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Geological and Economic Assessment and Comparative Analysis of Uranium ore Deposits in Russia and Iran

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P A P E R I N F O

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A B S T R A C T

This study conducts a comparative geological and economic assessment of uranium resources in Russia and Iran, with a focus on their ability to support the development of domestic nuclear energy. Unlike previous research, which has predominantly examined Russian–Iranian cooperation from political or institutional perspectives, this work evaluates uranium availability using geological classifications and economic cost categories of reserves. It distinguishes between recoverable resources reported for Russia and in situ resources reported for Iran, with the latter converted to a comparable basis through the application of appropriate recovery factors. In addition to analyzing the structure and potential of the resource base, the study takes into account historical and projected uranium production as well as consumption scenarios for both countries. On this basis, long-term self-sufficiency horizons are estimated through 2045. The findings show that Russia possesses a vast and geologically diverse uranium base, capable of ensuring long-term supply if new mining projects are developed to offset the expected decline in production after 2030. Iran, by contrast, holds more limited and higher-cost reserves, concentrated mainly in metasomatite deposits, which makes the achievement of sustained self-sufficiency unlikely without external cooperation or technological breakthroughs. At the same time, geological similarities between the two countries create a basis for potential collaboration in uranium exploration and development. By addressing a relatively underexplored aspect of the literature, this study provides a structured assessment of uranium supply sustainability and introduces a comparative perspective relevant not only to Russia and Iran but also to other countries with emerging nuclear programs.

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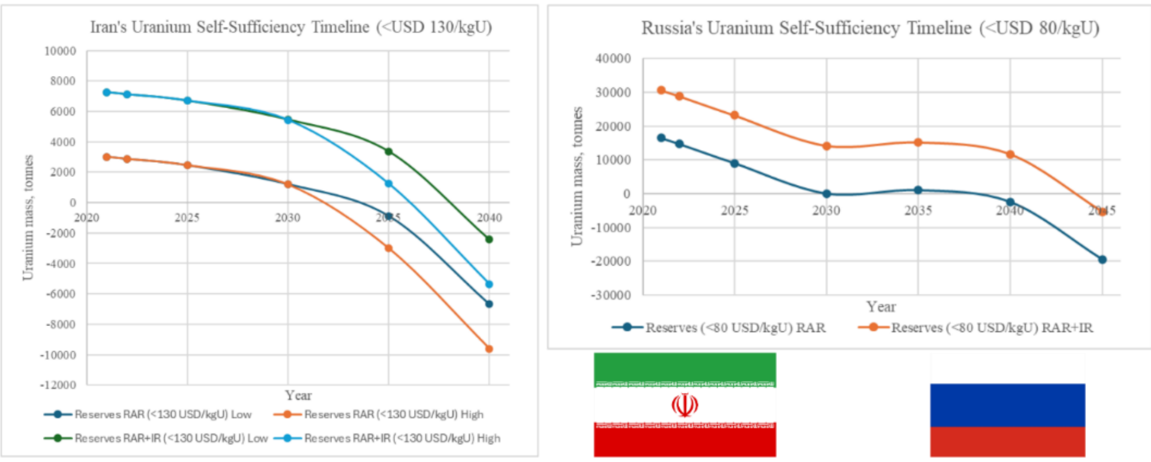
Graphical Abstract



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NOMENCLATURE

R_{rec}	Recoverable uranium reserves (tonnes U)	P	Annual uranium production (tonnes/year)
$R_{in\ situ}$	In situ uranium reserves (tonnes U)	C	Annual uranium consumption (tonnes/year)
RF	Recovery factor (%)	X	Target year
$R_{X/A}$	Uranium reserves in year X/A (tonnes U)	A	Base year
R_{last}	Last known positive level of reserves (tonnes U)	Y	Number of years remaining before exhaustion

1. INTRODUCTION

Uranium continues to play a key role in the global energy system, valued for its high energy density and its strategic importance in nuclear power generation (1). As global energy demand rises and climate targets become more urgent, nuclear energy is increasingly seen as an essential part of sustainable and secure energy strategies (2, 3). Many countries are expanding investments in nuclear capacity to ensure stable baseload electricity alongside decarbonization goals (4, 5).

In recent years, the uranium market has exhibited notable volatility. After a prolonged period of low prices, uranium experienced a sharp surge between 2021 and early 2024, driven by renewed nuclear interest, energy security concerns, and speculative restocking. This was followed by a correction, with prices declining toward US$ 140/kgU by early 2025. These fluctuations highlight the sector's sensitivity to short-term disruptions and its ongoing dependence on broader geopolitical and economic trends (6).

Understanding the availability, economic accessibility, and geological distribution of uranium resources is critical for anticipating future market dynamics (7). However, cross-country comparisons are complicated by differences in exploration maturity, reporting standards, and evolving production costs. Technological advances—such as recycling, fuel reprocessing, and advanced reactor designs—may also reshape both the quantity and the quality of economically viable uranium resources with respect to time (8, 9).

This study presents a comparative analysis of uranium resources in Russia and Iran—two countries with contrasting positions in the nuclear sector. Russia possesses one of the largest uranium resource bases globally, along with an integrated fuel cycle and substantial technological expertise. Iran, by contrast, has a smaller and less diversified uranium endowment but growing nuclear ambitions. Similar development barriers—such as dependence on external technology and institutional limitations—have been noted in emerging energy sectors like Mozambique's gas industry (10). By examining geological structures, production and consumption balances, and long-term self-sufficiency horizons, this work aims to assess their respective uranium security outlooks within a changing global nuclear landscape.

The aim of this research is to conduct a geological and economic assessment of uranium resources in Russia and Iran, with emphasis on analyzing absolute volumes and the potential of different deposit types and economic cost categories, determining their capacity for long-term self-sufficiency, and identifying complementarities that could serve as a basis for bilateral cooperation.

To achieve this aim, the study defines the following objectives:

1. To analyze the structure of uranium resources in Russia and Iran by type (RAR and IR) and by economic cost categories (<40, <80, <130, and <260 US$/kgU).
2. To harmonize differences in resource reporting and to analyze reserves by deposit type and mining method, applying recovery factors specific to each extraction technology.
3. To assess historical and projected uranium production, along with consumption scenarios for both countries, in order to evaluate the balance between supply and demand.
4. To estimate long-term self-sufficiency prospects and to identify complementarities that may provide a basis for bilateral cooperation

2. LITERATURE REVIEW

2. 1. Typology and Global Distribution of Economically Recoverable Uranium Resources

As of June 2025, uranium prices remain slightly above US$ 140/kgU, making it especially relevant to focus on deposits recoverable at prices below US$ 130/kgU. Based on January 2023 data, global reasonably assured and inferred resources at this threshold total approximately 5.93 million tonnes, distributed across a wide spectrum of uranium deposit types. The most significant category is sandstone-hosted deposits, contributing around 1.90 million tonnes. These occur in permeable fluvial and marginal marine sandstones, where uranium precipitates through redox reactions with organic matter or sulfides, and they are particularly amenable to in situ recovery. Key production regions include Kazakhstan, the United States (notably Wyoming and Texas), Uzbekistan, Nigeria and Mongolia (11).

Proterozoic unconformity-related deposits, although geographically limited, represent the richest known uranium ores by grade, with 699,000 tonnes recoverable at this threshold (12). Found primarily in the Athabasca Basin of Canada and the Alligator Rivers Province in Australia, these deposits form at the contact between sedimentary basins and older crystalline basement rocks and typically exhibit uranium concentrations well over 1% (13). Polymetallic iron oxide breccia complex deposits, typified by Olympic Dam in South Australia, contribute 1.35 million tonnes. Although the uranium content is low, it is economically viable as a by-product of copper, gold, and silver mining due to the vast size of the orebody (14). Ancient placer-type paleo-quartz-pebble conglomerates, mainly in South Africa's Witwatersrand Basin and Canada's Elliot Lake District, contain 311,000 tonnes of uranium; despite modest grades, they are valued for their scale and geological stability (15). Metasomatite deposits—linked to large-scale sodium or potassium metasomatism in Precambrian shields—yield about 573,500 tonnes and are prominent in Ukraine, Brazil, and Russia (16). Intrusive deposits, totaling 372,200 tonnes, are found in peralkaline complexes, anatectic granites, or carbonatites in regions like Namibia (Rössing, Husab), Greenland (Kvanefjeld), and Brazil (Poços de Caldas) (17-19). Volcanic-related deposits provide 233,000 tonnes and are concentrated in pyroclastic and caldera settings such as Russia's Streltsovska Caldera, Peru's Macusani Plateau, and areas of China (20, 21). Granite-related uranium systems, mainly in France, Germany, the Czech Republic, and China, add 102,900 tonnes and are associated with hydrothermal processes around peraluminous leucogranites (22, 23). Metamorphite deposits, hosted in high-grade metamorphic rocks, offer 87,500 tonnes and are especially notable in India, Canada, and Kazakhstan. Surficial uranium deposits contribute 209,100 tonnes, forming in calcrete-rich valley-fill and playa environments under arid conditions, with Namibia and Australia hosting the largest examples. Smaller but relevant contributions come from carbonate-hosted uranium deposits (19,800 tonnes), such as India's Tummalapalle, and phosphate-bearing formations (7,100 tonnes), with recoverable uranium found as a by-product in Morocco and Florida. Lignite- and coal-associated deposits, mainly in Kazakhstan, the USA, and South Africa, offer 30,900 tonnes through uranium accumulation in organic-rich layers (24). At the current price threshold, black shale and collapse breccia pipe deposits provide no recoverable uranium, though large low-grade resources in Sweden, the USA, and parts of Central Asia could gain relevance with technological advances or further price increases (25, 26).

The distribution of these deposit types is shown in Figure 1. The uranium resource base is not only geologically diverse, but also unevenly distributed in terms of economic recoverability. This distribution highlights both the geological complexity and geographic diversity of the world's uranium resource base, reinforcing the need for tailored mining and processing strategies aligned with deposit type and economic context.

2. 2. Mining Methods and Geological Determinants of Uranium Recovery

Uranium can be extracted using a range of mining and recovery techniques, each of which is selected based on the depth, grade, geological setting, and geotechnical properties of the deposit. The primary methods include open pit mining, underground mining, in situ leaching (ISL), and co- or by-product recovery. The selection of method is closely linked to geological and hydrogeological factors, which influence not only operational feasibility but also the efficiency and economics of uranium recovery (27). Table 1 provides an overview of these major extraction methods, their typical ore types, and key geological and operational characteristics.

Open pit mining is applied to ore bodies that are close to the surface and of sufficient lateral extent to economically justify the removal of overburden. The method is common for surficial, intrusive, and shallow sandstone deposits, as well as some metasomatite and lignite-associated uranium occurrences. The feasibility of open pit mining depends on factors such as orebody geometry, stripping ratio, and the mechanical properties of host rocks, which determine slope stability and excavation methods. While large-scale operations such as the Rössing mine in Namibia demonstrate the potential size of open pits, this method becomes uneconomical at greater depths unless justified by high ore grades or the presence of valuable co-products (29).

Underground mining is chosen when ore bodies are located at greater depths or when surface impact must be minimized. It is typical for high-grade unconformity-related deposits, granite-hosted veins, metamorphic or volcanic systems, and compact carbonate or conglomerate formations. A range of mining techniques is used depending on ore geometry and ground stability, including room and pillar, cut-and-fill, and jet boring.

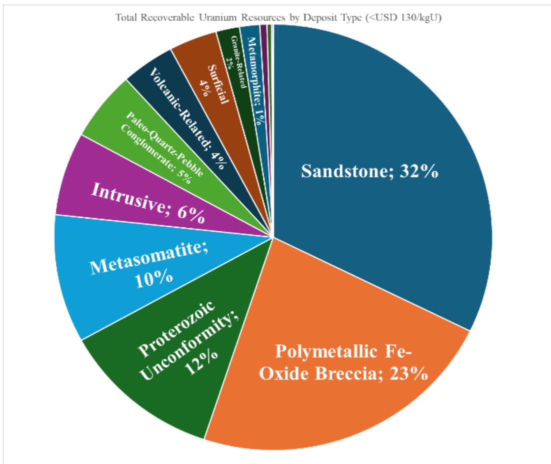

Figure 1. Total Recoverable Uranium Resources by Deposit Type (<US$ 130/kgU) (11)

TABLE 1. Mining Methods and Associated Ore Types (11, 27, 28)

Mining Method	Ore Types	Geological/Technical Features	Overall recovery factor, %
Open Pit Mining	Sandstone, Surficial, Intrusive, Metasomatite (shallow), Lignite – Coal	Applied to shallow deposits that are laterally extensive and near surface. Used in calcrete-hosted surficial deposits (e.g., in Namibia and Australia), intrusive anatectic uranium deposits (e.g., Rössing), and some metasomatite or coal-related deposits when conditions allow. Preferred where stripping ratio is favorable and ore grade justifies large-scale excavation.	80
Underground Mining	Proterozoic Unconformity, Volcanic-Related, Granite-Related, Metamorphite, Paleo-Quartz-Pebble Conglomerate, Carbonate, Collapse Breccia, Metasomatite (deep)	Used for deep or structurally complex deposits with high grade or steep geometry. Ground control is essential, particularly in water-saturated zones (e.g., McArthur River, Cigar Lake). Common for vein-hosted, stratabound, or breccia-type mineralization. Also used in steeply dipping granite-related or carbonate strata-bound.	75
In Situ Leaching (ISL)	Sandstone	Used exclusively for certain sandstone deposits with suitable hydrogeological settings—permeable, saturated, confined aquifers located below the water table, and uranium in mineral forms amenable to leaching (e.g., uraninite, coffinite). Most common in roll-front and tabular deposits with redox interfaces.	85 (Acid) 70 (Alkaline)
Co-/By-product	Polymetallic Fe-Oxide Breccia, Phosphate	Uranium is not the primary commodity. Extracted as a by-product in polymetallic operations like Olympic Dam (Cu-Au-U) or potentially during phosphate processing. Recovery is technically feasible but rarely commercialized for phosphate at present. Economics depend heavily on the primary mineral product.	65

Ground conditions are critical: saturated or weak host rocks require grouting or artificial ground freezing, as was done at McArthur River (30). Emerging monitoring solutions—such as UAV-based image segmentation systems used in infrastructure diagnostics—could be adapted to enhance site safety and environmental oversight in such geotechnically demanding settings (31). In such settings, ventilation design and dust and radon management also become major cost and safety considerations. The method's economic success is tied closely to geological complexity, rock strength, and access conditions (32-34).

In situ leaching, is used primarily for uranium hosted in permeable, saturated, and confined sandstone aquifers. The process involves circulating a lixiviant—typically acidic or alkaline—through injection and recovery wells to dissolve uranium in place. ISL avoids many of the environmental impacts of conventional mining and is especially prevalent in Kazakhstan and parts of the United States. However, it requires specific conditions: the host rock must be chemically and physically suited to leaching, the mineralization must be accessible to fluids, and the surrounding formation must effectively confine the lixiviant. Geological heterogeneity, carbonate content, and permeability variations can all affect recovery efficiency and cost (28).

Co-product and by-product recovery occurs when uranium is extracted alongside other minerals, often during the processing of copper, gold, or phosphate ores. At Olympic Dam in Australia, uranium is a by-product of a large-scale polymetallic mining operation. In phosphate-rich regions like Morocco and Florida, uranium recovery has been studied and piloted but is not practiced commercially today. In these settings, uranium is not the primary target, and its economic viability depends on integration with the main processing flow and the market value of the recovered uranium. Grades are typically low, and process design must be tailored to extract uranium without disrupting the primary product stream (35, 36).

Geological characteristics play a decisive role in determining both the cost and the method of uranium extraction. Critical factors include orebody depth, thickness, geometry, host rock strength, permeability, chemical composition, and the mineralogical form of uranium (37). For instance, carbonates and clay-rich rocks can increase reagent consumption, and refractory uranium minerals complicate leaching (38-40). Operational parameters such as overburden removal, ground control, and groundwater chemistry also shape project design and economics. As a result, the recovery factor in uranium production varies significantly across deposits and depends strongly on site-specific geological and technical conditions (41, 42).

2. 3. Global Leaders in Uranium Resources: Distribution, Costs, and Geological Profiles

Uranium resources are categorized internationally according to a two-dimensional classification system developed by the International Atomic Energy Agency (IAEA), which evaluates both the geological confidence and the estimated production cost of known deposits. The classification distinguishes between Reasonably Assured Resources (RAR) and Inferred Resources (IR), which together form the category of Identified Resources. RAR are defined by a high degree of geological confidence, based on detailed sampling and evaluation, and are considered recoverable under current economic and technological conditions. Inferred Resources are supported by more limited data and carry a greater degree of uncertainty. Resource categories are also grouped by cost of recovery, with thresholds set at less than US$ 40/kgU, US$ 40–80/kgU, US$ 80–130/kgU, and US$ 130–260/kgU. These are not market prices, but estimates that incorporate mining, processing, infrastructure, environmental management, and other associated expenses (11, 43).

Using this classification, the global inventory of identified uranium resources currently amounts to about 5.93 million tonnes recoverable at production costs below US$ 130/kgU. Several countries stand out as having particularly large and significant uranium endowments. Figure 2 presents the distribution of identified recoverable uranium resources by country, illustrating both the concentration of uranium stocks in a few leading countries and the broader distribution among other resource holders (44). Based on the most recent and detailed data, the leading countries by total identified uranium resources recoverable at costs below US$ 130/kgU—which includes both Reasonably Assured Resources (RAR) and Inferred Resources (IR)—illustrate a diverse global distribution shaped by geology, extraction methods, and national policy (45).

Australia holds the world's largest identified uranium resource base, with 1,236,200 tonnes of recoverable uranium in the < US$ 130/kgU category. This represents approximately 28% of global identified resources at this cost level. A major share of these resources—around 68%—is concentrated in a single site: the Olympic Dam deposit. This polymetallic iron oxide breccia complex is primarily mined for copper, with uranium recovered as a co-product. While vast in scale, the uranium grades at Olympic Dam are low, and production is shaped by the economics of other metals. Other deposits, such as Ranger and Four Mile, contribute smaller shares to Australia's overall total.

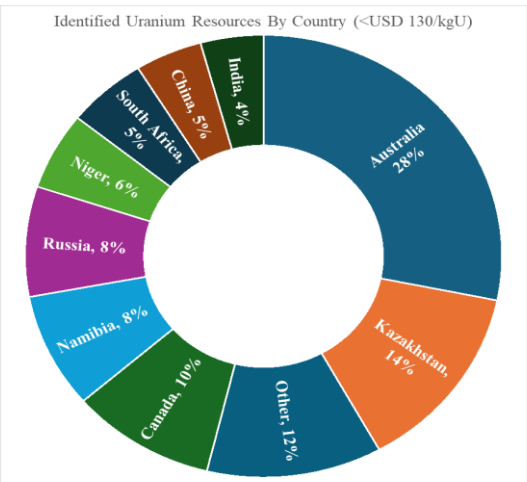

Figure 2. Identified Uranium Resources by Country (11)

Kazakhstan ranks second globally, with 814,000 tonnes of identified recoverable uranium in this cost category, corresponding to roughly 14% of the global total. The country's resources are dominated by roll-front sandstone deposits hosted in permeable aquifers, enabling extraction via ISL. These deposits are located mainly in the Chu-Sarysu and Syrdarya basins. Kazakhstan accounts for the majority of the world's lowest-cost uranium, with 272,000 tonnes in the <US$ 40/kgU bracket alone. State-owned Kazatomprom has optimized ISL techniques, allowing Kazakhstan to become the world's largest uranium producer.

Canada follows with a total of 582,000 tonnes of recoverable uranium below US$ 130/kgU, representing about 10% of global identified resources. These are primarily located in the Athabasca Basin in northern Saskatchewan and consist of high-grade Proterozoic unconformity-related deposits, including McArthur River and Cigar Lake. Although extraction is technically complex due to high water pressure and unstable ground conditions, the ore grades—often exceeding 10%—make these some of the most economically valuable uranium deposits in the world.

Russia possesses 652,500 tonnes of identified recoverable uranium, of which about 73% is recoverable at costs below US$ 130/kgU—this corresponds to roughly 477,000 tonnes. Russia's resource base is geologically diverse, comprising volcanic-related, metasomatic, and sandstone-hosted deposits. Volcanic and metasomatic types dominate in regions such as the Elkon uranium district in Yakutia and the Vitim region in Buryatia. Most of the country's uranium is expected to be extracted via underground mining, with a smaller share suitable for ISL. Russia's vertically integrated fuel cycle and domestic nuclear demand anchor its long-term production strategy.

Namibia has also increased its resource base significantly in recent years. As of January 2023, it holds roughly 498,000 tonnes of recoverable uranium, with 322,000 tonnes in the RAR category and 176,000 tonnes in the IR category at < US$ 130/kgU. Most of the country's uranium comes from large open-pit operations, such as Rössing and Husab, where ore grades are low but economies of scale make mining feasible. Recent discoveries at Tumas, Wings, and Koppies have added to Namibia's endowment.

In summary, five countries—Australia, Kazakhstan, Canada, Russia, and Namibia—collectively hold the majority of the world's identified recoverable uranium resources at economically competitive cost levels. Each country's position reflects a unique interplay of geological endowment, extraction technology, and development strategy, shaping its role in the global nuclear fuel supply chain (46).

2. 4. Iran's Uranium Sector: Development, Challenges, and Strategic Outlook It should be noted that Russia's uranium sector, as one of the global leaders in terms of reserves and production, has been examined in the preceding sections of this study. This subsection is devoted to Iran in order to explain the reasons for its inclusion in the analysis and to consider its specific challenges and strategic outlook. Iran's uranium sector has undergone substantial development in recent decades, but its current position in the global uranium landscape remains limited, both in terms of scale and maturity. The country reports a total of 9,851 tonnes of identified conventional uranium resources recoverable at production costs below US$ 130/kgU. This includes 4,316 tonnes of reasonably assured resources (RAR) and 5,535 tonnes of inferred resources (IR) (11). Iran has developed specific elements of the uranium supply chain, including exploration, mining, and processing.

Iran's resource base is geologically diverse, encompassing metasomatic, granite-related, metamorphite, and volcanic-related deposit types, with metasomatic deposits accounting for the overwhelming majority of both RAR and IR. However, no resources are reported in < US$ 40/kgU or < US$ 80/kgU cost categories, indicating that none of Iran's current resources qualify as low-cost. Instead, all identified uranium resources are grouped in < US$ 130/kgU band, without further cost breakdowns. This cost profile, combined with a reliance on underground mining and relatively low ore grades (e.g., Saghand: 0.0552% U), highlights the technical and economic constraints facing the sector.

Iran's main production infrastructure consists of the Saghand uranium mine (mines No. 1 and No. 2) and the Ardakan processing plant, which began operating in 2017 with a nominal capacity of 50 tonnes U per year. The Saghand operation uses both open pit and underground mining, depending on ore depth, and employs acid leaching in combination with ion exchange and solvent extraction for processing. A second mine, Gachin, which supplied uranium to the Bandar Abbas plant, ceased operations in 2016. Total recoverable resources linked to Saghand are estimated at 500 tonnes, and those from Gachin at 84.1 tonnes, illustrating the constrained scale of Iran's currently active resource base.

Plans for the development of additional production centres are underway. The Narigan and Khoshumi deposits have reached the conceptual and detailed design stages, respectively, but have not yet transitioned into active production. Their feasibility reflects an effort to diversify the portfolio beyond Saghand, though their technical parameters and expected outputs remain limited.

Iran continues to explore a range of metallogenic trends across the country, including Kerman-Sistan, Naiin-Jandagh, Birjand-Kashmar, and Hamedan-Marand. These areas are under evaluation for granite-related, volcanic, sedimentary, and polymetallic uranium potential. Most of the work remains at the surface or early drilling stage. While official documents cite 9,800 tonnes of prognosticated resources and 48,100 tonnes of speculative conventional resources, these remain undeveloped. In addition, 53,000 tonnes of speculative unconventional uranium resources have been identified in phosphate rocks, black shales, and other non-traditional hosts. Their extraction would require significant technological advances and long-term development.

Details regarding recent exploration and development expenditures, including drilling activity and physical effort, are not available in publicly accessible sources. This absence of open data makes it difficult to assess the momentum or continuity of Iran's investment in uranium development. While it has been reported that eight mines were operating in 2023, and that six more are planned by early 2024, only Saghand appears to have a defined and active production pipeline. Iran's production forecast for 2025 stands at 71 tonnes of uranium, a figure that remains modest by international standards.

The sector is entirely state-owned, with the Atomic Energy Organization of Iran (AEOI) serving as both regulator and operator. Employment data for the uranium sector suggest a stable but limited industrial footprint, with around 280 personnel involved in production-related activities in recent years.

In conclusion, Iran's uranium industry is characterized by a strategic intent to build self-sufficiency, but remains constrained by modest geological reserves, relatively high extraction costs, and limited production capacity. Although exploration continues and speculative resources appear substantial, most of Iran's uranium remains either uneconomic or undeveloped. The country's ability to expand its role in the global uranium market will depend on the outcome of ongoing exploration efforts and the successful transition of known deposits into active, efficient production. For now, Iran remains a small but steadily consolidating player in the international uranium landscape (47).

Current assessments of uranium resources face several methodological limitations. International comparisons often treat reported figures as directly comparable, despite differences in geological data quality, classification systems, and levels of exploration between countries. Additionally, resource estimates are typically presented as static snapshots, with limited integration of long-term trends in production, consumption, and pricing. As a result, the strategic significance of uranium endowments—and the feasibility of turning resources into production—can be difficult to assess consistently across national contexts.

2. 5. Comparative Position of This Study in the Existing Literature

Research on nuclear energy and uranium resources has been conducted from various perspectives, yet several significant gaps remain. El Khalfi analyzed the Joint Comprehensive Plan of Action (JCPOA) and highlighted the geopolitical and diplomatic implications of Iran's nuclear program, emphasizing the challenges of international negotiations and the impact of sanctions. However, this study focused mainly on political processes and did not address the quantitative assessment of uranium reserves or Iran's ability to maintain long-term self-sufficiency in nuclear fuel (48).

Kalbasi (49) examined Russian–Iranian cooperation in the nuclear sector, emphasizing the influence of sanctions, bilateral agreements, and foreign policy discourses on the development of these relations. The work effectively illustrated the political context but did not include an evaluation of geological and economic indicators, particularly the structure and recoverability of uranium resources, which are essential for assessing the sustainability of nuclear programs.

Mirgorod and Parubochaya (50) assessed Rosatom as a key instrument of Russian foreign policy in the Middle East. They emphasized the corporation's competitive advantages, including technological leadership, flexible financing models, and the capacity to enhance Russia's diplomatic influence through nuclear projects in countries such as Egypt, Iran, and Turkey. Nevertheless, their analysis remained focused on geopolitical leverage and external influence, without considering the comparative economic value of uranium reserves or the long-term self-sufficiency prospects of Russia and its partners.

Siddi and Silvan (51) analyzed Rosatom's role in international relations through the lenses of realism, liberalism, and dependency theory. Their study demonstrated the complexity of global nuclear supply chains and identified Rosatom's dominant position in uranium enrichment and reactor construction. However, their analysis was largely theoretical and institutional, omitting country-specific assessments of resource bases and calculations of self-sufficiency horizons.

Kharitonova (52) discussed the prospects for Russian–Iranian energy cooperation, focusing primarily on oil, gas, and related infrastructure projects. While the study provides valuable insights into the broader framework of bilateral energy relations, it does not examine uranium resources or the nuclear fuel cycle. In this regard, the present study contributes by extending the analysis of Russian–Iranian energy cooperation to the strategic dimension of uranium, thereby addressing a gap in the literature.

Taken together, these works highlight the gap that defines the novelty of the present study, which lies in its integrated geological and economic perspective. Unlike previous research, which has predominantly emphasized political, diplomatic, or institutional aspects, this analysis consolidates heterogeneous data into a single framework by converting recoverable resources for Russia and in situ resources for Iran to a comparable basis through the application of recovery factors. Beyond this adjustment, the study examines the differentiation of uranium resources by deposit type and their classification by economic cost categories, which indicate the share of reserves feasibly developed under specific price levels. Previous studies have not addressed the issue of long-term self-sufficiency horizons, leaving a gap in understanding how resource availability translates into future supply security. While the existing literature has discussed Russian–Iranian cooperation primarily in the fields of oil and gas, uranium resources have not been analyzed in this context. By introducing this dimension and linking geological characteristics with economic and energy policy considerations, the present study enriches the literature and provides a more comprehensive view of the sustainability of Russia's and Iran's nuclear energy programs, including the potential for bilateral cooperation in the uranium sector.

3. METHODS

This study is based on a detailed comparative analysis of uranium reserves, production, and consumption in Russia and Iran. The methodology follows a structured sequence of stages to ensure the thoroughness and validity of the analysis.

First, the uranium reserves were examined by type: RAR's and IR's. For each type, reserves were considered across different economic categories, based on cost ranges of uranium production (<40, <80, <130, and < US$ 260/kgU). Russia's reserves were provided as recoverable tonnes, while Iran's were reported as in situ tonnes, which required special attention during interpretation and comparison.

To adjust for the difference in reporting standards, a standard formula was used to calculate the recoverable reserves for Iran:

$$R_{rec} = R_{in\,situ} \cdot (\frac{RF}{100}) \quad (1)$$

The recovery factor reflects the efficiency of uranium extraction depending on the mining method (53, 54). For example, for underground mining, recovery rates between 80 and 90% were assumed.

Second, reserves were broken down by mining methods, namely underground mining, open-pit mining, in situ leaching (ISL), and co-product or by-product mining. Each method was analyzed separately, with adjustments made according to the specific recovery factor applicable to each mining technology.

Third, historical uranium production was assessed, based on records by mining method and by year through 2023. In addition, mid-term production projections up to 2045 were incorporated to reflect planned production dynamics for both countries.

Fourth, uranium consumption was evaluated. For Russia, a relatively stable forecast of annual reactor-related uranium requirements was used. For Iran, two consumption scenarios—low and high—were considered to capture uncertainty linked to the potential expansion of nuclear energy use.

To assess the dynamic change in available reserves over time, the following formula was applied:

$$R_x = R_A + (P - C) \cdot (X - A) \quad (2)$$

Additionally, to estimate the number of years until uranium reserves are exhausted once a deficit occurs, the following formula was used:

$$Y = \frac{R_{last}}{C - P} \quad (3)$$

Throughout the analysis, reserves for each country were considered from multiple perspectives—by type of resource and by mining method—to identify commonalities, differences, and potential grounds for cooperation. Special attention was paid to finding comparable structures in resource classification and mining practices, which could support further strategic alignment.

Finally, based on the data obtained, initiatives were proposed for developing bilateral relations in the field of uranium exploration and mining between Russia and Iran. Possible points of contact for technological cooperation, joint ventures, and knowledge sharing were outlined, recognizing the complementarity of the two countries' resource bases and mining experiences. Future studies may consider binary discounting approaches, as used in hydrogen project evaluations, to better reflect cost-revenue risk asymmetry in uranium economics (55).

4. RESULTS

4. 1. Uranium Price Scenarios: 2025–2045

This section does not provide an original econometric forecast but rather summarizes findings from authoritative sources. The analysis is broadly consistent with the IAEA/NEA Red Book, where uranium prices are considered in relation to supply–demand adequacy without quantitative projections, and it additionally draws on recent analytical work, which employs a mathematical model to forecast the cost and volume of uranium production under various global nuclear energy development scenarios (56). The price ranges presented here should therefore be understood as illustrative scenarios that reflect different combinations of demand growth, supply responses, and project economics, rather than strictly deterministic forecasts.

Over the past two decades, uranium prices have exhibited cyclical behavior, with sharp peaks followed by long correction phases. As shown in Figure 3, the most recent surge in both spot and long-term prices peaked in early 2024, reaching levels near US$ 190/kgU, before declining again toward US$140/kgU range by early 2025. While this increase was significant, it remains unclear whether it reflects a durable structural shift or a short-term correction driven by speculative activity, restocking cycles, or temporary supply disruptions. What is clear, however, is that the current price level—slightly above US$ 130/kgU—brings a much broader segment of the global uranium resource base into potential economic viability, particularly those deposits situated in < US$ 130 and < US$ 260/kgU cost categories.

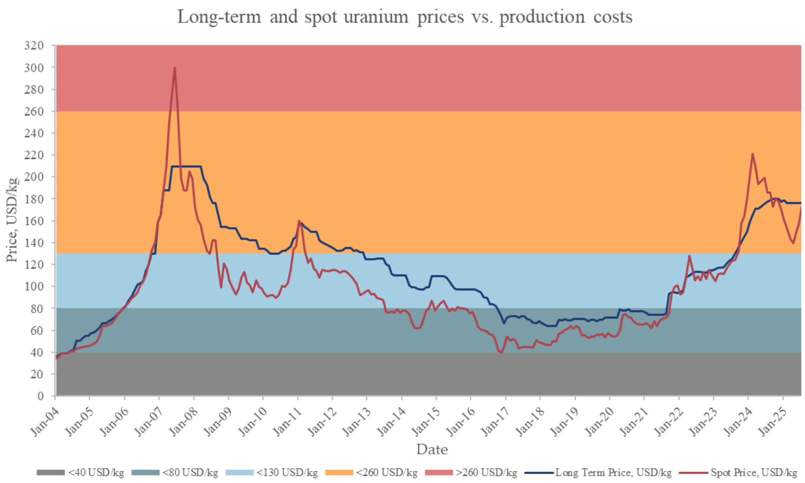

Figure 3. Long-term and spot uranium prices vs. production costs (57)

Looking ahead, several price scenarios may unfold depending on policy, supply chain dynamics, and technological developments. In a moderate-demand scenario, where global nuclear expansion continues at a measured pace and supply steadily recovers, prices are expected to stabilize in the range of US$ 150–170/kgU by 2030. This would be supported by gradual restarts of idled production, new capacity in countries like Kazakhstan and Canada, and improvements in secondary supply. In a high-demand scenario, driven by accelerated nuclear deployment for decarbonization and geopolitical competition over energy security, prices could rise more sharply, reaching US$ 180–200/kgU by 2030 and exceeding US$ 220/kgU by 2035. This would reflect constrained project pipelines and longer permitting timelines for new mines.

A low-demand or oversupply scenario—resulting from delayed reactor construction, wider adoption of alternative fuels, or faster development of small modular reactors (SMRs) with lower uranium requirements—could lead to a price retreat to US$ 100–120/kgU, particularly if new supply enters the market too quickly. However, even under such conditions, long-term prices are unlikely to return to pre-2021 lows, given higher input costs and a more risk-aware investment environment.

For the 2040–2045 period, prices will likely converge in the US$ 160–200/kgU range under most realistic scenarios. At that point, many high-cost deposits in < US$ 260/kgU band may become competitive, especially in countries with integrated fuel cycles or stable mining environments. Overall, future pricing will be shaped not only by physical supply and demand, but also by project economics, geopolitical alignments, and the willingness of states and utilities to support uranium procurement as a strategic priority.

4. 2. Uranium Deposit Types in Russia and Iran by Production Cost To compare the geological composition of uranium resources in Russia and Iran, Figure 4 presents the distribution of deposit types in relative terms (%), grouped by production cost categories. Since Russia's total uranium endowment is significantly larger than Iran's, the data are shown proportionally to highlight structural differences rather than absolute quantities. Only < US$ 130/kgU and < US$ 260/kgU categories are included, as no information has been found indicating that either country holds reserves in < US$ 40/kgU cost band. Although Russia does hold a small volume of sandstone-hosted resources in < US$ 80/kgU category, Iran has none in this cost range, and therefore it was decided to limit the comparison to the two broader thresholds where both countries have meaningful data.

An additional feature worth noting is that Iran's uranium resource composition does not change between < US$ 130/kgU and < US$ 260/kgU categories, indicating that all currently identified reserves fall within the lower-cost band. This may suggest that either Iran's resources are uniformly moderate in extraction cost, or that higher-cost reserves have yet to be discovered or disclosed. In contrast, Russia's profile expands significantly in < US$ 260/kgU range, incorporating a wider array of deposit types and highlighting the economic scalability of its uranium base.

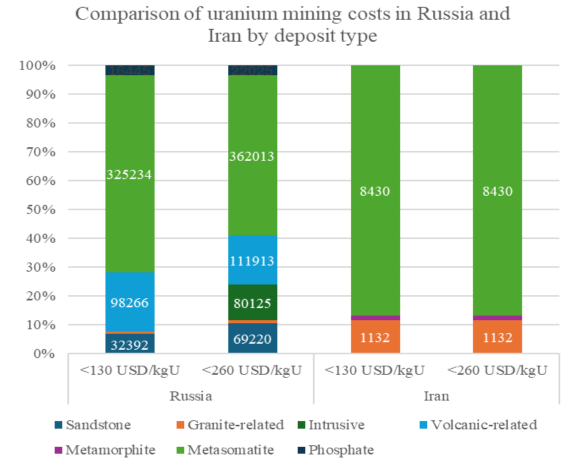

Figure 4. Comparison of uranium mining costs in Russia and Iran by deposit type (11)

The chart reflects that Iran's uranium resources are overwhelmingly metasomatite in origin, while Russia shows a more diverse distribution that includes not only metasomatite, but also significant shares of volcanic-related, intrusive, and sandstone-hosted deposits. This contrast highlights the broader geological base supporting Russia's uranium sector, in contrast to Iran's heavier reliance on a single deposit type.

4. 3. Russia and Iran: Uranium Supply and Demand Outlook In Russia, uranium consumption is projected to increase only slightly over the coming decades—from 4,400 tonnes in 2021 to 4,900 tonnes by 2045—indicating a stable demand outlook based on long-term reactor operation and planned capacity additions. In contrast, production follows a non-linear path. It rises from 2,635 tonnes in 2021 to a peak of 4,900 tonnes by 2030, achieving full domestic supply coverage at that point. However, this is followed by a sharp decline to 1,500 tonnes by 2040, a level that remains unchanged through 2045 (11). This creates a projected shortfall of over 3,000 tonnes per year by the end of the period. The pattern reflects the expected depletion of existing deposits and the absence of new capacity being added in the model. The corresponding production and consumption figures are shown in Figure 5.

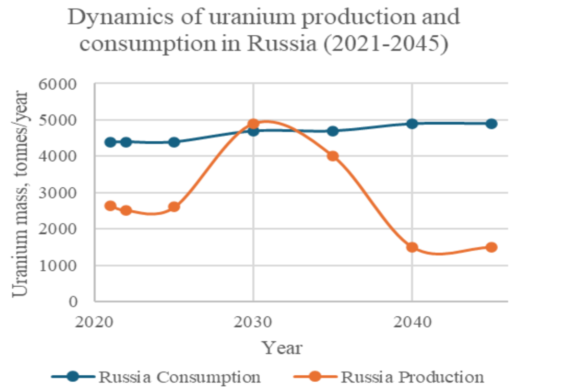

Figure 5. Dynamics of uranium production and consumption in Russia (2021-2045)

Iran, by contrast, faces a different type of imbalance. Uranium consumption is projected under two alternative demand scenarios, depending on the pace of reactor development. In the high scenario, consumption rises from 160 tonnes in 2021 to 1,390 tonnes by 2040. In the low scenario, it reaches 1,230 tonnes over the same period. Meanwhile, production increases only modestly—from 21 tonnes per year in 2021–2022 to 71 tonnes from 2025 onward—and then remains flat (11). In both scenarios, the gap between demand and domestic supply widens steadily, indicating that Iran will remain heavily dependent on imports or cooperation to meet its future needs. These projections are presented in Figure 6.
Taken together, the Russian and Iranian cases illustrate two distinct challenges. Russia risks a supply deficit after 2035 despite currently strong production, while Iran will face chronic underproduction relative to even modest growth in demand. These dynamics underscore the strategic value of cooperation in uranium development, particularly in areas such as reserve expansion, exploration technology, and long-term supply agreements.

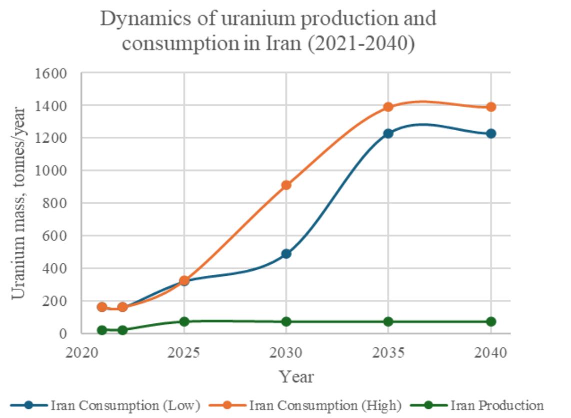

Figure 6. Dynamics of uranium production and consumption in Iran (2021-2045)

4. 4. Uranium Self-Sufficiency Horizons in Russia and Iran An important outcome of this study is the estimation of how long Russia and Iran can meet their domestic uranium demand using their own identified resources, differentiated by cost categories and resource classifications (RAR and RAR+IR). The results provide a direct timeline for potential resource depletion under current consumption projections.

For Russia, two cost-based resource thresholds were considered. In the < US$ 80/kgU category, where the country holds a moderate reserve (18,224 tonnes RAR and 14,168 tonnes IR), calculations show that reasonably assured resources (RAR) alone will be depleted by 2036, while RAR+IR combined will last until 2041. These dynamics are illustrated in Figure 7, which shows a steep decline in both reserve types over time, especially beyond 2030. When evaluating the broader < US$ 130/kgU category—which includes a significantly larger resource base (202,304 tonnes RAR and 274,269 tonnes IR)—the self-sufficiency horizon expands substantially.

As shown in Figure 8, reserves in this category remain relatively stable across the period 2021–2045. In this case, RAR would suffice until 2093, and RAR+IR would extend the timeline until 2174. Since the < US$ 130/kgU band already provides such long-term coverage, additional analysis of higher-cost categories was deemed unnecessary for Russia.
For Iran, no reserves exist in the < US$ 80/kgU range, and the < US$ 260/kgU category does not add any new resources beyond what is already classified under < US$ 130/kgU. Therefore, only the < US$ 130/kgU category was analyzed. Given Iran's much smaller resource base and growing projected demand, self-sufficiency timelines are significantly shorter. As illustrated in Figure 10, under the low consumption scenario, Iran can meet its needs using RAR alone until 2033, and with RAR+IR until 2039. Under the high consumption scenario, these timelines shorten further: until 2031 for RAR and 2038 for RAR+IR.

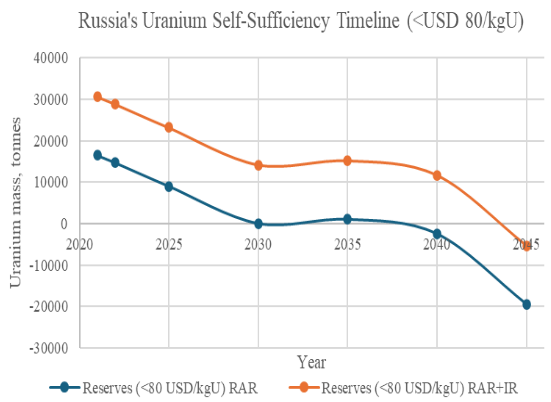

Figure 7. Russia's uranium self-sufficiency timeline (<US$ 80/kgU)

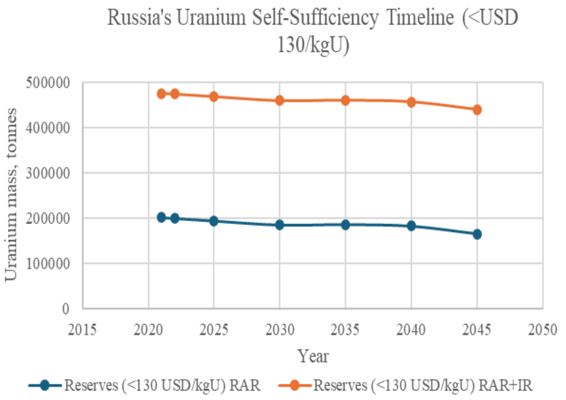

Figure 8. Russia's uranium self-sufficiency timeline (<US$ 130/kgU)

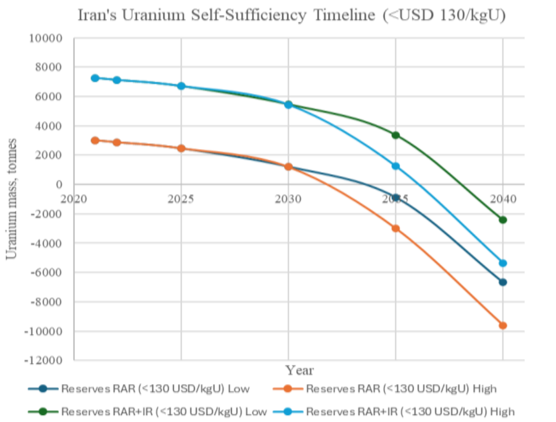

Figure 9. Iran's uranium self-sufficiency timeline (<US$ 130/kgU)

These results highlight a key structural difference between the two countries. While Russia has sufficient domestic reserves to support its nuclear program for decades—particularly at cost levels under US$ 130/kgU—Iran's limited resource base, especially in the context of rising demand, leads to a much earlier depletion horizon. This calculation of specific depletion years represents a core methodological feature of the study and provides a clear benchmark for assessing long-term uranium security under varying economic and policy scenarios.

5. DISCUSSION

The analysis of uranium price dynamics and resource self-sufficiency provides a clear framework for assessing national vulnerability and long-term planning needs. However, the practical impact of future price changes—despite their potential volatility—is likely to be limited for both Russia and Iran in the near to medium term. For Iran, the reason is straightforward: the country's uranium reserves are modest in size, concentrated in a narrow geological category, and largely insufficient to meet future demand under either low or high consumption scenarios. As such, even if uranium prices were to shift significantly, the overall strategic position of Iran's domestic supply would remain largely unchanged. The issue is not one of cost, but of scale.

In contrast, Russia possesses a substantial uranium endowment, including large volumes of reasonably assured and inferred resources at < US$ 130/kgU. This suggests that price increases would not pose an immediate threat to supply security, as sufficient reserves are already technically and economically viable at current market levels. However, the analysis also shows that only a small share of these reserves is actively being developed. As production is expected to decline after 2030, Russia's long-term self-sufficiency will depend not only on the size of its reserves but also on its ability to bring new capacity online. Without proactive development, even large resource bases can become bottlenecks—particularly if geopolitical uncertainty or global market tightening reduces access to foreign supply chains (58, 59).

It is also important to acknowledge that the presented figures and forecasts are based on conventional uranium fuel use and do not account for potential shifts toward MOX fuel or broader implementation of closed fuel cycle technologies. As these technologies continue to evolve, they may fundamentally alter the economics of resource use, extending the effective lifespan of current reserves and introducing new recovery pathways from previously uneconomic or unrecoverable sources (60). Similarly, improved processing, modular mining systems, or environmental permitting innovations could lead to a reclassification of existing reserves across price tiers (61-63). In this sense, today's marginal resources may become tomorrow's baseline supply (64).

Altogether, while the current outlook favors Russia in terms of scale and buffer capacity, and poses more urgent concerns for Iran, both countries face important challenges. For Iran, these relate to securing external partnerships or developing alternative technologies (65). For Russia, the challenge lies in converting its geological potential into timely, sustained production. Addressing these asymmetries will require long-term strategic planning that goes beyond price forecasting and into active resource policy and technology integration (66-68).

An additional consideration is the geological similarity of uranium reserves in both countries. As shown in the deposit-type analysis, metasomatite-hosted deposits dominate the resource base in Iran and also form a significant part of Russia's uranium portfolio. This commonality may offer technical advantages for bilateral cooperation, particularly in the areas of ore processing, exploration techniques, and mine planning. Given

Russia's greater experience in developing metasomatite resources, shared geological challenges could serve as a practical foundation for deeper collaboration—not only in fuel cycle agreements, but also in joint field development, personnel training, and technology transfer (69).

6. CONCLUSIONS

The results of this study provide a detailed response to the stated aim and objectives. The analysis of uranium resources in Russia and Iran by type (RAR and IR) and by economic cost categories (<40, <80, <130, and < US$ 260/kgU) reveals significant differences in scale and composition. Russia possesses one of the world's largest uranium resource bases, with a substantial share of reserves classified in categories below US$ 130/kgU. In absolute terms, Iran's endowment is much smaller, and although its reserves also fall within these cost categories, their limited volume constrains the country's long-term supply potential.

Since Russia reports recoverable resources while Iran reports in situ values, recovery factors specific to each mining method were applied to adjust the Iranian figures. This adjustment enabled a comparable assessment of the resource bases of both countries. Based on this, a structural analysis by deposit type shows that Iran's uranium resources are concentrated mainly in metasomatite deposits, whereas Russia's reserves are distributed across a broader spectrum, including metasomatite, sandstone, volcanic, and other deposits. Geological diversity strengthens Russia's resilience, while Iran's reliance on a single deposit type increases its vulnerability to domestic constraints.

The evaluation of production and consumption further underscores these differences. Russia has traditionally maintained substantial uranium output, but a decline is projected after 2030 if new projects are not developed. Forecasts to 2045 indicate that Russia can remain self-sufficient provided additional capacity is commissioned. In Iran, current uranium production remains limited, reflecting both the smaller scale of its resource base and institutional barriers to development. At the same time, the country is preparing feasibility studies for additional deposits such as Narigan and Khushumi, which may expand its production potential in the future. However, under both low and high consumption scenarios, the currently identified resources are insufficient to sustain demand beyond the 2030s.

The analysis also reveals complementarities between the two countries. Both possess significant metasomatite-hosted deposits, and Russia's broader experience in the exploration and development of such deposits could provide a basis for bilateral cooperation in exploration, mining, processing, and technology transfer. This creates a practical foundation for strengthening uranium security through joint initiatives, while also underscoring the broader strategic implications of geological similarities.

Overall, the findings demonstrate that Russia's extensive and geologically diverse uranium base can ensure long-term self-sufficiency with timely investment in new projects, whereas Iran's more limited endowment makes external cooperation and technological breakthroughs essential for sustaining its nuclear program. These results address the stated objectives by delivering a comparative geological and economic assessment, establishing data comparability through recovery factors, analyzing resource structures by deposit type and cost category, evaluating production and consumption balances, and estimating long-term self-sufficiency horizons together with opportunities for bilateral collaboration.

In contrast to earlier works, which primarily focused on the political, diplomatic, or institutional dimensions of Russian–Iranian cooperation or emphasized Rosatom's foreign policy role and global positioning, the present study provides a quantitative geological and economic perspective. It takes into account that Russian uranium resources are reported as recoverable while Iranian resources are presented in situ, and it applies appropriate recovery factors to bring them onto a comparable basis. By examining reserve volumes by deposit type and economic cost category and by estimating long-term self-sufficiency horizons, this study presents findings that have not been addressed in previous literature and thereby broadens the understanding of uranium supply security in both Russia and Iran.

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Ethics Approval and Consent to Participate

This article does not involve any studies with human participants or animals performed by any of the authors. Therefore, ethics approval and consent to participate are not applicable.

Competing Interests

The authors declare no financial or organizational conflicts of interest.

Data Availability

The data that support the findings of this study are available upon reasonable request.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors did not use generative artificial intelligence or AI-assisted technologies in the writing or preparation of the manuscript. The authors take full responsibility for the content of the published article.

Authors Biosketches

The authors are researchers in the field of sectoral economics, focusing on the analysis of industrial sectors and the assessment of their economic performance. Their research interests include quantitative methods, comparative analysis, and applied economic evaluation.

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Persian Abstract

چکیده

این مطالعه ارزیابی مقایسه ای زمین شناسی و اقتصادی منابع اورانیوم در روسیه و ایران را با تمرکز بر توانایی آنها در حمایت از توسعه انرژی هسته ای داخلی انجام می دهد . برخلاف تحقیقات قبلی که عمدتا همکاری روسیه و ایران را از دیدگاه سیاسی یا نهادی بررسی کرده است ، این کار در دسترس بودن اورانیوم را با استفاده از طبقه بندی های زمین شناسی و دسته بندی های هزینه اقتصادی ذخایر ارزیابی می کند .این روش بین منابع قابل بازیابی گزارش شده برای روسیه و منابع داخلی گزارش شده برای ایران تمایز قائل است و این مورد دوم از طریق استفاده از عوامل مناسب بازیابی به یک پایه قابل مقایسه تبدیل شده است .علاوه بر تجزیه و تحلیل ساختار و پتانسیل پایگاه منابع ، این مطالعه تولید اورانیوم تاریخی و پیش بینی شده و همچنین سناریوهای مصرف برای هر دو کشور را در نظر می گیرد .بر این اساس ، افق های بلند مدت خودکفایی تا سال ۲۰۴۵ تخمین زده می شود .یافته ها نشان می دهد که روسیه دارای یک پایگاه اورانیوم گسترده و زمین شناسی متنوع است که قادر به تضمین عرضه بلند مدت است اگر پروژه های معدن جدید برای جبران کاهش تولید پس از سال ۲۰۳۰ توسعه یابد .در مقابل ، ایران ذخایر محدودتر و گرانتر دارد که عمدتا در ذخایر متاسوماتیت متمرکز شده است ، که دستیابی به خودکفایی پایدار را بدون همکاری خارجی یا پیشرفت های تکنولوژیکی بعید می کند .در عین حال ، شباهت های زمین شناسی بین دو کشور پایه ای برای همکاری بالقوه در اکتشاف و توسعه اورانیوم ایجاد می کند .با پرداختن به جنبه نسبتا کم کشف شده ادبیات ، این مطالعه ارزیابی ساختاری از پایداری عرضه اورانیوم را ارائه می دهد و دیدگاه مقایسه ای را نه تنها برای روسیه و ایران بلکه برای سایر کشورهای دارای برنامه های هسته ای در حال ظهور نیز معرفی می کند.