figure 1), based on aggregate production totals from 1945 to 2022. Demand increased with the Manhattan Project's exploitation of its fission potential and the subsequent nuclear arms race of the Cold War (Rhodes 2012). The deployment of uranium for civilian use, exemplified by reactors such as the USSR's Obninsk and the USA's Shippingport, marked the transition to the Atomic Age (Groves 2009). As the twentieth century progressed, nations like Canada, South Africa, and Australia increased their uranium production,

Table 1. Uranium Reserves Distribution Across Nations and Annual Production (Source: OECD NEA & IAEA 2022, World Nuclear Association, 2023).

Country	Reserves (Tonnes U) as of 2021	% of World Reserves	Production (2021)	Production (2022)	% Increase in Production
Australia	1,684,100	28%	4,192	4,553	8.61%
Kazakhstan	815,200	13%	21,819	21,227	−2.71%
Canada	588,500	10%	6,938	7,351	5.94%
Namibia	470,100	8%	5,476	5,613	2.50%
Russia	480,900	8%	2,846	2,508	−11.86%
South Africa	320,900	5%	192	200	4.17%
Niger	311,100	5%	2,248	2,020	−10.14%
Brazil	276,800	5%	29	43	48.28%
China	223,900	4%	1,600	1,700	6.25%
Mongolia	144,600	2%	N/A	N/A	N/A
Uzbekistan	131,300	2%	3,520	3,300	−6.25%
Ukraine	107,200	2%	455	100	−78.02%
Botswana	87,200	1%	N/A	N/A	N/A
USA	59,400	1%	8	75	837.50%
Tanzania	58,200	1%	N/A	N/A	N/A
Jordan	52,500	1%	N/A	N/A	N/A
World Total	**6,078,500**	**100%**	**47,808**	**49,355**	**3.24%**

Note: Identified resources recoverable (reasonably assured resources plus inferred resources), to $130/kg U, 1/1/21; from OECD NEA & IAEA, Uranium 2022: Resources, Production and Demand ('Red Book'). The total recoverable identified resources to $260/kg U is 7.918 million tonnes U.

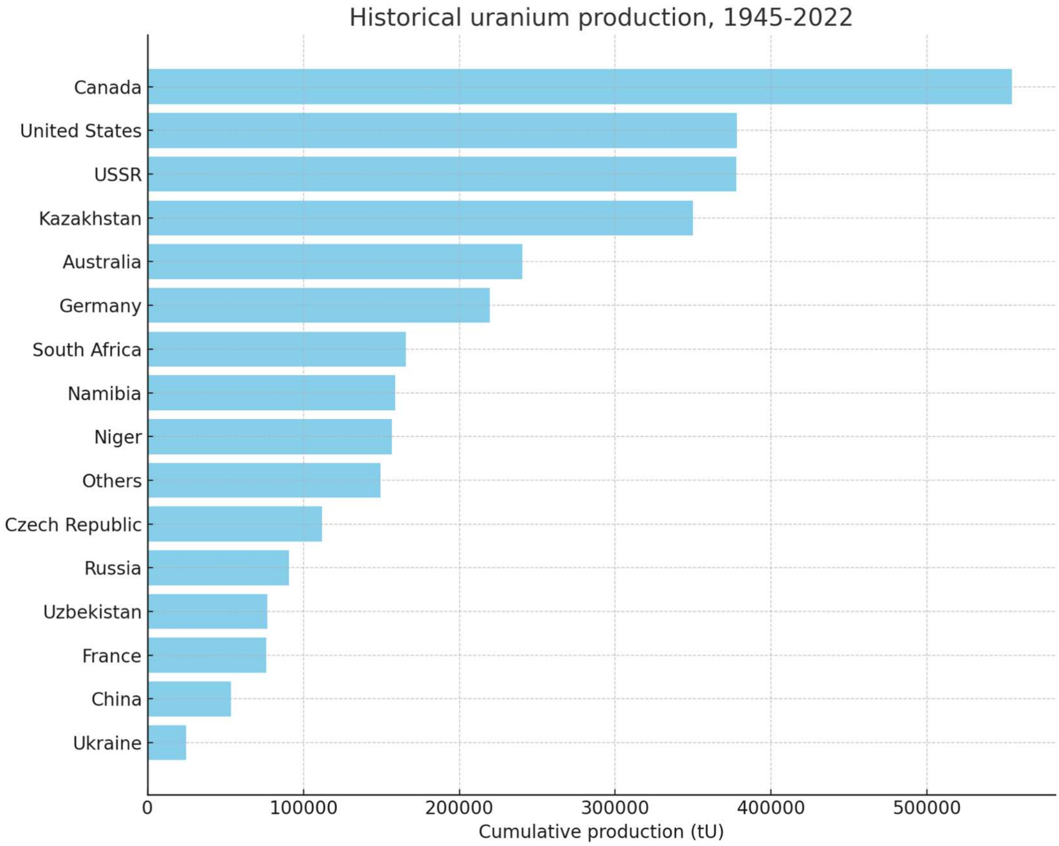

Figure 1. Historical Uranium Production, 1945–2022, in Tonnes of Uranium (tU) (sourced from: World Nuclear Association, 2023); data by country source, which presents challenges due to the changes of the USSR in 1991, disaggregated data by specific source requires additional study.

responding to the demand in the nuclear energy expansion. The dramatic rise in global uranium requirements during the 1960s and 1970s reflects this widespread adoption for electricity generation. The oil crisis of the 1970s advanced nuclear power's role in the energy sector. However, the late 1980s saw a significant drop in uranium output, coinciding with the end of the Cold War's and a corresponding decline in military demand. Despite this, the global need for uranium persisted, driven by the civilian nuclear power sector's continued expansion (Medvedev 1992; Walker 2004).

Turning to production, the geopolitical concerns of uranium become more evident. Kazakhstan is the world's largest uranium producer. Due to sanctions on Russia, their ability to export uranium through the Port of St. Petersburg has become more difficult. Significant effort has been devoted to investigating an alternate logistical route across the Caspian Sea, crossing through Armenia and Azerbaijan on the way to a Turkish Black Sea port (Uranium Report 2023). The Kazakh company, Kazatomprom, supplies the market with in excess of 40% of total supply, making it the larger global producer (Pistilli 2023). Several international businesses, notably Rosatom, Cameco from Canada, and Orano from France, have stakes in Kazatomprom's different areas of work (Smertina 2023). Kazatomprom produced 21.2 thousand tons of U3O8 in 2022, with international partners accounting for 9.85 thousand tons of the amount. Rosatom produces more than 60% of its yearly 7 thousand tons of uranium (representing 15% of the world market) in Kazakhstan. This is done through five joint ventures formed with Kazatomprom (Smertina 2023). Cameco states that the global nuclear industry is seriously dependent on Russia: the country's share in uranium supplies is

14%, in uranium conversion services (converting uranium into UF6) is 27%, in uranium enrichment is 39% (Supply & Demand. Cameco).

Because Western nations account for over 70% of the world's reactor fleet, there is a significant disparity in conversion, enrichment, and fuel manufacturing capacity. As a result, the West has developed a major reliance on Russia in these critical components of the nuclear fuel cycle (Uranium Report 2023). In 2023, following the ongoing conflict in Ukraine, the U.S. sanctioned Russian uranium, which led to the fall of the net profit of Rosatom by 14% (more than 166 billion rubles), according to Vedomosti estimates based on the state business Rosatom's public financial records on its website (Volobuyev, Milkin, and Stepanov 2023). Moreover, the desire of the United States to transition from coal-fired electricity generation to a significant reliance on nuclear power facilities during the next decade has started a geo-economic battle that is rapidly turning into a geopolitical conflict. This situation is likely to deepen because, in the short term, Kazakhstan may confront constraints in boosting exports or prioritise import destinations for geopolitical reasons (Goble 2023).

The global uranium supply chain, despite being managed by a small number of corporations, remains intricately complex. Within this industry, multinational enterprises often operate as joint ventures with multiple subsidiaries, with varying degrees of vertical integration. For example, Paladin Energy Ltd, an Australian firm, primarily focuses on uranium mining and production, while entities like Rosatom, the Russian state enterprise, cover the entire nuclear fuel cycle and nuclear power plant development. The trend over time has been increasing vertical integration, particularly as governments aspire to strengthen their nuclear capabilities (Mendelevitch and Dang 2016). Enrichment, a crucial facet of the uranium market, involves highly sensitive technology governed by strict international regulations due to proliferation concerns (Krass, Elzen Boskma, and Smit 2020; Meyer 2023). To mitigate the risk of proliferation, this technology is not freely traded worldwide. Over 90% of the world's enrichment capacity is controlled by a few countries (Russia, Germany-Netherlands-UK, China, France, and the United States). In addition to enrichment, prior to its use as nuclear fuel, uranium must undergo conversion into nuclear fuel rods within specialised fabrication facilities. Unlike certain intermediary products in the uranium supply chain, such as low enriched uranium (LEU), nuclear fuel assemblies are intricate and customised to meet specific requirements of each site, encompassing reactor specifications, operating strategies, fuel cycle management, and compliance with national licensing regulations. Consequently, many primary fuel manufacturers also serve as suppliers to nuclear reactors, aligning with the unique criteria of individual facilities (Mendelevitch and Dang 2016).

Trades in this market are often classified into three types: spot pricing (purchases done on the same day), midterm contracts, and long-term contracts. These contracts govern critical features for both buyers and sellers, such as pricing, volume, and production levels. Over the long term, the market functions cyclically, with demand lead periods stretching decades, creating significant obstacles to entry – navigating permissions, building, and constructing nuclear power plants – in comparison to the more volatile supply side including mining and processing uranium ores. Transactions between buyers and sellers in the uranium market are performed discreetly and without transparency. As a result, there is no widely accepted worldwide market price. Instead, prices are published by independent market experts such as UxC LLC (UxC) and TradeTech. These companies do not establish uranium prices in the traditional sense; instead, they derive spot prices by evaluating numerous uranium transactions throughout the world and assessing the general status of the market. As a result, the spot price inferred by these organisations is extremely unlikely to be the actual transaction price. A similar, but less severe, lack of accuracy exists for mid- and long-term contract rates (Uranium Market 2019).

Following a uranium price spike in 2007, there was a steady decline in global prices and resultingly many major companies began to decrease production. For example, Cameco, a major Canadian uranium producer, suspended operations at the McArthur Mine, the world's biggest, which accounts for 40–45% of its mining capacity (Green 2018). The justification for this move was a projected lack of sustained increase in uranium demand. Similarly, Kazakhstan's state-owned uranium company, KazAtomProm, decided to reduce uranium output, announcing a 20% reduction in output in 2019. KazAtomProm CEO Galymzhan Pirmatov stated that this strategic move sought to provide stability to the uranium market by balancing supply and demand through appropriate production cuts (Kazatomprom announces continued … 2019). Kirill Komarov, Director of the Development and International Business Unit at Rosatom, called attention to a major shift in the pricing dynamics of derivative-enriched uranium throughout 2018 at the Atomexpo-2019 event. A turnaround was witnessed following these reductions, starting in 2018. The price increase was due not just to the development of the worldwide nuclear energy sector, but also to a significant reduction in supply (Kazakhstan to cut … 2017). The International Energy Agency (IEA) predicts a significant increase in worldwide energy consumption, with an estimated 18% increase by 2030 and a significant 39% increase by 2050. This rising need for a range of energy sources, including nuclear energy, highlights the anticipated increased demand for uranium (Chernykh 2020). As noted above, 2023 was a breakout year for uranium, both in aspirations to expand nuclear production and in sustained increases of uranium spot prices.

The rapid expansion of nuclear power in future decades may drastically increase uranium demand, such as many new nuclear station builds as well as Small Modular Reactors (SMRs; Schneider et al. 2009). The uranium market's complexity, driven by technology, politics, and economics, will continue to evolve as it plays a crucial role in addressing global energy demands and climate change challenges (Hall and Coleman 2013). Despite spot price increases in 2023, it might take 2–3 years for previously suspended or reduced operations to regain significant output, necessitating higher costs. Although operating costs vary based on location and industry, recent supply chain delays and cost increases have raised the average breakeven point for Western uranium mines to around $90 per pound (Reddy 2023). Due to an overstock of worldwide enrichment capacity, SWU (Separative Work Unit) prices had stayed historically low. However, it is expected that the European conglomerate Urenco and the French firm Orano would begin centrifuge manufacturing and extend their enrichment capacity (Sondgeroth 2022). This strategic shift is projected to result in increased purchases of both SWU and natural uranium from non-Russian sources. Presently, conversion services, involving the transformation of uranium from an oxide state into uranium hexafluoride gas for enrichment, are offered by Canada, China, France, and Russia. The Metropolis conversion factory in the U.S. was originally planned to have a capacity of 15,000 tonnes per year, however, this was reduced to 7,000 tonnes per year in 2017 (Converting Uranium, Opportunities … 2020). The ConverDyn Metropolis plant's operator was reopened in 2023 with the capacity of 7000 tU (Pan 2024). With the restored ConverDyn facility, Canadian, US, and French conversion capacity will reach 34,500 tonnes per year in 2023, exceeding the present demand of the US and EU combined (about 31,000 tonnes per year) (Conversion and Deconversion 2022).

North American and European utilities are actively investigating alternative supply sources. In the uranium supply market, Australia and Canada are generally considered to be lower risk jurisdictions, with Canada argued to be better positioned to take greater market share (Geopolitical risk and … 2023). Despite challenges related to equipment reliability at Cigar Lake and uncertainties surrounding Key Lake's production rates due to ongoing ramp-up, operational adjustments, workforce shortages, and supply chain disruptions affecting material and chemical availability, Cameco indicated that beginning in 2024 their mines will reopen at two-thirds capacity, resulting in an annual production output of 11,000 tonnes. Global Atomic, a Canadian uranium mining firm, announced an arrangement with an unnamed large North American utility, which includes the construction of a mine in Niger that will produce roughly 2,000 tonnes of natural uranium per year and is expected to begin operations in 2025 (Diaz-Maurin 2022). This predicted output would exceed the amount required to replace the United States' and European Union's imports of uranium and SWUs from Russia (Cameco reports Q4). In terms of alternative choices for the West, Namibia and Niger, the fourth and fifth major worldwide uranium producers, respectively, are higher risk operational contexts. According to globalEDGE research, Namibia has uncertainty in its economic future, political climate, and general business environment, classifying it as a somewhat high-risk region (Geopolitical risk and … 2023). In the case of Niger, the 2023 coup signalled the conclusion of the largely unsuccessful French military operation 'Barkhane' in the Sahel, leading to the termination of France's presence in the region and, as a consequence, severing its access to uranium mines (Bourgery-Gonse 2023).

The engagement of Russian companies in Kazakhstan's uranium sector poses significant geopolitical issues. If tensions between Russia and Western nations rise further (such as Public Law No 118-62 that limits the importation of uranium from Russia), the bifurcation of global supply chains may further widen (Kazakh supplies of uranium have largely been going to China, which has comparatively less domestic resources than the United States; Chen, Xing, and Du 2017; Economist 2024; Shang et al. 2021). As the geopolitical environment shifts, Kazakhstan may face growing pressure to diversify its ties and lessen reliance on Russian enterprises, or it may deepen ties with alternative partners. Kazakhstan has begun to diversify with other international partners, such as from Canada and France (EFE Comunica 2023) and has become the focal point of the Middle Corridor project, which connects China and the European Union via Kazakhstan, the Caspian Sea, Azerbaijan, Georgia, and Turkey while bypassing Russia (Mikovic 2023). The possibility of geopolitical instability may also lead to a restructuring of Kazakhstan's foreign policy, as it seeks more autonomy over its resources (not only uranium). If the geopolitical situation continues to deteriorate, it might result in a massive reconsideration of global nuclear supply chains, with countries attempting to reduce their dependency on any single source.

Turning to existing research on these dynamics, there are a significant number of studies investigating the long-run relationship between uranium supply and prices by employing econometric modelling (Arnaut 2022; Cordano and Zevallos 2021; Lazarus 2022; Omland and Andersen 2023). For instance, Dahl (2009) showed that the long-run price elasticity of uranium supply in the United States could range between 0.74 and 3.08, suggesting a significant response of supply to changes in prices. This study, as well as others, shows that uranium is similar to other energy commodities in that it has a relatively elastic supply in the long run, which would allow the market to adjust production in response. Moreover, Graham (2013) estimated both short- and long-run elasticities of uranium production. They concluded that supply responds differently to short and long terms elasticities, with long-run elasticity being larger. Other research applied more advanced methods to analyse this relationship (Fally and Sayre 2018; Trieu, Savage, and Dwyer 1994 and UxC 2024). These studies employed dynamic models to assess this complex relationship between supply and prices. The studies emphasised that there is a delay in response of uranium production to price signals and this was explained due to the long times associated with permitting, extraction and geopolitical influences. Additionally, they highlighted that price elasticity for uranium can vary based on external drivers, but in the long run, supply elasticity remains vital for understanding market adjustments. These findings contribute to the broader literature on the long-term economics of uranium supply and the importance of economic modelling as a tool in capturing market dynamics.

Global progression of nuclear power capacity

Recently, the main driver of uranium demand is nuclear power, particularly with the COP28 and COP29 aspiration to triple nuclear power generation by 2050 in 28 countries. Figure 2 shows an analysis of the current operational nuclear power capacities alongside those under construction, pre-construction and announced. The United States holds the largest operational capacity, however, the extensive increase in nuclear programmes in China implies a seismic shift in future uranium demand. However, it is not only a story of these two big countries; the global picture includes demand from countries like India and United Kingdom, each making significant investments in nuclear power (World Nuclear Association 2023). The global analysis reveals a heterogeneous but concerted shift towards nuclear energy, with the underlying narrative being a robust increase in uranium demand. Countries are strategically leveraging nuclear power to ensure energy security, meet climate objectives, and foster economic growth. The ripple effects of these national

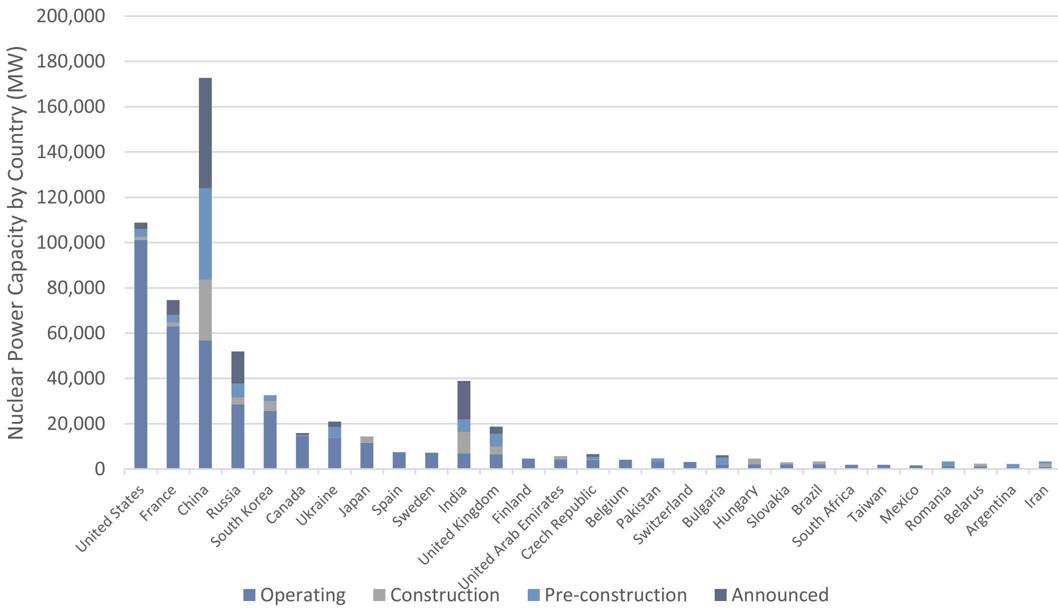

Figure 2. Nuclear Power Capacity by Country (MW). A cut-off was selected for plants with operating capacity above 1000 MW. (World Nuclear Association, 2023)

strategies will be felt across the uranium market, influencing everything from mining to price stabilisation efforts.

The uranium consumption landscape is dominated by countries with significant nuclear power infrastructure. The United States, despite its own uranium resources, stands as the largest consumer, heavily reliant on imports to fuel its fleet of nuclear reactors. China's ambitious nuclear expansion has rapidly elevated its status to one of the top consumers, aligning with its strategic energy goals and commitment to reducing carbon emissions. France, with its heavy reliance on nuclear power for electricity generation, is another major consumer. South Korea and Japan have traditionally been significant consumers, though Japan's usage has seen dramatic shifts following the Fukushima Daiichi disaster in 2011 (Oxford Analytica 2021; Yan et al. 2011). However, the industry is susceptible to severe shocks, as demonstrated by the Chernobyl disaster in 1986 and more recently by the Fukushima incident. These events not only impacted immediate demand but also led to long-term regulatory reforms and shifts in public perception of nuclear energy's safety (Grancea 2018; McKillop 2011). The inherent volatility of the uranium market is a reflection of its sensitivity to geopolitical events, policy decision and shifts, and societal attitudes towards nuclear energy (Considine 2019). Despite the periodic instability, the sector's importance is underscored by the ongoing dialogue around clean energy transitions and the role of nuclear power in achieving carbon neutrality (Monnet, Gabriel, and Percebois 2017). As the global community continues to grapple with the challenges of climate change, the strategic significance of uranium as a resource persists, with its market poised to respond to the evolving landscape of energy policies, technological advancements, and the construction and decommissioning of nuclear reactors around the world.

In 2022, the uranium trade landscape underwent a remarkable transformation, with imports of 'Uranium or thorium ores and concentrates' surging to over \$374 million, a substantial leap from \$142 million in the previous year. This uptick in trade is indicative of an increasing global demand, essential for sustaining and expanding nuclear energy capabilities (Trend Economy 2023). China's role as the dominant importer, constituting 57% of global imports with an expenditure of \$215 million, emphasises the country's aggressive expansion in nuclear energy and its strategic positioning in the global energy matrix. The United States followed closely, accounting for 41% of imports at $156 million, signalling its continued reliance on nuclear power and the strategic importance of securing a stable uranium supply chain (Trend Economy 2023). Despite these significant imports, the trade data reveals that uranium constitutes only a small fraction of total imports for both China and the USA, underscoring the specialised nature of the nuclear industry within their larger national economies. The absence of trade data for several smaller importers in 2022 suggests a potential realignment or reassessment of nuclear energy strategies or a shift toward alternative energy sources within these nations. Notably, the current global power reactors require approximately 67,500 tonnes of uranium annually, and the current measured resources are estimated to last for about 90 years under the present consumption rates and prices (World Nuclear Association 2023). Appendix 1 provides an overview of geopolitical and technological factors influencing uranium supply, highlighting gaps in current research and emerging innovations.

Global uranium market dynamics: future scenario projections

Recognising the importance and implications of uranium resources, it is vital to take into consideration the broader dynamics of the uranium supply market. As indicated by Gabriel et al. (2013), the principles governing the uranium supply suggest that any increase in uranium prices would result in an increase in exploration and mining activities. However, it is worth noting that the response of uranium production to price changes is typically slow, which is attributed to many factors such as permitting, constraints in production capacity, the complex and risk-intensive nature of expanding mining operations as outline by Mays (2005), Kahouli (2011), inter alia. This lag in response is documented in the historical patterns. For example, in 1973, uranium prices increased tremendously; however, increases in production were only noticeable in 1975. Similarly, in 1980, prices of uranium dropped significantly but the reduction in output was observed after several years (Kahouli 2011). These trends emphasise the challenges in promptly adapting uranium supply strategies to meet the variations in market demand, a vital aspect for policy makers to take into consideration.

Approaches to uranium supply estimation

Two distinct methods were employed in this study to project the future availability of uranium from mining operation: (A) the Supply Curve Approach and (B) Econometric Modelling. Figure 3 below provides a schematic flow illustrating the development of these two methodologies in projecting future uranium supply.

a) Supply Curve Approach:

The first method is Supply Curve approach. Under this method, the global uranium prices from 1990 to 2023 were aggregated (by converting monthly into yearly). The prices data are in USD per pound was obtained from Federal Reserve Bank of St. Louis (Figure 4; FRED, 2023)

Additionally, uranium production data from mines (in tonnes of uranium) for the period 2013–2022 were compiled, and acquired from the World Nuclear Association. These data were synthesised to produce annual global production total (Figure 5). A conservative approach was employed, under which the uranium extraction costs are inversely correlated with ore concentration. The model applied for this purpose was developed by Schneider, E. A., & Sailor, W. C. (2007) and can be expressed as follows:

$$\frac{Q}{Q_0} = \left(\frac{P}{P_0}\right)^{\alpha\beta}$$

where Q is the quantity of uranium

P is the price of the uranium.

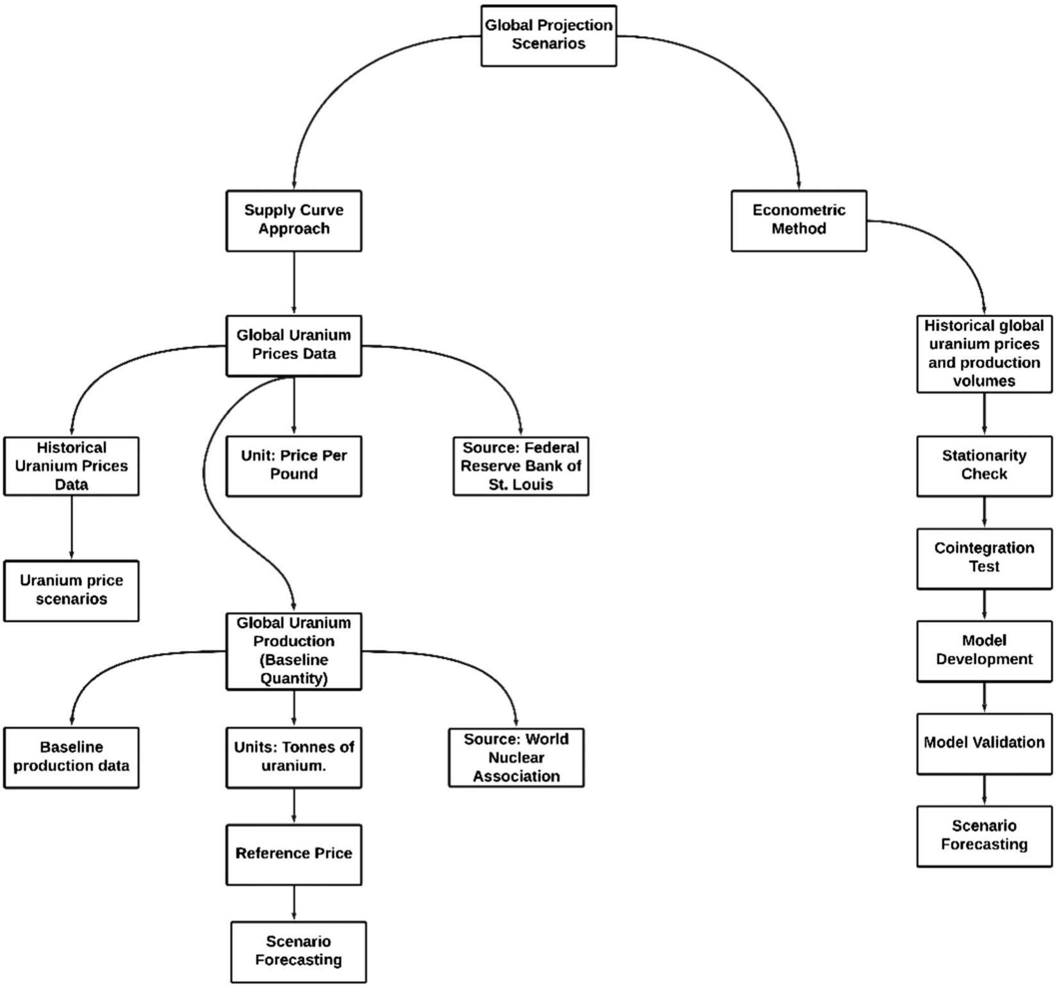

Figure 3. Schematic of the methodology for the two approaches followed in this study, combining the Supply Curve Approach and the Econometric Model to estimate future uranium supply. Source: Authors.

Q_0 is the baseline quantity.
P_0 is the reference price.
$\alpha = 2.48$ and $\beta = 1$ values were chosen based on U.S. Department of Energy report for conservative estimates (USDE 2002).

The model was calibrated using 2013 data as a reference point. The calibrated model was verified against data spanning from 2013 to 2022 and was subsequently used for suture supply projections.

The future price trends were estimated in order to project uranium supply up to 2050. For this purpose, three scenarios were constructed: low, medium, and high. Each scenario corresponds to a specific price. Based on the IAEA projections, uranium prices are expected to stabilise around $50, under the low scenario (IAEA 2023). The medium scenario is anticipated to reach $100 per kg by 2050 and the high scenario is projected to reach $200 per kg. Additionally, a growth rate to extend the values from 2013 to 2050 was applied. By employing the Supply Curve model mentioned above, the potential supply outputs under the different scenarios were analysed. The results of the analysis are shown in Figure 6.

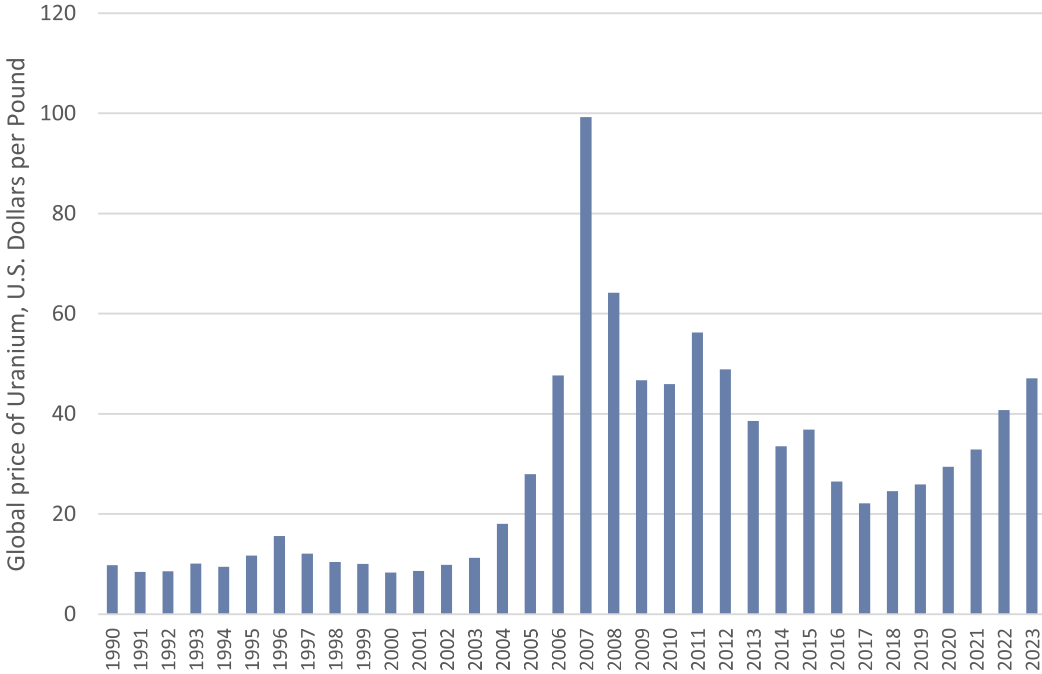

Figure 4. Global price of Uranium, U.S. Dollars per Pound. Sourced from FRED, 2023.

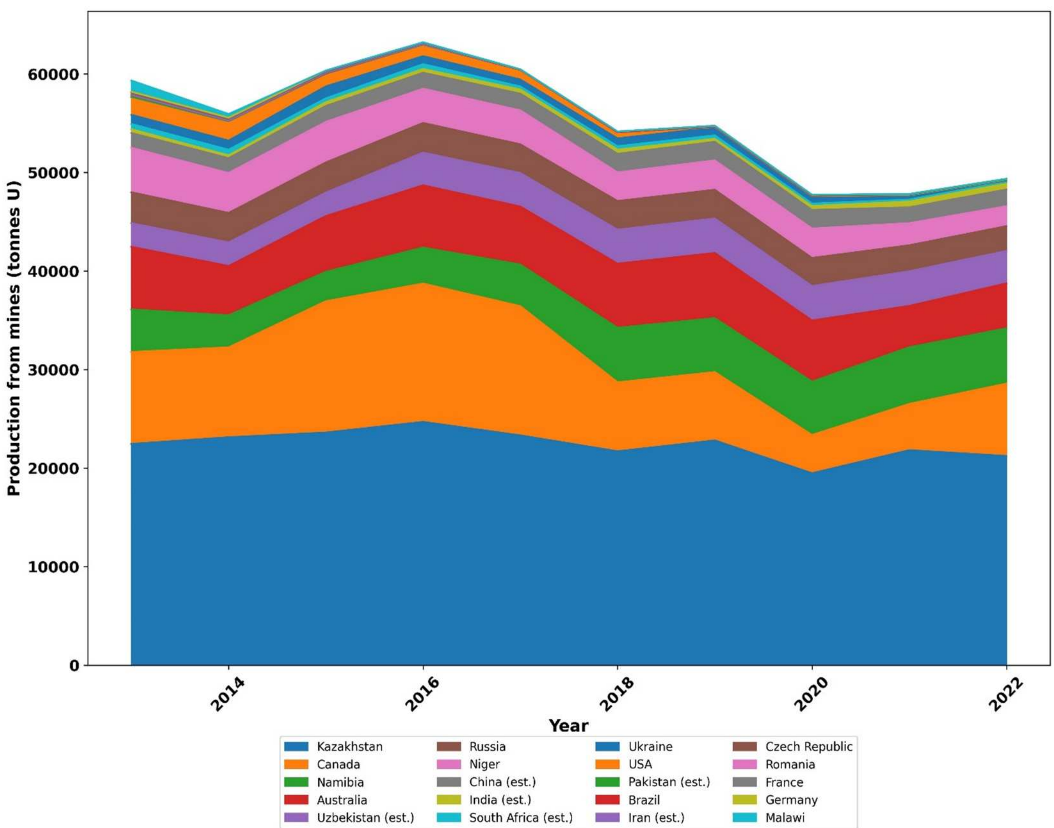

Figure 5. Uranium Production from Mines (tonnes). Data Source: World Nuclear Association 2023.

b) Econometric Modelling

The second method is econometric modelling. This approach constructs econometric models by utilising production volumes and price data. Several econometric methods were applied to ensure the robustness of the models (Appendix 3 provides detailed information on the model development). The model can be expressed as (y), which represents the global quantity of uranium produced and (p) represents the prevailing uranium price. This model was formulated as:

$$y = f(p)$$

The function (f) represents the complex relationship between production quantity (y) and price (p), capturing the complex dynamics of the uranium market. Using the projected uranium price data from our initial analysis, the global uranium production trends up to 2050 were forecasted. To achieve this, the approach was to employ the three scenarios discussed earlier: low, medium, and high (see Figure 7).

Under the low scenario, a cautious market with stable uranium prices was assumed, resulting in minimal changes in production trends. The medium scenario is expected to see a moderate price increase, which was expected and resulted in increasing production volumes as mining operations adjust to the changing market. Lastly, the high scenario is optimistic, expecting a significant price increase that would correspond with a substantial rise in production, as mining activities ramp up to meet growing demand.

The rationale behind the studied scenarios is to provide a range of potential futures for uranium production and to highlight how sensitive the uranium mining activities are to changes in price. This understanding is vital for policy makers as they seek to prepare for various potential

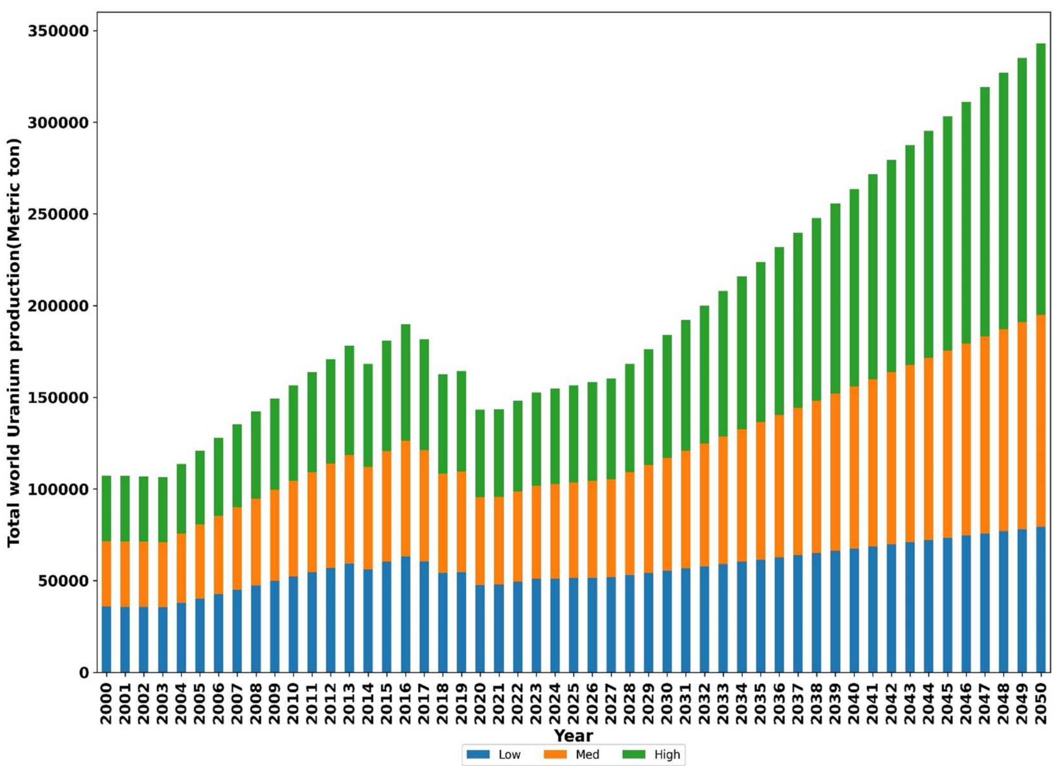

Figure 6. Projected Uranium Production Trends through 2050 Utilising Supply Curve. Source: Authors.

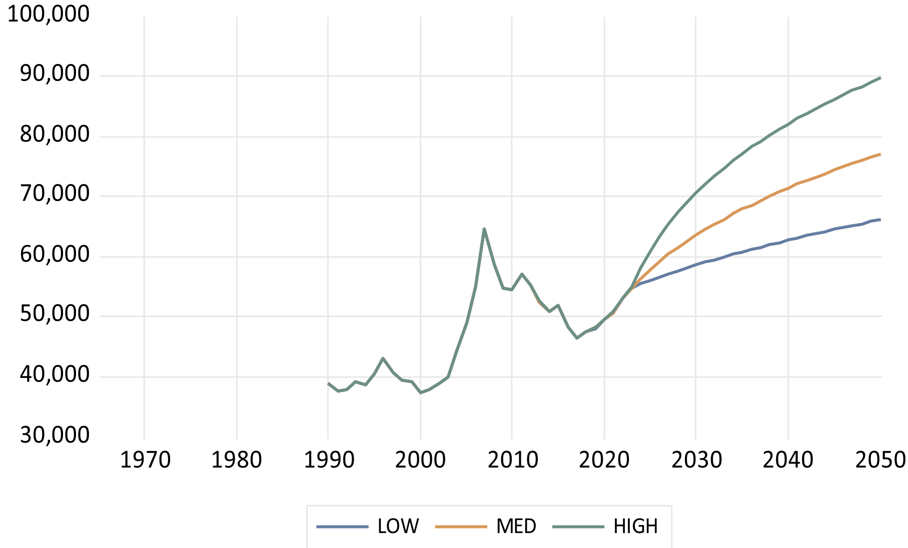

Figure 7. Projected Uranium Production Trends through 2050 Utilising the Econometric Model. Source: Authors.

developments in the uranium market over the coming decades. The outcomes of this analysis will be explored further in the following sections.

Table 2 shows the main specifications of the econometric models were applied, accompanied by key statistical measures such as standard error, t-statistics and probability. Our study sheds light on the elasticity of supply in response to price fluctuations. Additionally, our findings indicate that for each one percent change in uranium prices there is a corresponding increase in supply by 0.21%. This positive increase relationship shows the sensitivity of uranium supply to market price dynamics. It is worth noting that the variables of these models were represented using the natural logarithm to facilitate their interpretation as elasticity.

To ensure the robustness of the analysis, three statistical methods were applied to estimate the relationship between prices and supply: Fully-Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), Canonical Cointegrating Regressions (CCR). The coefficient of prices across the three estimate methods (CCR (0.201), FMOLS (0.202), and DOLS (0.219)) are very close, indicating the robustness of the results (Table 2). This consistency across different methods enhances the credibility of the relationship between uranium production and prices. Appendix 3 details the prerequisite tests for these methods along with the results. Interested readers regarding this methodology can refer to Shannak, Cochrane, and Bobarykina (2024) among others.

Future demand analysis:

For projecting uranium demand through IAEA scenarios, the scenarios developed by the International Atomic Energy Agency (IAEA) were applied. The rationale of these scenarios is to capture

Table 2. Econometric model specifications.

Method	Variable	Coefficient	Std. Error	t-Statistic	Prob.
CCR	LOG(PRICE)	0.201	0.058	3.479	0.002
	C	10.286	0.150	68.242	0
FMOLS	LOG(PRICE)	0.2025	0.065	3.082	0.005
	C	10.283	0.173	59.171	0
DOLS	LOG(PRICE)	0.2190	0.072	3.009	0.006
	C	10.242	0.193	52.825	0

Source: Authors.

different levels of economic growth and energy policies providing a range of possible future demand for uranium.

1. Low Demand Scenario: This scenario is based on medium economic growth. It assumes that an ecologically oriented energy policy framework will be developed and in place. Additionally, this framework is characterised by low energy demand growth and a gradual phase-out of nuclear power by 2100.
2. Medium Demand Scenario: The development of economy is around medium ranges under this scenario, between the high and low scenarios. According to IAEA, this scenario is driven by ecology and energy policies that are coupled with sustained development of nuclear power across the globe and including developing nations.
3. High Demand Scenario: this scenario assumes the global energy mix will be characterised by mainly clean energy sources and there are no stringent environmental policies. It also assumed a significant growth in nuclear power. This represents an optimistic scenario with high economic growth and high adoption of nuclear energy.

The demand data from the IAEA for the period 2000–2023 were employed to translate these scenarios into tangible demand projections, regression models for each scenario were also crafted, extending our projections to the year 2050 to bridge the gap between the present and the future. These regression models are thoroughly developed to predict the demand for uranium from 2024 to 2050, under each distinct scenario (Figure 8).

The Holt-Winters Exponential Smoothing model (Chatfield 1978) was applied, a well-established time series forecasting technique, to project uranium production data across the studied scenarios. This type of model is particularly effective for scenarios where historical data show a clear trend, as is the case with uranium. An additive trend model was utilised, which means that the forecast assumes a constant rate of change over time. This approach is suitable given the steady increase in uranium production observed historically. Initially, a model was fitted covering the existing historical data ranging from 2000 to 2023 to accurately capture the underlying trend and growth pattern of uranium production. Next, production values from 2024 through 2050 were forecasted, relying on the learned trend. As an additive model, it assumes that the linear trend observed in the past will continue. This approach not only enhances the reliability of the projections but also provides a clear framework for understanding future uranium production trends. Below are the developed models:

1. Low Demand Scenario Model:

- Model: $y = -52.046\times^2 + 3064.4x + 46170$.

This model includes a second-order term, indicating that the relationship between the studied variables is non-linear. In other words, as economic growth or improvements in energy efficiency increase, this could result in a larger drop in uranium demand than expected. This reflects a slow growth in energy demand combined with a gradual shift away from nuclear power, which aligns well with the trends anticipated in this scenario.

2. Medium Demand Scenario Model:

- Model: $y = 1092x + 57770$

This model has a linear relationship between the studied variables. The medium scenario suggests that uranium demand is mainly driven by stable economic growth and the constant expansion of nuclear power, particularly in emerging economies. In other words, the relationship between economic drivers affecting demand and uranium consumption is relatively straightforward. Hence, this ensures the model's reliability, in forecasting medium trends in uranium demand.

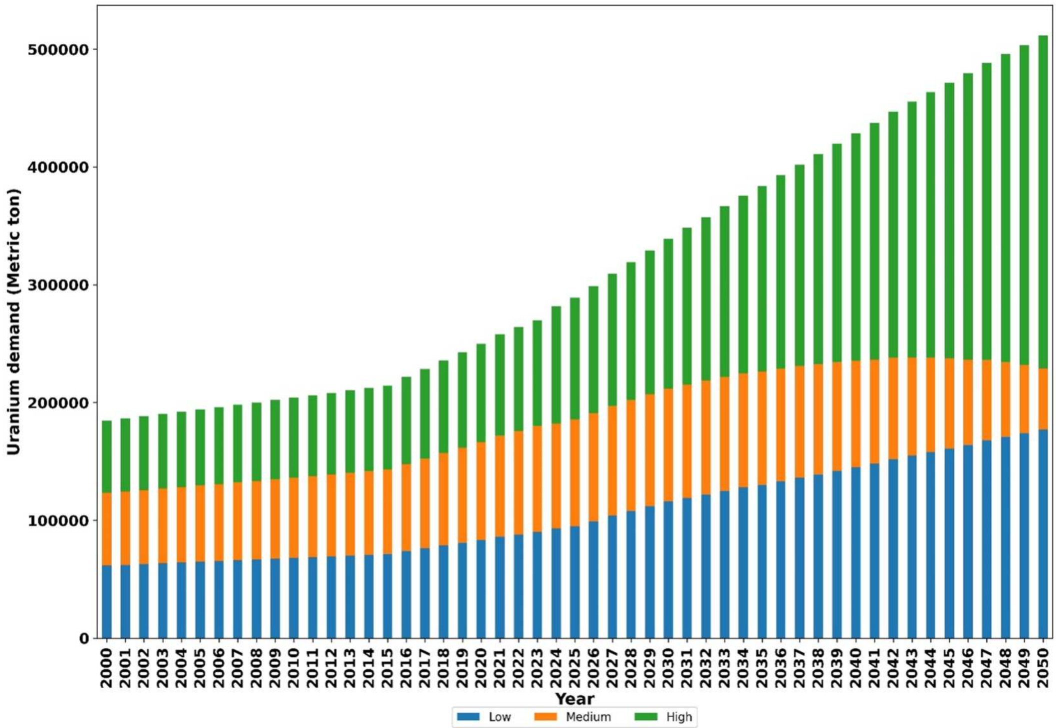

Figure 8. Projecting Uranium Demand through IAEA Scenarios. Source: Authors.

3. High Demand Scenario Model:

- Model: y = 4276.9x + 16750.

The high demand scenario model suggests a linear relationship, indicating that uranium demand increases as a result of economic growth and ambitious expansion of nuclear power, particularly in regions where environmental regulations may be less strict. The positive coefficient of 4276.9 indicates that as economic growth increases, so does the demand for uranium, highlighting a direct and substantial correlation between the two.

It is worth noting that previous models do not account for nuclear plants currently under construction, due to a lack of country-level data. Additionally, the analysis defines uranium demand based on production, imports and exports, which provides complexity to understanding future demand trends.

Geopolitical analysis

For the geopolitical analysis, country-level analysis was conducted to indicate key players in both uranium supply and demand. This is to complement the global supply and demand analysis conducted in the previous sections. For this purpose, the approach focused on 2022 data to determine the key suppliers and importers of uranium. These volumes were also correlated with the overall global scenario (Figure 9) to establish a baseline for our future projections. This analysis at a country level provides critical insights into the potential future scenarios of uranium utilisation. Considering several factors such as existing commitments, potential increase in nuclear energy reliance, and resource limitations, the analysis offers a comprehensive overview of the geopolitical dynamics in uranium supply and demand. This analysis should assess in clarifying the broader implications of uranium's role in global energy markets and policies.

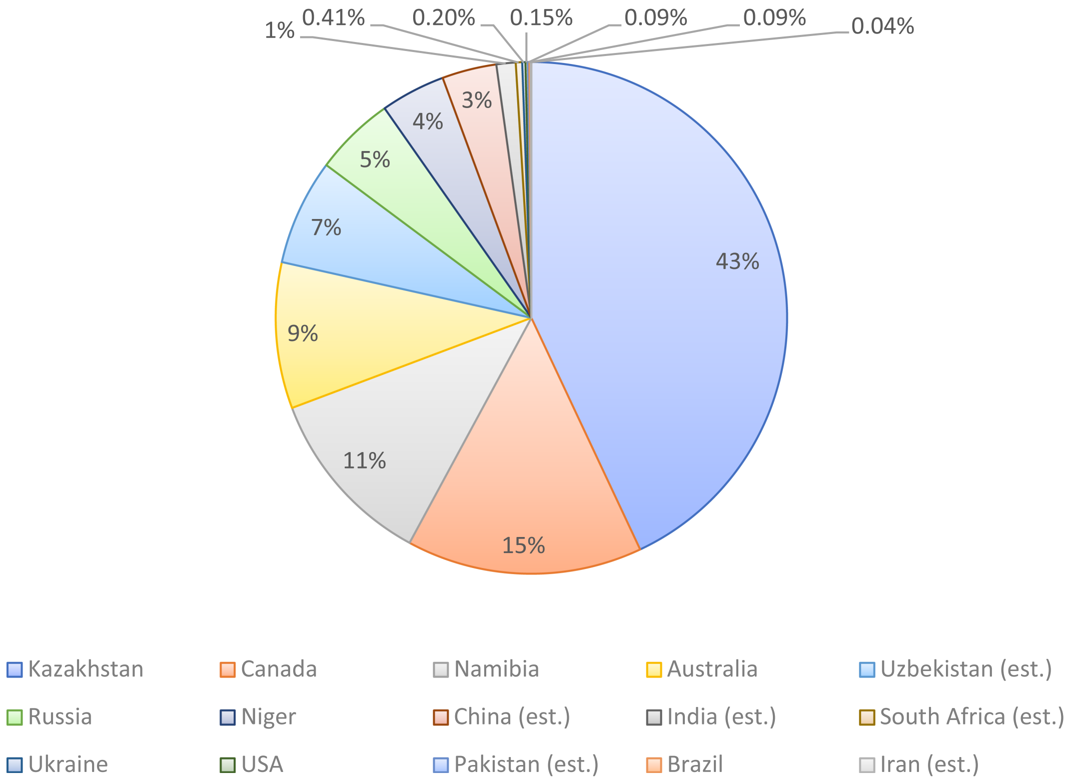

Figure 9. Shares of uranium production from mines (in tonnes U) as of 2022, with the total world production being 49,355 tonnes. Source: World Nuclear Association, 2024.

In the subsequent analysis, the evolution of scenarios for both the supply and demand of uranium was presented, detailed at a country-specific level. However, country specific data for supply analysis are fraught with uncertainties. In Appendix 2 some scenarios based on increases and decreases were provided, however these remain instructive and largely theoretical. For this section, a more qualitative approach is taken to analysis the geopolitical risks of uranium supply and enrichment. These risks have increased substantially due to sanctions on Russia, bifurcating global supply chains with efforts of on-sharing and friend-shoring, instability in the Sahel as well as rising demand for nuclear fuel. There are some reasons for optimism. Cameco is expecting to produce 18 million pounds at each of the two Canadian operations (McArthur River / Key Lake and Cigar Lake) in 2024, with the former aimed to extend its mine life to 2036. High grade deposits held by Denison and NextGen are promising, but are medium to long-term factors for production. However, with Cameco, Canada will be a key producer for the decades to come. Investment in mining in Australia is increasing, exemplified by the restart of Honeymoon Mine as well as several mines in various phases of development. Production in Namibia (at Husab Mine and Rossing Mine) contributes a significant global share (∼12% in 2022). For enrichment, Orano (French company) is expanding capacity (Georges Besse 2 plant, production expected in 2028), which Orano's Board of Directors linked explicitly to changing geopolitical dynamics. However, there are also concerning shifts, such as reduced production in Kazakhstan due to sulphuric acid shortages and insecurity of supply due to the coup d'etat in Niger.

If global trends of onshoring and friend-shoring continue, Canadian mining may supply North America and European markets, while Kazakh and Namibian supply may be oriented to Russia, China and India. The current trends suggest that this bifurcation will deepen (but policy changes are possible). Sanctions against Russian supply and enrichment are forcing rapid change within the United States (as it does not have domestic capacity for self-sufficiency of enrichment and supply has not been significant). Russia is a global leader of enrichment (~40% of market), creating the infrastructure cannot be done immediately to replace those supplies. The 2022 Inflation Reduction Act included a focus on domestic supply, and there is increasing political pressure to improve self-sufficiency (critical as around 1/5th of US electrical supply is from nuclear power, having 92 reactors). This is further supported by the Nuclear Fuel Alliance, which entrenches the bifurcation, as its members are the US, France, Japan, Canada and the UK. It is anticipated that geographies outside the direct influence this Alliance will face intensified competition over resources and influence, such as in Namibia, Niger and Uzbekistan. It is worth noting that uranium is not scarce per se, however high-grade deposits are scarce, and it will be these resources that draw investor attention and geopolitical competition.

Geopolitical factors will not only be influenced by power, politics and economics, these outcomes of the competition for uranium supply and enrichment will also be shaped by domestic and international regulation. Examples of domestic factors include environmental regulation regarding mining, and if an accident were to occur there may be setback for extended periods (there are risks in operations in Canada, for example, requiring freeze walls for containment). Similarly, regulation regarding developments in the sector, such as small modular nuclear reactors, will either enable or inhibit the sector within domestic spheres. This raises questions not only of geopolitics of supply, but also of access to technology and regulation.

Uranium demand analysis

Similar to supply, it is very difficult to create future scenarios due to high levels of uncertainty. If construction of nuclear power plants was considered, for example, China has plans to expand its 55 reactors by commissioning 17 more and a vision to expand to 220 by 2050. Moreover, China is the world's greatest producer of phosphate rock, which includes natural uranium, however, the majority of its resources have modest quantities (20–30 mg/kg; Shang et al. 2021). Some deposits in Sichuan and Yunnan contain greater amounts (≥90 mg/kg), which may allow for considerable uranium recovery. In 2016, it was projected that these resources may yield roughly 648 metric tonnes of uranium, which would supply around 9.7% of China's uranium requirements (Fang et al. 2018; Shang et al. 2021). By 2030, this figure might climb to 1158 metric tonnes, particularly as imports from countries such as Morocco increase, boosting China's uranium supply security (Shang et al. 2021).

These plans may not materialise in full and if they do, they may not occur on the current timeline. India is also planning to expand nuclear capacity substantially, aiming to increase its current 22 reactors to 40 by 2050. Notably also are a wide range of countries moving into nuclear energy, albeit on a much smaller scale. These shifts are indicative of a broader transformation in thinking about future energy sources (e.g. Argentina, Bangladesh, Brazil, Egypt, Turkey, UAE). Given the uncertainty, countries importing uranium were calculated using the broad equation (using 2022 data):

$$\text{Net Imports} = \text{Consumption} - (\text{Production - Exports})$$

Consumption data from Statista 2024 in 1,000 metric tons were acquired, while production data were sourced from the World Nuclear Association and export data as shares from Statista (2024). The existing data were complemented with fundamental calculations as below, due to incomplete international databases like UNComtrade, where major exporting countries like Kazakhstan were missing. This approach allows us to define the demand for uranium on a country level (Figure 10), by employing the following relationship:

$$\text{Demand for Uranium} = \text{Production} + \text{Imports - Exports.}$$

The global demand projections were applied to determine volumes distribution across countries based on different scenarios (Figures 11–13):

- Business as Usual Scenario: The main assumption here is that the current conditions will persist. The total demand projections were used from the middle scenario discussed earlier. Importantly, the analysis factored in the uranium expected to be used in future nuclear plants currently under construction. (World Nuclear Association, 2024). The plans for nuclear plants scheduled to be built between 2024 and 2030 were reviewed, and based on their announced capacities, the uranium demand was estimated and added that to the total demand for each corresponding year.

- Optimistic Scenario: This scenario examines current conditions alongside the pledge made by 22 countries to triple their nuclear power capacity by 2050. The nations committed to this goal include the USA, Canada, the UK, France, Japan, and others across Europe, Asia, and Africa, such as Bulgaria, the Republic of Korea, and Ghana (S&P Global Commodities, 2024). For this outlook, the high-demand scenario discussed earlier was applied to better understand the potential impact of these ambitious commitments on future energy needs.
- Pessimistic Scenario: In this scenario, a 25% reduction in demand from countries currently using uranium was considered. To reflect this shift, the approach applied the low-demand model, which aligns with the projected decrease in usage.

Figures 11–13 show three different scenarios for uranium demand across various countries to highlight potential trends in this market. The business-as-usual scenario shows that USA, China, France are major consumers, with growing demand over time, suggesting a continued reliance on nuclear power. Other countries such as UAE, Belgium and Taiwan have stable demand but significantly less than the first group. A significant amount also comes from Rest of World category. On the other hand, the Pessimistic scenario shows a significant decline in uranium demand, particularly from major consumers, which could imply changing in energy policies in these countries or improvements in reactor efficiency, or a shift toward other energy alternative sources. Combined, these studied scenarios highlight nuclear power's lasting presence in the global energy mix, with demand shaped by geopolitical decisions, policy changes, and technological progress. The optimistic outlook reflects a global push towards nuclear energy as a reliable, clean option to meet rising energy needs and combat climate change. Meanwhile, the more conservative growth seen in the pessimistic scenario might result from the increasing focus on renewables, safety concerns, or advances in energy efficiency.

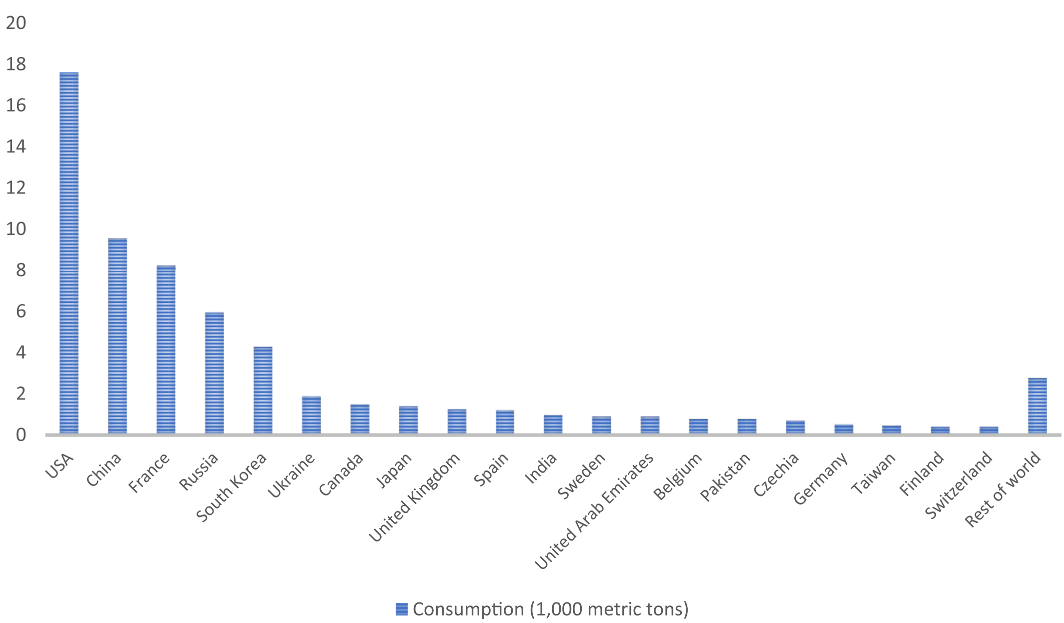

Figure 10. Uranium total consumption per country as in 2021; Data Source: Statista 2024.

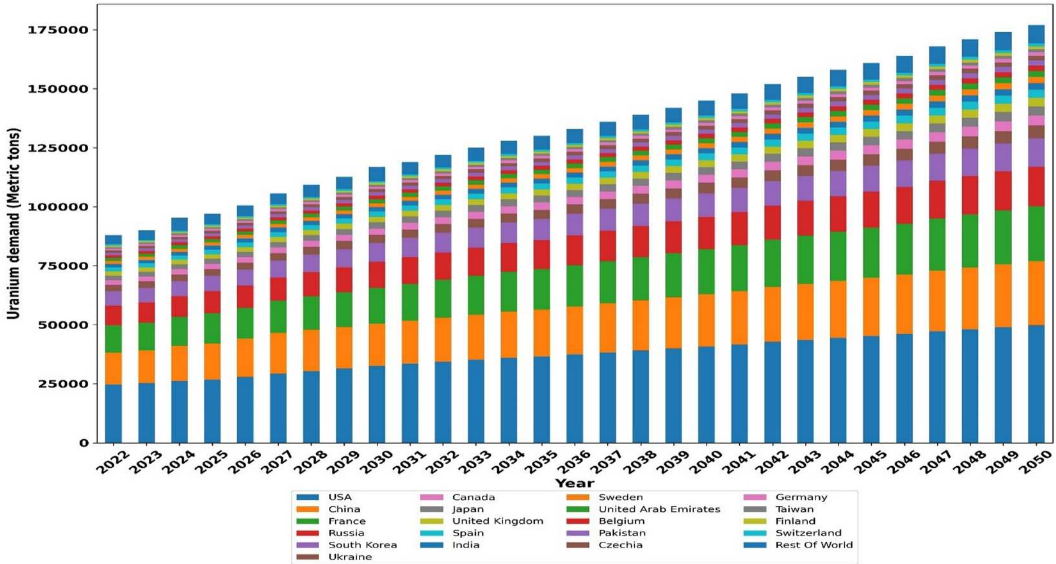

Figure 11. Country-Level Projected Uranium Demand: Business as Usual Scenario. Source: Authors.

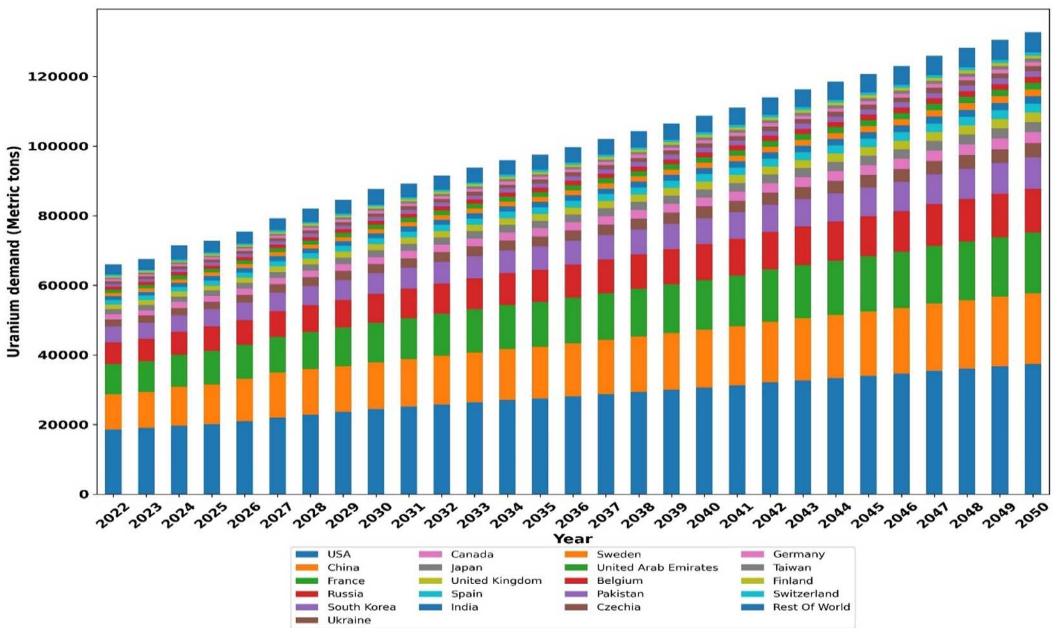

Figure 12. Country-Level Projected Uranium Demand: Pessimist Scenario. Source: Authors.

Discussion

In this study, uranium supply projections with demand were analysed and revealed a detailed narrative on the future dynamics of uranium economics. A comparison across several countries was conducted and by employing different scenarios. The results showed evident trajectories in the demand and supply curves that indicate potential market conditions. A consistency among both

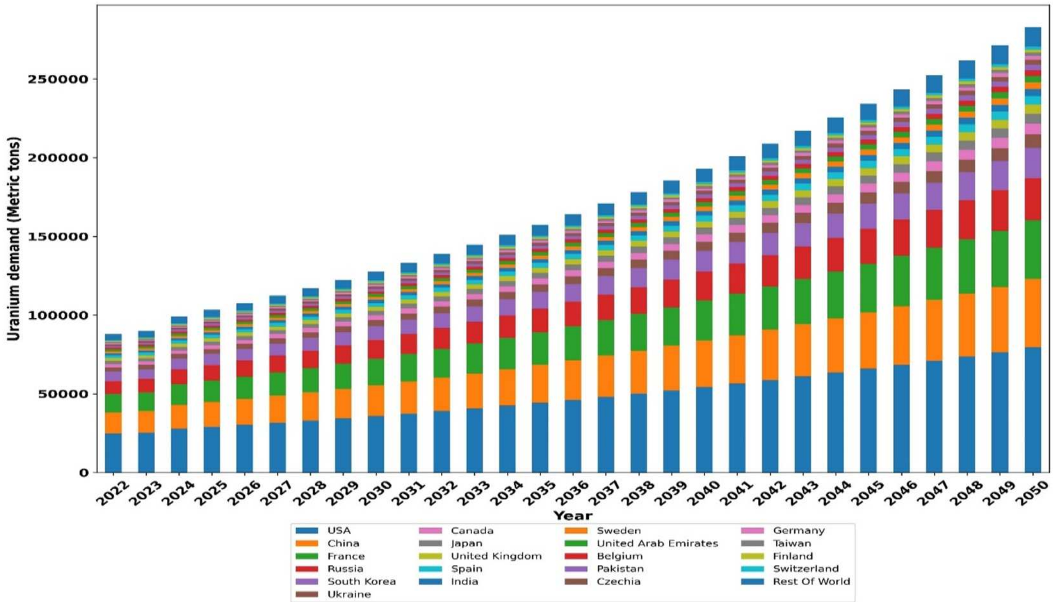

Figure 13. Country-Level Projected Uranium Demand: Optimistic Scenario. Source: Authors.

studied methods was noticed to estimate supply projections (econometric method and supply curve method), yielding closely aligned results with no significant differences between them. Given this consistency and for the sake of brevity, the following discussion will focus on the econometric model findings as a representative example in the forthcoming comparison estimates with the demand projection. The same insights derived from the supply curve method apply to the econometric model. Looking at the demand scenarios, one can see that the low demand graphs show a gradual rise, followed by a levelling off and a drop past 2035, revealing a possible gradual withdrawal from nuclear energy in certain countries. Additionally, the medium scenario suggests a constant and balanced increase in nuclear power, which is aligned with both environmental initiatives and economic growth, namely in developing countries. On the other hand, the high demand scenario proposes a steeper increase, illustrating a future where nuclear energy development increases aggressively, with less regard for environmental policy constraints. Interestingly, the supply side tells a different story when demand projection scenarios are compared. In the case of Low and Medium demand scenarios, uranium supply grows steadily, however after 2035 it starts to lag behind demand. The high demand scenario shows an even larger gap, sending a message of potential supply shortfall, which raises a critical need for strategic action if strong economic growth and nuclear expansion do materialise.

The deviation between supply and demand, particularly in the Medium and High Scenarios indicates several vital considerations that should be highlighted to enable the design of future agile policies. First, the shortage in uranium supply could drive uranium prices up and new exploration and mining activities. One the other hand, the historical record of uranium industry shows slow response to price changes, meaning these demand gaps might not be filled in a timely manner. Second, this lag in response between price changes and production has several implications for national strategies. For instance, countries with an abundance of uranium will need to adjust their export and production policies in order to meet the potential shortfall, while countries that heavily rely on nuclear power and require substantial volumes of uranium should focus on policies to manage their uranium reserves and imports. This could involve investing in uranium mines to create a secure buffer for future supplies or securing long-term contracts with exporters.

Technology plays an important role in defining the uranium market, as it contributes to advancing production and ensuring efficient use of resources. For instance, new nuclear technologies, including innovative reactor designs, could significantly shift our view of the demand side by aiding in providing more accurate demand projections. Also, these advancements could allow us to use existing uranium resources more efficiently, which would extend their availability. However, the projected deficit of uranium stresses the importance of diversifying our energy mix. One option is to invest in renewable energy and other clean energy sources to provide a buffer against potential over-reliance on nuclear power. Lastly, this also offers an opportunity for countries to collaborate and integrate efforts in areas related to uranium trade agreements and joint mining ventures, enabling them to achieve energy security targets using shared resources.

Additionally, it is vital to closely monitor the uranium market to make informed investment decisions at both the country and global levels. In this study, the supply and demand analysis showed that they serve not only as a market indicator but also reveals vital dynamics in the broader energy landscape. Therefore, understanding these dynamics is crucial for identifying investment opportunities and defining industry trends. This nexus of economic, technological, and geopolitical factors offers a comprehensive picture of what the market might look like in the future. Moreover, this analysis equips policy makers with essential tools to develop effective and agile policies.

Finally, the supply analysis in this study is based on uranium mining only, which is considered the primary supply. The focus on primary uranium supplies in this study is based on the latest reports from IAEA that outline that mining is the major future uranium supply. This is also based on several factors including the limited information on secondary sources, current changes in regulations and policies, difficulty anticipating mining technological advancements and shifting dynamics between primary and secondary supplies. Secondary supplies are not included and could play a role in meeting future demand, they include the following resources (NEW & IAEA 2022):

1. HEU: Highly Enriched Uranium: covers the uranium that has been processed to increase concentration of isotope U-235 to 20% or more. The main usage of this type of secondary supply is in nuclear weapons and some types of nuclear reactors.
2. LEU: Low Enriched Uranium: It contains 0.7% isotope U-235 and is commonly used as fuel for commercial nuclear power plants.
3. MOX: Mixed Oxide Fuel: contains multiple fissile oxide materials, typically plutonium blended with natural uranium, reprocessed uranium or depleted uranium.
4. RepU: Reprocessed Uranium: This type is recovered from spent nuclear fuel and has been processed so it can be used as fuel. It contains a higher concentration of U-235 than natural uranium.
5. Depleted Uranium Tails: This represents the remaining uranium after enrichment, and it contains a lower concentration of U-235. It can be stored or further processed for other uses.

At this point, it is vital to note that the cumulative uranium supply projected in this study, up to 2050, does not deplete the accessible resources reported as of 2021. The identified recoverable resources (reasonably assured resources and inferred resources) amount to 6,078,500 tonnes of uranium (World Nuclear Association 2023). These reserves are identified from the authoritative OECD NEA & IAEA's 'Red Book' titled: Uranium 2022: Resources, Production and Demand. Additionally, the identified resources mentioned earlier are at a cost boundary of 130$ per kg U, however if resources recoverable are considered up to a cost of $260 per kg U, the total identified resource will increase to a more substantial 7.918 million tonnes of uranium. This suggests that there is sufficient uranium supply capable to accommodate future demand fluctuations and potential increase in nuclear energy production.

There are several takeaways one can observe within the geopolitical context of uranium production and demand and among major exporting countries such as Kazakhstan, Canada, and

Russia, and how they affect global supply chains. For instance, Kazakhstan had a dominant share of 43% as of 2022, while Canada contributed 15%, which indicates the focus of supply in a few key countries. Moreover, there is shift in geopolitical landscape, particularly the West's intent to decrease reliance on Russians uranium, meaning these countries will need to solidify their positions as primary suppliers. This is obvious in the case of India given its reliance on imports from Kazakhstan and Canada. Similarly, the United States' intention to diversify away from Russian uranium also aligns with this trend. Projecting 2050 supply and demand is mainly driven by factors such as political relations, energy security policies and the strategic plans of uranium-rich countries. These factors combined will shape the global uranium market and could lead to new alliances and trade patterns. The future of the uranium market will depend on how current and new alliances will navigate geopolitical relationships and leverage their uranium resources to meet growing global demand.

Conclusion

Analysing current and projected nuclear power capacity across the globe shows a dynamic uranium market, with potential expansion in certain countries indicating strong future demand. Looking at China, India, and the UK, they have robust plans to increase their nuclear power capacities; on the other hand, the United States and France show mature markets with steady demand. Additionally, the international landscape indicates a complex interplay of energy policy, environmental commitments, and market forces that will shape the uranium market for years to come. Future work should examine these developments, taking into account the potential impacts of factors such as new technologies, policy shifts, and environmental constraints. Such studies could build upon this study by expanding the scenarios of geopolitical pathways, and conducting foresight analyses regarding potential supply chain impacts.

The findings of this study show a significant gap between projected uranium demand and supply, with the most noticeable divergence in the Medium and High scenarios. These differences indicate that it is vital to have strategic interventions to safeguard against any potential shortfall in uranium supply as early as 2035. The projected supply is primarily established based on mining production, underlining the IAEA's projection that mining will be the main source of uranium in the coming years, although secondary sources could contribute to the total supply.

Kazakhstan, Canada, and Russia are the major players shaping the geopolitical landscape of uranium production and demand up to 2050. Western countries are working on reducing their reliance on Russian uranium, which contributes to reshaping global trade dynamics. By 2050, the strategic decisions of uranium-rich nations in response to political and energy security considerations will affect the creation of new global alliances and trade patterns. The main focus is on how current and new alliances manage their geopolitical relationships and utilise uranium to meet the growing demand for nuclear energy.

The uranium market's response to price changes needs to be studied in depth to explore the long-term sustainability of resources, considering secondary uranium sources. Therefore, this would open up research that is multidisciplinary and includes researchers in economic modelling, policy analysis, and techno-economic analysis within the nuclear sector. The findings of this study identify a future where challenges and opportunities lie ahead for the uranium supply chain. It is important that actors from different sectors across countries collaborate to ensure that opportunities in this field can be harnessed.

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Data availability

The data supporting the findings of this study are publicly available and can also be requested from the corresponding author, [SS], upon reasonable request.

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Appendices

Appendix 1: Geopolitical and technological factors in uranium supply: gaps in current research and emerging innovations

While there is a substantial body of research on modelling the uranium supply curve and the relationship between uranium pricing and production, an important gap remains in incorporating geopolitical factors into these calculations. This oversight is especially significant in light of recent developments, such as the Russia-Ukraine conflict and the subsequent Western sanctions on Russia, both of which have reshaped the global uranium market. Moreover, Kazakhstan's pivotal role as a major uranium supplier introduces additional complexities that are sometimes neglected in current analyses.

For example, Monnet, Gabriel, and Percebois (2017) critique the simplified assumptions in resource estimation models in their work, focusing primarily on ore grade while neglecting factors like ore body size and mining techniques. Additionally, a market-clearing model developed for the uranium and enrichment industries (Schneider et al. 2013) provides key insights into supply-demand dynamics through 2030, shedding light on important industry trends. Another notable contribution comes from a dynamic model that examines the global uranium market from 1990 to 2050, incorporating stocks and flows of uranium throughout the nuclear fuel cycle. This model emphasises the role of time lags in price volatility and explores strategies for demand reduction and external shocks (Rooney, Nuttall, and Kazantzis 2015).

Despite these advances, most studies fail to examine how geopolitical tensions, particularly those related to the Russia-Ukraine war, could influence the accessibility and availability of uranium resources. This omission is crucial, especially given the increasing reliance of countries like China on foreign uranium supplies (Chen, Xing, and Du 2017). Furthermore, many analyses overlook how shifts in geopolitical alliances might alter market dynamics, especially Kazakhstan's role as a key supplier.

Another research effort focuses on the long-term supply dynamics of uranium within the broader context of energy resources (Bidaud et al. 2015). This study highlights that uranium's cost is not only determined by cumulative output but also by competition from alternative energy sources. However, it too fails to address how evolving geopolitical dependencies could impact market stability, especially Kazakhstan's significant role in the uranium supply chain.

Technologies

Research on uranium-related technologies takes a multifaceted approach, integrating advancements in remediation strategies, economic assessments, and emerging nuclear technologies. The growing demand for uranium has amplified concerns about environmental contamination. Li and Zhang (2012) review remediation technologies for uranium-contaminated environments, categorising these into physical, chemical, and biological methods. Physical approaches are suitable for localised contamination, while chemical methods, though efficient, remain largely experimental. Bioremediation, including phytoremediation and microbial remediation, offers sustainable solutions with minimal environmental disruption, highlighting the need for context-specific strategies.

Much of the literature also focuses on the advancements in Small Modular Reactors (SMRs). Although SMRs are often perceived as less economically competitive due to assumptions about economies of scale, they have distinct advantages, such as modularity and shorter development times (Locatelli and Mignacca 2020). Stewart and Shirvan (2022) further underscore these advantages, identifying five factors that could make SMRs more economically viable than traditional large reactors (LRs), including factory production efficiencies and streamlined designs. However, establishing a strong economic case for SMRs remains challenging, as comprehensive, bottom-up studies that quantitatively assess these aspects are still lacking.

Economic assessments of advanced nuclear power technologies are especially critical in the early design phases. Khan, Almutairi, and Alanazi (2021) conducted a study using the Generation-IV economic programme (G4-ECONS) to estimate total costs for advanced reactors like the System Modular Advanced Reactor (SMART), concluding that SMART offers a cost-effective alternative to both Generation-III and Generation-IV reactors. This underscores the importance of rigorous economic modelling in evaluating emerging nuclear technologies.

Technological innovation is key to the future of nuclear energy. Elhegazy and Kamal (2022) argue that newer nuclear technologies could significantly reduce costs, provided there are substantial advances in manufacturing processes. However, the slow pace of regulatory approvals and plant construction continues to pose challenges to the competitiveness of nuclear energy, reinforcing the need for systemic improvements. The evolving landscape of nuclear technology is further highlighted by Arostegui and Holt (2019), who outline various advanced reactor designs, such as advanced water-cooled, gas-cooled, and molten salt reactors. While many of these concepts have historical roots, their commercial viability remains an open question.

Appendix 2: country-level: projected supply scenarios

Considering the global supply projections previously discussed, the potential availability of uranium on a country level under three scenarios was anlayzed: for the business as usual scenario, the shares of key players were maintained at current levels; for the optimistic scenario, these shares were increased by 25%; and for the pessimistic scenario, they were reduced by 25%.

Analysing the projected uranium supply scenarios depicted across three figures, the following insights emerge: The first figure, representing the 'Business as Usual' scenario, shows Kazakhstan, Canada, and Australia as the leading suppliers, with the overall production increasing gradually. This stability suggests no significant policy or capacity changes. The 'Pessimistic Scenario,' depicted in the second figure, illustrates a notable reduction in supply from all countries, hinting at potential resource depletion, economic challenges, or geopolitical tensions impacting production. Despite this, the diversity of supply sources is maintained. Conversely, the 'Optimistic Scenario' in the third figure demonstrates a substantial rise in production, particularly from Kazakhstan, Canada, and Australia, possibly reflecting new mining developments or increased nuclear energy investment. This scenario could be driven by higher demand and favourable market conditions, with countries like China and India aiming for greater uranium self-sufficiency.

Across these scenarios, Kazakhstan is consistently the top supplier, indicating its significant role in the uranium market. The variety in supply patterns underlines the geopolitical stability and strategic value of uranium for energy security. While the optimistic outlook suggests an expanding nuclear power sector in response to rising energy needs and a shift to low-carbon sources, the pessimistic view could indicate limitations facing the nuclear industry, such as environmental, economic, or competition from alternative energies. These projections underscore the influence of various factors on future uranium supply, including policy shifts, market dynamics, and global energy trajectories.

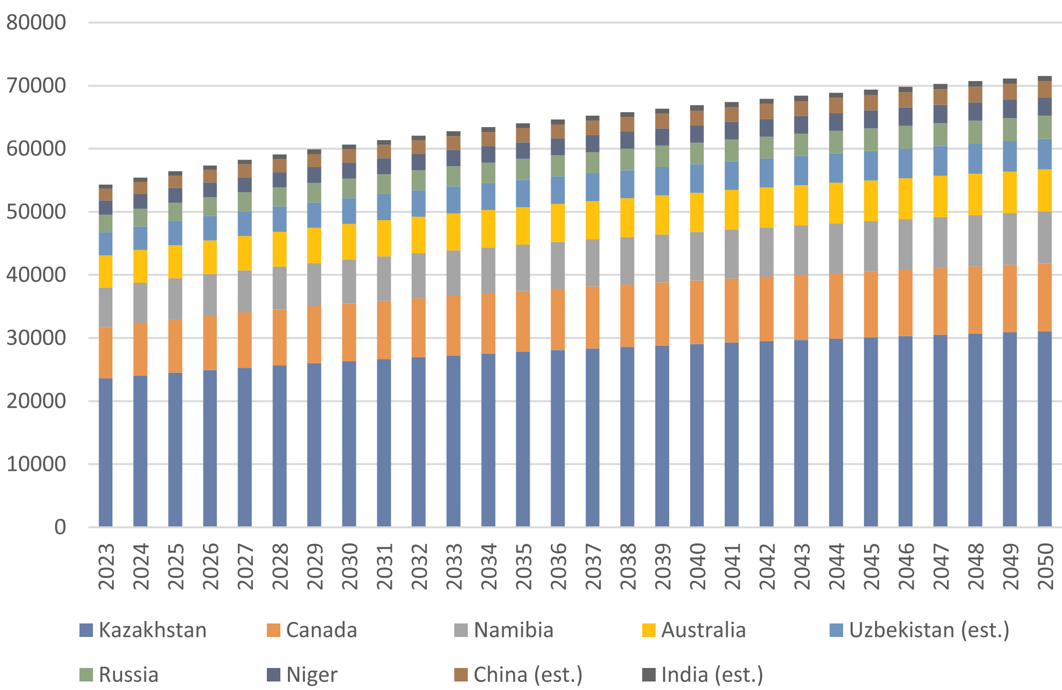

Figure A1. Country-level projected uranium supply: Baseline scenario. Source: Authors.

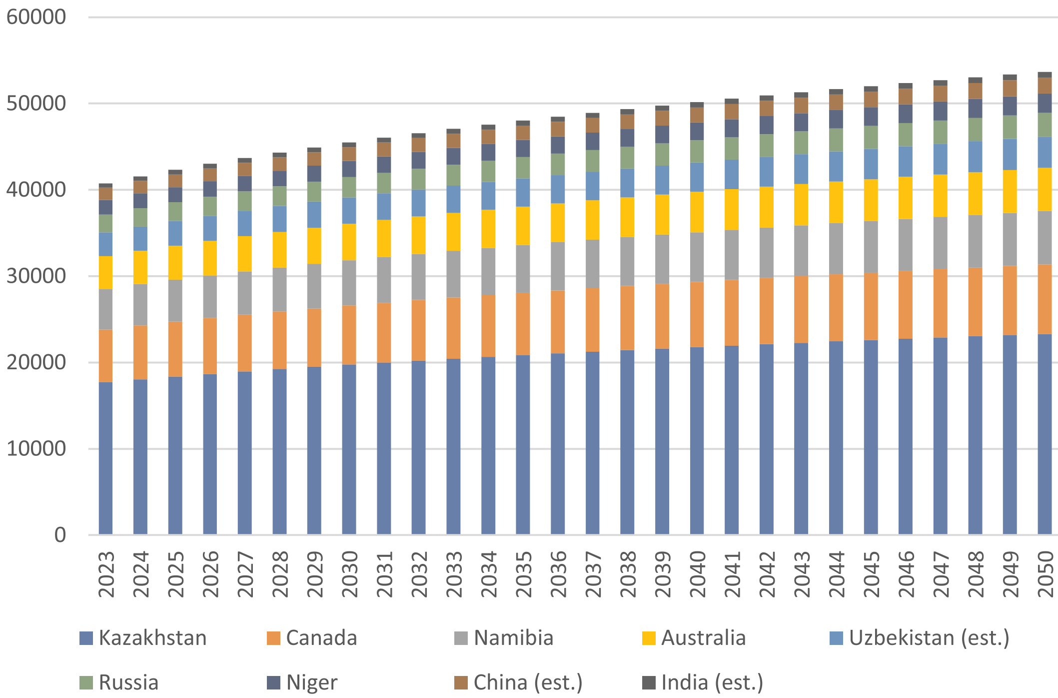

Figure A2. Country-level projected uranium supply: Pessimistic scenario. Source: Authors.

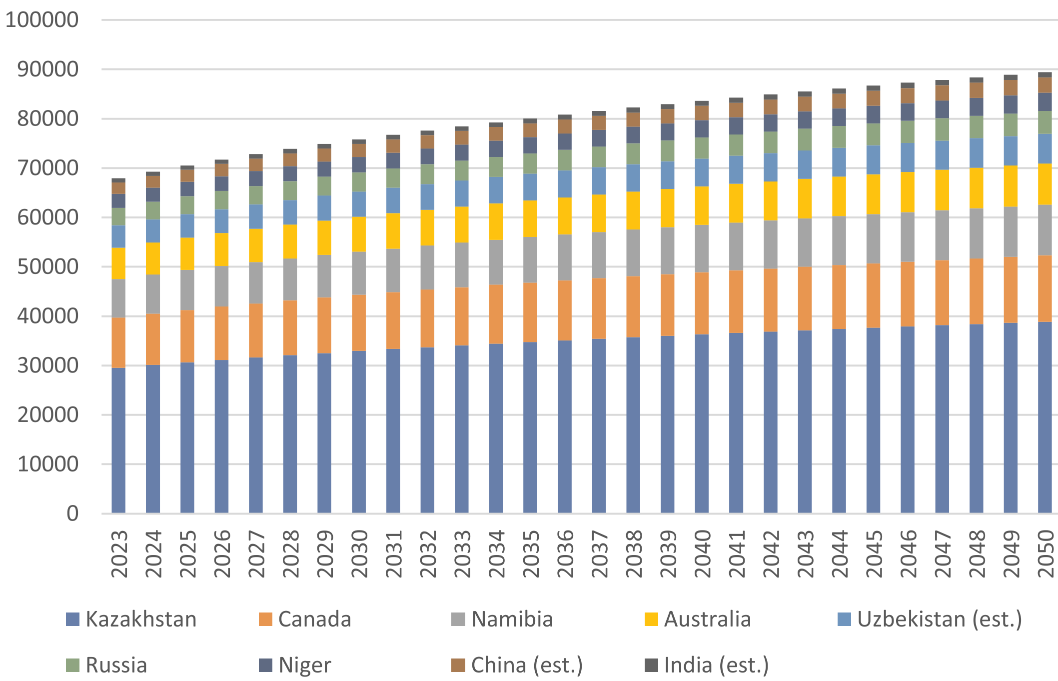

Figure A3. Country-level projected uranium supply: Optimistic scenario. Source: Authors.

Appendix 3: model estimation

In this study, the econometric analysis started by investigating the unit-root characteristics of the time series data, an essential step to verify its suitability for deeper exploration. Standard methods were applied to assess the stationarity of the variables, specifically through the use of the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) Unit Root Tests (URT). These tests operate under the assumption, or null hypothesis, that the variables are non-stationary.

Table A1. Unit root tests.

Test Type	At Level		At First Difference	
	PP Test	PP Test	PP Test	PP Test
With Constant	t-Statistic: -1.6264	−1.0965	t-Statistic: -3.3359	−5.2195
	Prob.: 0.4536	0.7118	Prob.: 0.0254	0.0001
	n0	n0	n0	***
With Constant & Trend	t-Statistic: -0.1309	−2.5092	t-Statistic: -3.9716	−5.1867
	Prob.: 0.9907	0.3229	Prob.: 0.0259	0.0004
	n0	n0	n0	***
Without Constant & Trend	t-Statistic: 0.9602	1.061	t-Statistic: -3.2187	−5.0508
	Prob.: 0.9049	0.9229	Prob.: 0.0026	0
	n0	n0	***	***
	ADF Test	**ADF Test**	**ADF Test**	**ADF Test**
With Constant	t-Statistic: -3.6242	−1.4896	t-Statistic: -3.3583	−5.2195
	Prob.: 0.0168	0.532	Prob.: 0.0242	0.0001
	** **	n0	** **	***
With Constant & Trend	t-Statistic: 0.6033	−3.0663	t-Statistic: -4.0237	−5.1867
	Prob.: 0.9986	0.1239	Prob.: 0.0233	0.0004
	n0	n0	n0	***
Without Constant & Trend	t-Statistic: 1.1833	0.8301	t-Statistic: -3.2502	−5.0024
	Prob.: 0.9340	0.888	Prob.: 0.0024	0
	n0	n0	***	***

Source: Authors.

***, **, and * indicate a rejection of the null hypotheses at the 1%, 5%, and 10% significance levels, respectively. n0: not statistically significant.

From the table above, one can notice that all variables were integrated in the same order, and it proceeded to apply the Hansen Parameter Instability Test. This was aimed at identifying any long-term cointegration relationships among the variables. The null hypothesis of the test points to the existence of such a relationship, which was further corroborated by the park-added variables test, similarly indicating that the series were cointegrated.

Table A2. Long-term cointegration test.

	Stochastic	Deterministic	Excluded	
Lc statistic	Trends (m)	Trends (k)	Trends (p2)	Prob.*
0.468	1	0	0	0.039

*Hansen (1992b) Lc(m2 = 1, k = 0) *p*-values, where m2 = m-p2 is the number of stochastic trends in the asymptotic distribution

Source: Authors.

The Hansen Parameter Instability Test result suggests that there is evidence of a stochastic trend in the time series data being analysed. In the context of econometric modelling, this may indicate that you can proceed with further analysis such as cointegration testing, as it supports the existence of a long-term relationship among the variables.

To estimate these long-run relationships more precisely, several robust estimation techniques were employed. These included Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegration Regression (CCR). Each of these methods addresses potential issues with endogeneity and serial correlation, thereby improving the reliability of the long-term coefficient estimates. FMOLS directly corrects these issues, while DOLS introduces leads and lags of the differenced independent variables to account for endogeneity and autocorrelation. CCR uses canonical decomposition to manage endogeneity within the cointegrating equation effectively.

Table A3. Long term estimations outputs using different techniques.

Method	Variable	Coefficient	Std. Error	t-Statistic	Prob.
CCR	LOG(PRICE)	0.201	0.058	3.479	0.002
	C	10.286	0.150	68.242	0
FMOLS	LOG(PRICE)	0.2025	0.065	3.082	0.0053
	C	10.283	0.173	59.171	0
DOLS	LOG(PRICE)	0.219	0.072	3.009	0.0069
	C	10.242	0.193	52.825	0

Source: Authors.

By integrating these econometric techniques, the study aims to offer a comprehensive and reliable forecast of uranium production trends relative to price fluctuations. These insights will be critical for policy makers, investors, and industry professionals as they navigate the evolving landscape of essential minerals and metal resources. For those interested in delving deeper into the technical aspects of the unit root and cointegration tests, foundational works by Dickey and Fuller (1979), Phillips and Perron (1988), and Johansen (1988) provide detailed methodologies and discussions.