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Exploratory Analysis of the Statistical Characteristics of Nuclear Fuel Cost Trends

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Abstract

Nuclear power reactors of the current fleet mainly use uranium as the fissile fuel material. The economics of nuclear fuels are mainly governed by the prices of uranium. This work is an analysis of monthly uranium price data available from public data sources, covering the time frame from January 1990 to April 2025. In the near term, from 2021 to 2024, monthly uranium spot prices have been between \$ 35.28±6.64/lb U_3O_8 to \$ 85.14±7.82/lb U_3O_8, with a mean price showing an annual increase of 25.5 to 41.2%. Long-term contract prices during the same time frame for uranium have been \$ 36.81±4.44/lb U_3O_8 to \$ 78.88±2.97/lb U_3O_8. The highest overall volatility was observed in 2023. From the long-term data spanning 424 months, the distributional characteristics show the right-skewed and non-stationary nature of uranium price distribution, and the more symmetric nature of the distribution of the month-on-month price changes. The distributions are not Gaussian in nature. Uranium prices have been highly volatile but have also shown relatively low correlation coefficient values with prices of other major energy commodities such as crude oil, coal, and natural gas, indicating that the electricity system diversification also makes it resilient to price shocks. This analysis further highlights that uranium price dynamics are influenced by both market fundamentals and geopolitical factors, including supply disruptions, policy changes, and shifts in nuclear energy demand. Periods of heightened volatility often coincide with renewed global interest in nuclear power or supply constraints from major producers.

Keywords: Futures, nuclear fuel, price, spot price, statistics, uranium

INTRODUCTION

Nuclear power is gaining increasing interest as a source of low-carbon emissions intensity heat and electricity in the context of economy-wide decarbonization for climate change mitigation [1]. Most deep decarbonization and net-zero emissions scenarios envisage a growing role of nuclear power to complement the capacity build-out of variable renewable technologies such as solar PV and wind energy [2]. Continued operation of existing nuclear power plants and expansion of the nuclear fleet require a sustainable and economical supply of nuclear fuel. Most nuclear reactors make use of uranium as the nuclear fuel material; in the form of uranium oxides placed inside cladding made of materials such as zirconium alloys [3]. Thus, the economics of nuclear fuels are mainly governed by the prices of uranium, though the cost of zirconium and of fuel material processing under strict regulation and quality control regimes are also contributors to the final nuclear fuel cost.

Economic studies of nuclear power projects indicate that fuel is typically a small contributor to the life cycle or levelized cost of nuclear power production. This fraction is typically about 10–20%, depending on the type of nuclear reactor being

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considered [4]. This arises due to the extremely high energy density of nuclear reactions, compared to energy liberation in combustion reactions involving fossil fuels like coal, natural gas, and fuel oils. However, this does not negate the importance of understanding the economics of nuclear fuel materials, especially as nuclear power programs are on an expansionary path in many developing and developed economies. This is because of the following factors:

1. Uranium reserves are geographically concentrated in relatively few countries, and the supply chain and pricing trends of nuclear fuel could potentially be affected by geopolitical factors.
2. Due to rising demand for nuclear power, including in many newcomer countries, reserves of uranium not considered economical today will have to be harnessed in the future; this will directly affect nuclear fuel costs.
3. The development of alternate nuclear fuel cycles based on materials such as thorium may also influence the prices of uranium-based fuels.
4. Rising investor interest in nuclear power programs, including development finance institutions like The World Bank, requires a detailed understanding of the pricing trends along all elements of the nuclear fuel cycle.

While there is obvious uncertainty in the evolution of these pathways and the corresponding impacts on uranium prices, some initial estimates and correlations can be derived from historical data. For this, the need to analyze historical data and its trends is the major motivation behind this work.

The objective of this study is to analyze openly available uranium price data over different time frames and provide numerical estimates as inputs for representing the fuel cost aspect in deterministic and statistical techno-commercial assessments of nuclear power programs, energy scenario development studies, price forecasting, energy systems modeling, and similar tasks to help represent the price trajectories and uncertainties in a data-driven manner. Uranium is not traded in the market as other energy commodities, and available information about its price trends is less extensive. Thus, the analysis of these data reported in the literature is also quite sparse, unlike that for other commodities or asset classes, particularly with respect to recent data. This work attempts to fill this gap area and analyzes monthly uranium price data from January 1990 to April 2025. The distributional characteristics and key descriptive statistics are determined. Time series characteristics from the price data set are derived, and comparisons with other major energy commodity prices over the same time frame are made.

DATASETS AND ANALYSIS METHODOLOGY

The monthly long-term global uranium price trends, as well as the price of other traded commodity energy materials like natural gas, Brent Crude, West Texas Intermediate Crude, and coal, are all obtained from the repository of the Federal Reserve Bank of St Louis, USA, for the period January 1990 to April 2025, i.e., for 424 months [5]. Uranium prices are indicated by the cost of the uranium compound U_3O_8, which contains about 85% of uranium by weight. This compound is converted to UO_2 for use as fuel in nuclear power reactors. The short-term spot uranium price and long-term contract price data at monthly intervals are also recorded from the website of Cameco for the years 2021–2024 [6]. The monthly uranium futures price data from June 2007 to June 2025 are obtained from the Investing.com data repository [7].

The key analyses performed using the uranium price time series data sets are as follows:

From the time series, the month-on-month percentage uranium price change is calculated for months t-1 and t as:

$$\Delta P(t) = 100 \times \frac{[P(t) - P(t-1)]}{P(t-1)} \tag{1}$$

The coefficient of variation (COV) of uranium prices is calculated as a percentage from the distribution of values as:

$$COV = \frac{100 \times \sigma}{\mu} \tag{2}$$

The autocorrelation function (ACF) of a time series P(t) with itself at different time lags given by k =0, 1, 2, etc., is defined as [8]:

$$\mathrm{ACF(k)} = \frac{\mathrm{Covariance\ (P(t),P(t+k))}}{\sqrt{\mathrm{variance\ (P(t)\times variance\ (P(t+k))}}} \tag{3}$$

The correlation coefficient between two time series, P_1 and P_2 (of equal length), shows the extent of linear association between them, and it is calculated as [9]:

$$\mathrm{Corr}(P_1, P_2) = \frac{\mathrm{Covariance}(P_1,P_2)}{\sqrt{\mathrm{Var}(P_1)}\times\sqrt{\mathrm{Var}(P_2)}} \tag{4}$$

The logarithmic or log returns on the uranium price between time frames (t-1) and t are calculated as:

$$R(t) = \ln\frac{P(t)}{P(t-1)} \tag{5}$$

Uranium price volatility at any time t is estimated as the rolling standard deviation of all available price data from the initial time up to the time t using the following expression:

$$\sigma(t) = \mathrm{sqrt}[\tfrac{1}{t}\textstyle\sum_{t=0}^{t=t}(P(t) - \overline{P(t)})^2] \tag{6}$$

RESULTS AND DISCUSSION

Recent Trends in Uranium Prices

The average uranium price data from 2021 to 2024 at monthly intervals, shown in Figures 1 and 2, indicate the upward trend of uranium price on a year-on-year basis, though within a given year, there may be upward and downward trends in specific months. In this time frame, the monthly average uranium spot prices have varied from \$ 35.28±6.64/lb U_3O_8 to \$ 85.14±7.82/lb U_3O_8. The mean price for the year has shown an annual increase of 25.5 to 41.2% on a year-on-year basis. The long-term contract prices during the same time frame for uranium have been between \$ 36.81±4.44/lb U_3O_8 and \$ 78.88±2.97/lb U_3O_8. In general, the long-term contract prices have been lower than the corresponding spot prices. From Table 1, it can be seen that the year 2023 showed the greatest coefficient of variance in the uranium spot price, while the year 2021 had the maximum coefficient of variance in the long-term contract price.

Long-term Trends in Uranium Prices

Figure 2 shows the long-term uranium price characteristics over 424 months starting January 1990. Huge price shocks are seen in the months 177 to 246, corresponding to the phase in which the global financial crisis of 2007–08 took place. Prices had a generally downward trend till about month 340, after which the trend reversed and an upward drift was noticed in recent times. This recent trend is indicative of renewed interest in nuclear power as part of climate change mitigation and decarbonization, as well as geopolitical factors affecting uranium supply chains.

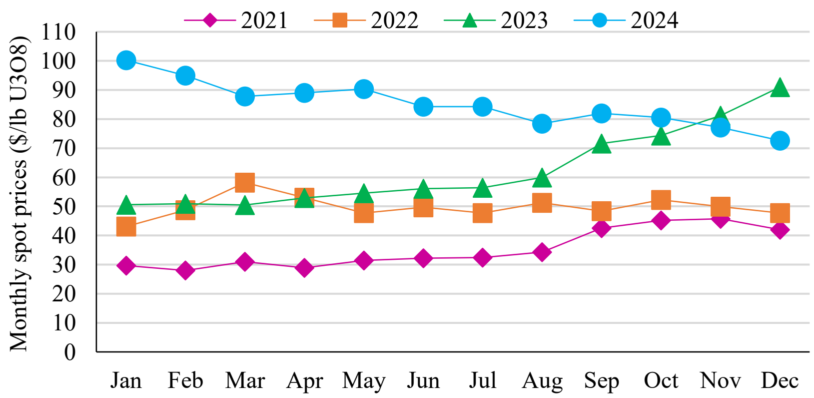

Figure 1. Monthly spot prices of U_3O_8 in the recent term.

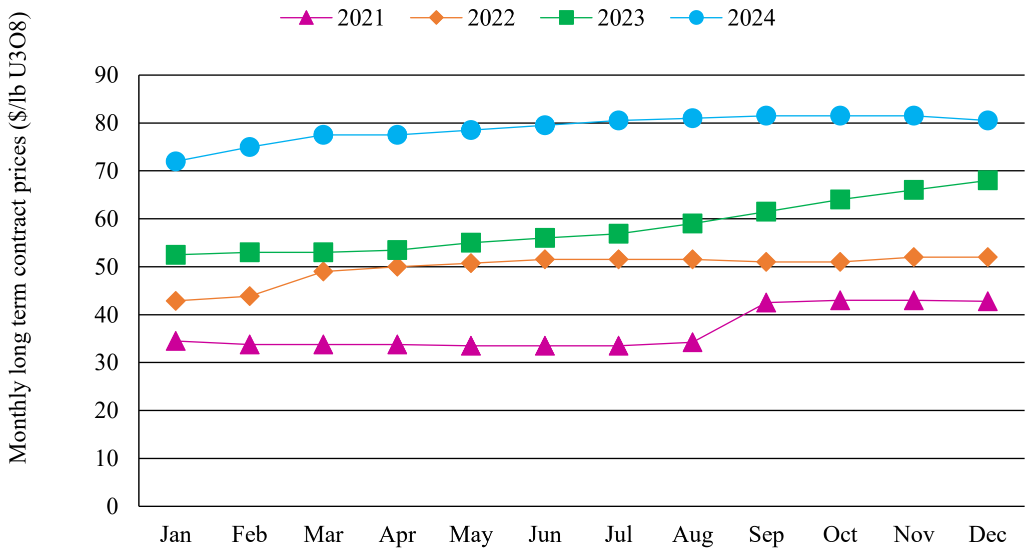

Figure 2. Monthly long-term contract prices of U_3O_8 in the recent term.

Table 1. Key statistics from the monthly uranium price data of 2021–2024.

Spot prices ($/lb U_3O_8)				
Year	2021	2022	2023	2024
Mean	35.28	49.81	62.51	85.14
Standard deviation	6.64	3.70	13.64	7.82
COV (%)	18.83	7.42	21.82	9.18
Long term prices ($/lb U_3O_8)				
Year	2021	2022	2023	2024
Mean	36.81	49.75	58.19	78.88
Standard deviation	4.44	3.10	5.46	2.97
COV (%)	12.07	6.23	9.38	3.77

Figure 4 shows the calculated uranium price changes over time, derived from data in Figure 3. The values are nearly uncorrelated with time (linear correlation coefficient of 0.002), showing that the price differences have no discernible trend component and are showing nearly random variations with time. Similar characteristics are also exhibited by the log returns of uranium prices with time. Steepest prices of uranium have occurred during the global financial crisis of 2007–08, the highest positive price rise of +40.22% month-on-month was seen during August–September 2021 (in the midst of the COVID pandemic), and the lowest negative price change of –22.6% was seen during August–September 2007 (in the global financial crisis).

Figures 5–7 show various aspects of the distributional characteristics of the uranium price data. Figure 5a shows that price distribution is positively skewed to the right, while Figure 5b shows that price changes are more symmetrically distributed (also evident from much lower values of skewness of these two distributions compared to that for the uranium price, in Table 2). The right skew is a departure from typical trends in equity asset price distributions, which are often left skewed [10]. Figure 6(a and b) shows the probability plots of the same data in Figure 5(a and b), respectively, and they indicate that the distributions are not well approximated as Gaussian or normal, especially due to large deviations at the lower and upper tail ends. Figure 7(a and b) shows the details of the distribution of the log returns on uranium prices. They have similar characteristics to the uranium price change data series. The main descriptive statistics of these three distributions are shown in Table 2. It is also seen that the kurtosis of each distribution is greater than 3 (i.e., the kurtosis value for a normal distribution), which shows that outlier values are occurring with greater probabilities in these fat-tailed distributions compared to a normal distribution.

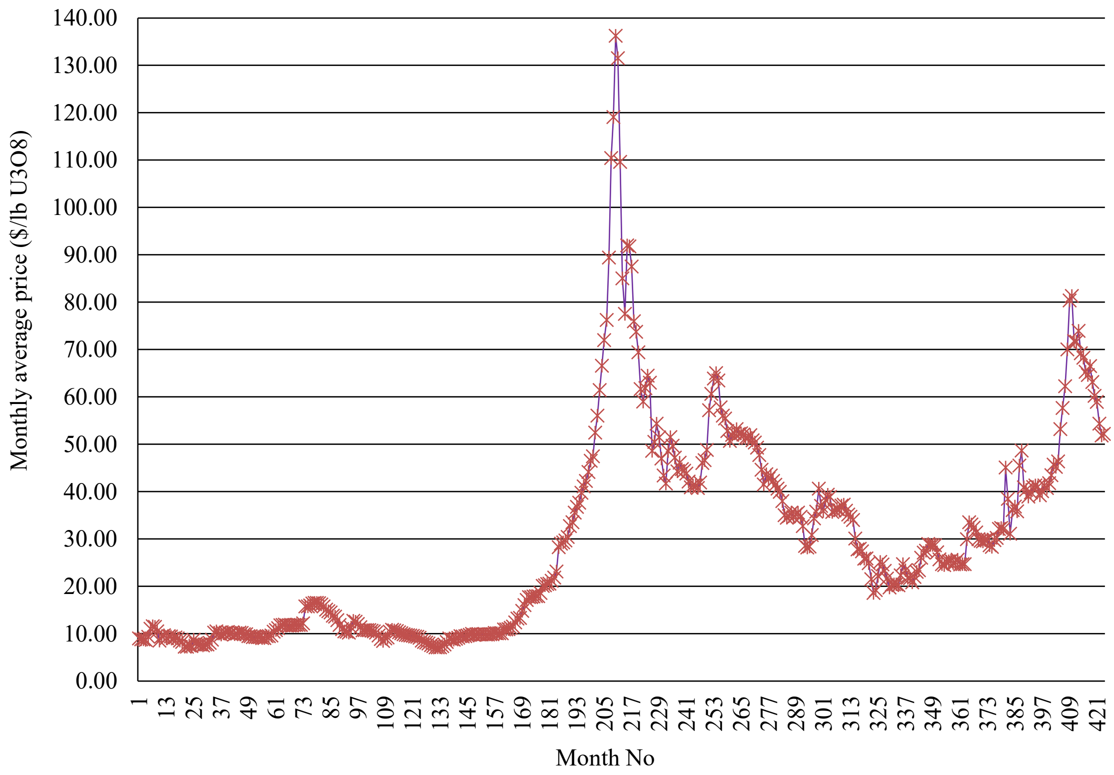

Figure 3. Long-term trend of prices of U_3O_8 (Month No. 1 = January 1990, data up to April 2025).

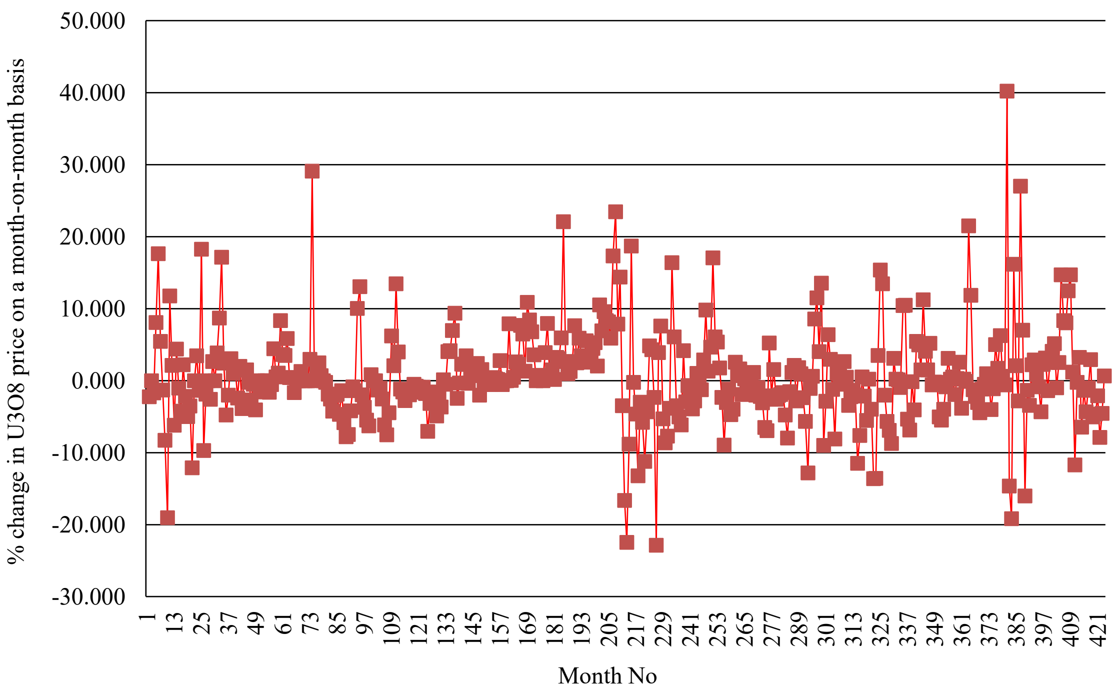

Figure 4. Month-on-month percentage variation of prices of U_3O_8 (Month No. 1 = January 1990, data up to April 2025).

Table 2. Key statistics from the distributions of long-term monthly U_3O_8 prices.

Type of distribution	Mean	Standard deviation	COV (%)	Skewness	Kurtosis
Actual monthly price	29.62	21.94	74.07%	1.399	5.750
Percentage change in price (month on month)	0.634	6.726	1061%	0.947	8.010
Log returns on price (month on month)	0.004	0.066	1650%	0.370	6.924

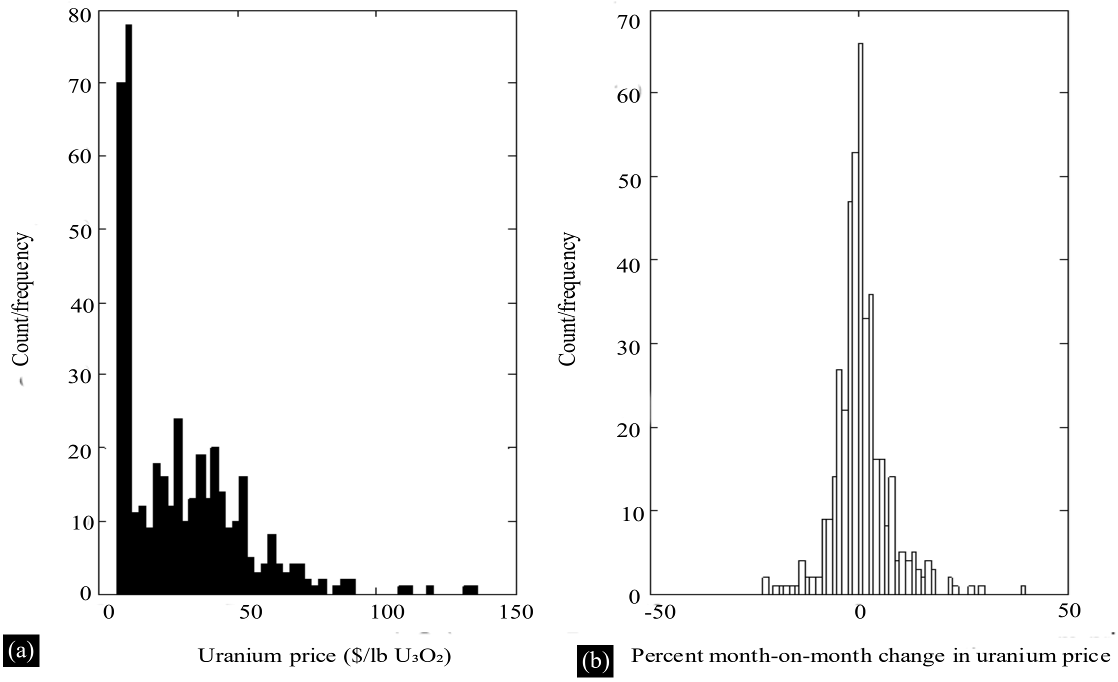

Figure 5. Histogram of (a) U_3O_8 price trends and (b) month-on-month U_3O_8 price changes (January 1990–April 2025).

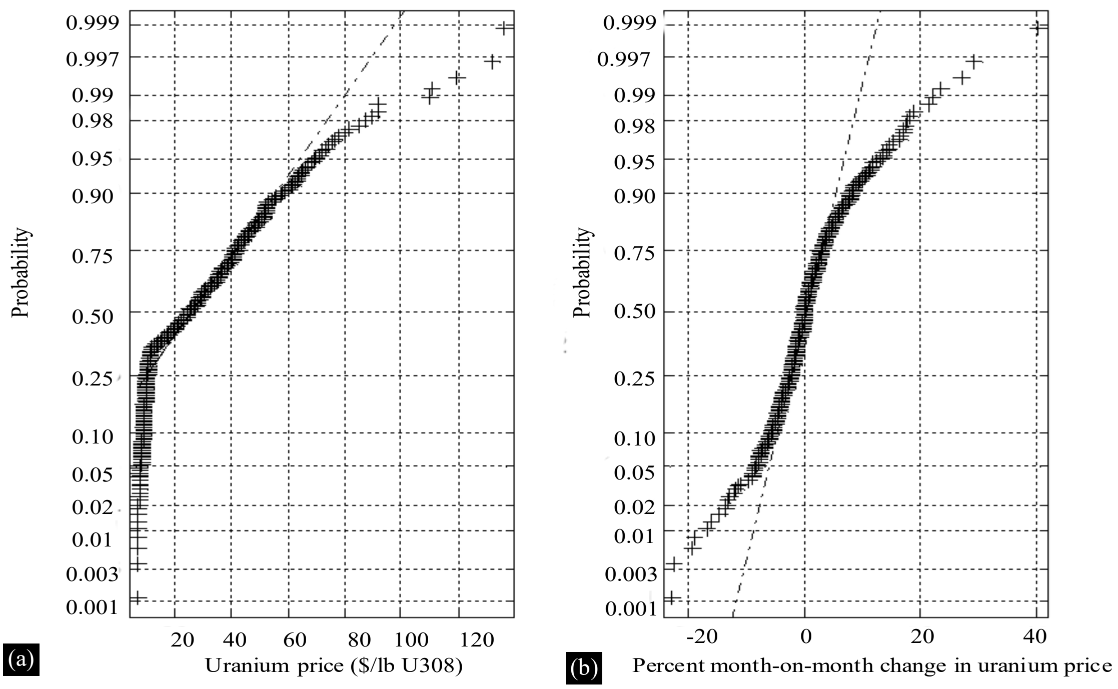

Figure 6. Normal probability plot of (a) U_3O_8 price trends and (b) month-on-month U_3O_8 price changes (January 1990–April 2025).

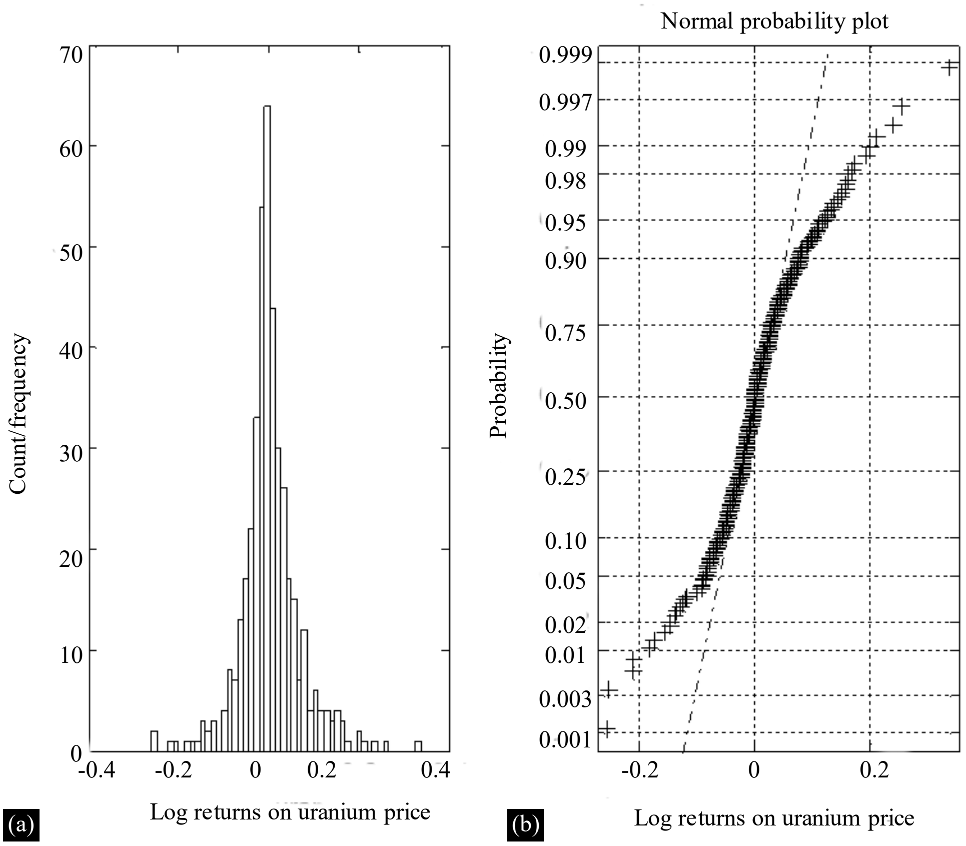

Figure 7. (a) Histogram of log returns of monthly U_3O_8 prices, (b) Normal probability plot of log returns of U_3O_8 prices (January 1990–April 2025).

Time Series Characteristics of Uranium Prices

Figures 8 and 9 show major time series characteristics of the uranium price data and price change and log returns data in the form of the autocorrelation function values at different values of time lags. For uranium price data, it is seen in Figure 8 that the values of the autocorrelation coefficient drop very slowly with time lag; it takes almost 65 time lags for the value to decrease to the 95% confidence interval level (indicated by the horizontal blue lines in Figure 8). This means autocorrelation is significant in this time series up to high values of time lag, from the initial time. From Figure 9, the autocorrelation coefficients of uranium price change or log returns data show very fast decay and are not statistically significant after lag 1. The coefficient values also indicate a reversal in sign from positive to negative. Thus, the price differences or log returns are well represented mathematically by a simple autoregressive model of order 1, leading to simplifications in price forecasting.

Figure 10 shows the uranium futures prices at the Chicago Mercantile Exchange from June 2007 to June 2025. Uranium futures are mechanisms to hedge against uranium price risk for owners/operators of nuclear power plants or nuclear fuel manufacturers. The general trend is that the futures prices have moved in tandem with the spot prices of uranium over the same time frame, showing the highest values during the global financial crisis and then a downward trend up to about month 113, followed by a steadily increasing trend up to the present time.

Volatility Characteristics of Uranium Price Trends

The volatility in uranium prices (expressed as the rolling standard deviation of price) as a function of time is indicated in Figure 11. It is seen that over the long term, the price data are non-stationary and highly heteroscedastic due to time-varying values of the price standard deviation, with volatility sharpening increasing during the global financial crisis of 2007–08 (i.e., between months 177 and 228 in Figure 11). Over shorter durations in specific phases (e.g., months 12 to 71 in Figure 11), the standard deviations of uranium prices are seen to have remained nearly constant or homoscedastic. There is also evidence of volatility clustering, with persistent periods of low volatility and persistent phases of high volatility at different times during the timeline of analysis.

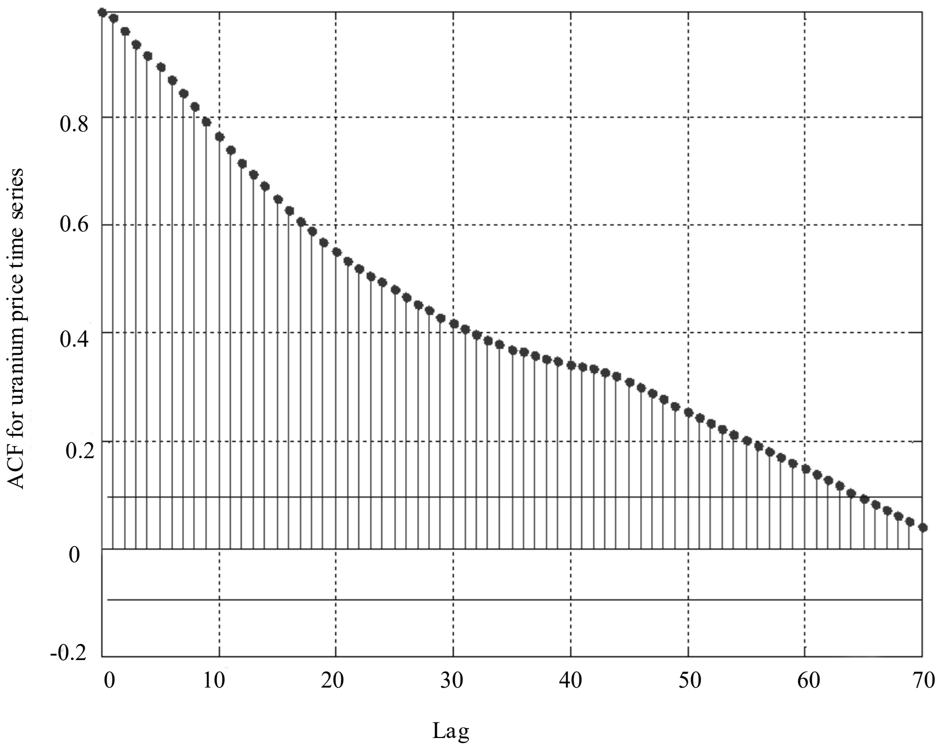

Figure 8. Autocorrelation coefficients of uranium price time series (January 1990–April 2025).

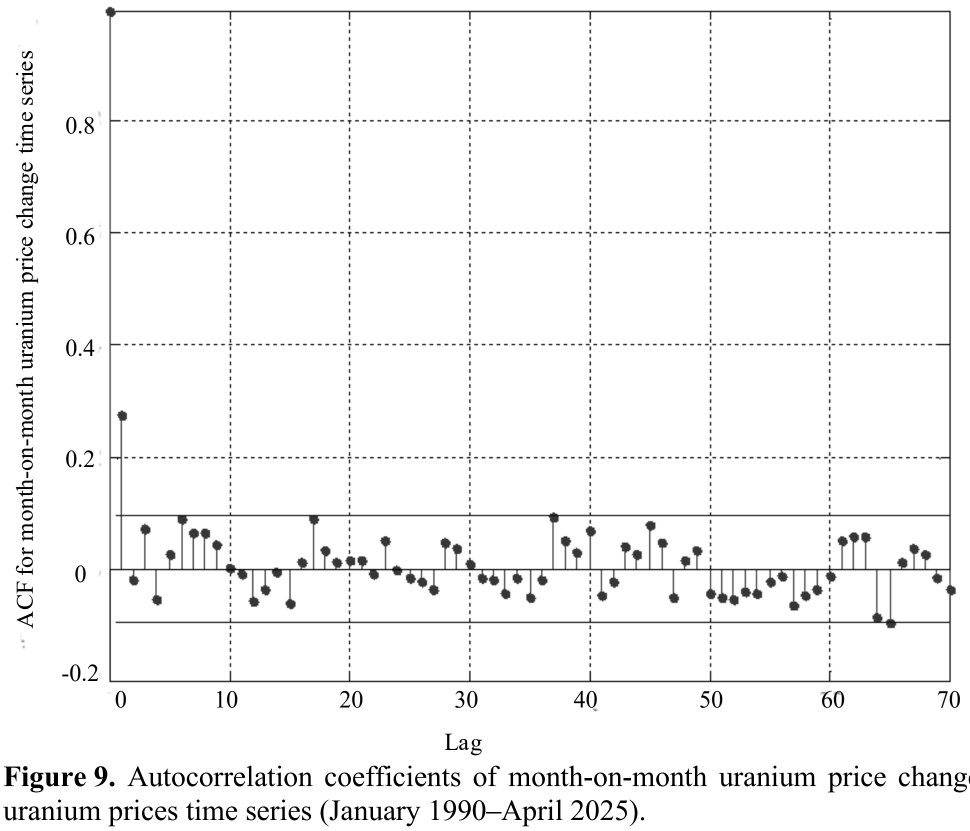

Figure 9. Autocorrelation coefficients of month-on-month uranium price change/log returns on the uranium prices time series (January 1990–April 2025).

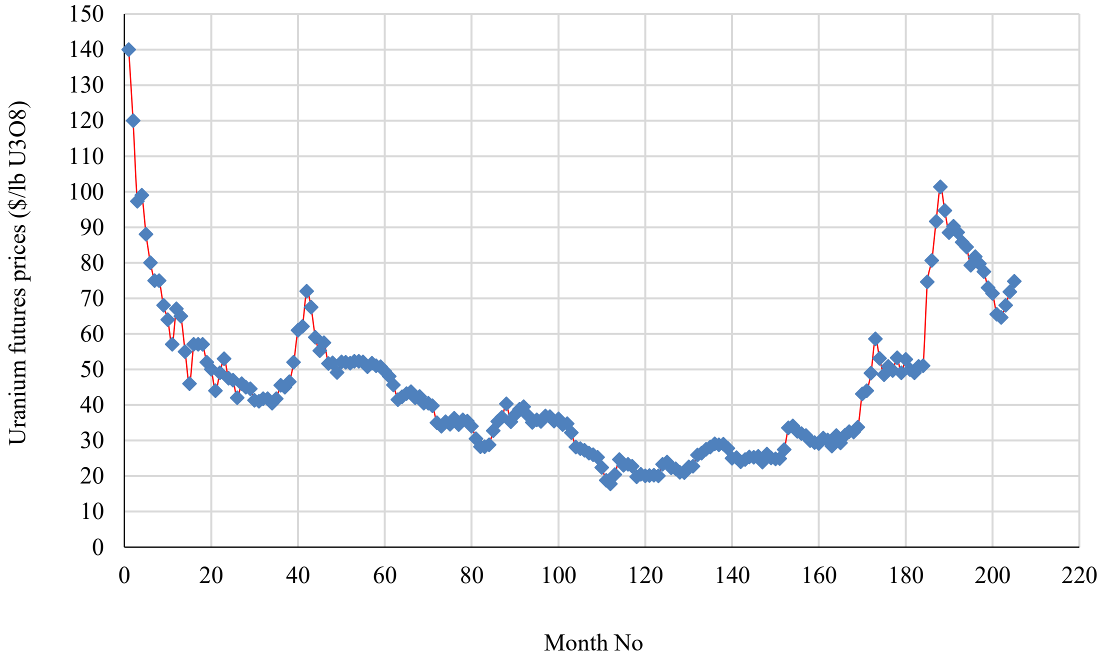

Figure 10. Uranium futures price trend (Data from Chicago Mercantile Exchange, covering June 2007–June 2025).

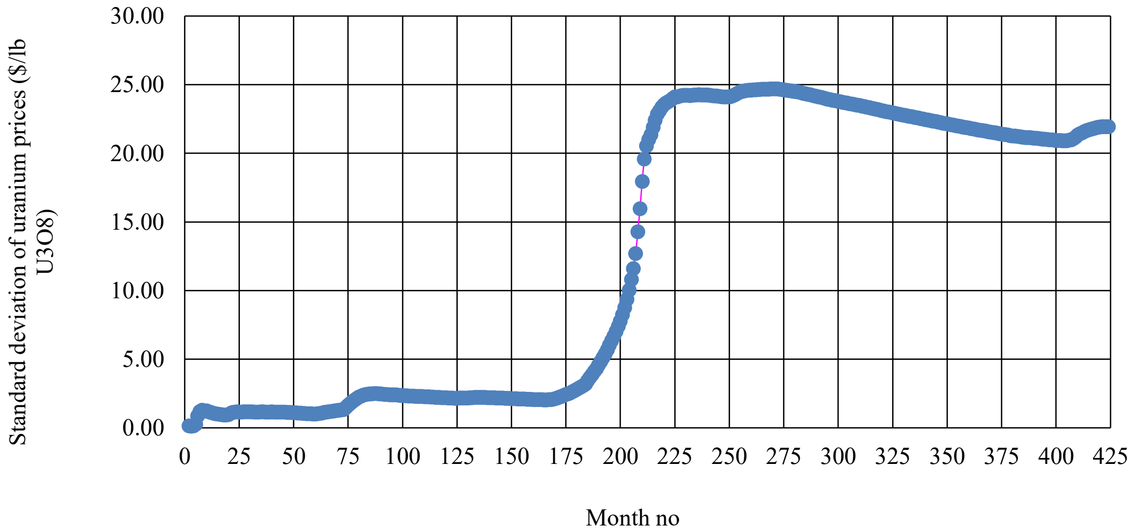

Figure 11. Dynamic volatility characteristics of uranium prices (January 1990–April 2025).

Comparison of Uranium Price Trends with Price Trends of Other Energy Commodities

The price data for several energy commodities, along with uranium over the same time frame of January 1990 to April 2025, are shown in Figure 12. All of them show large fluctuations over time, especially in response to global events representing systemic risks. The calculated pairwise linear correlation coefficients for the prices of each pair of commodities are shown in the correlogram of Figure 13. It is seen that uranium prices are relatively weakly correlated to fossil fuel prices like that as coal and natural gas (coefficients are about ~0.45); however, the correlation is stronger with that of crude oil prices over the same timeline (coefficients of ~0.73). This indicates that from the point of view of electric power production, the low correlation between fossil fuel and nuclear fuel prices is a beneficial trend, as they do not exhibit price jumps in tandem in response to external events at the same time. Thus, a diversified electricity generation system is more resilient to price shocks as it experiences relatively uncorrelated price risks of the principal fuel materials. This is an important component of energy security as well. Figure 14 shows the pair-wise correlation coefficients for price changes or log returns on prices of the energy commodities. The correlation coefficients are weakly positive in all cases and negative in the case of uranium-WTI crude oil price returns. This also reinforces the notion that investing in a diversified energy system is a way to build a robust and resilient energy portfolio in the financial sense as well, less susceptible to economic shocks.

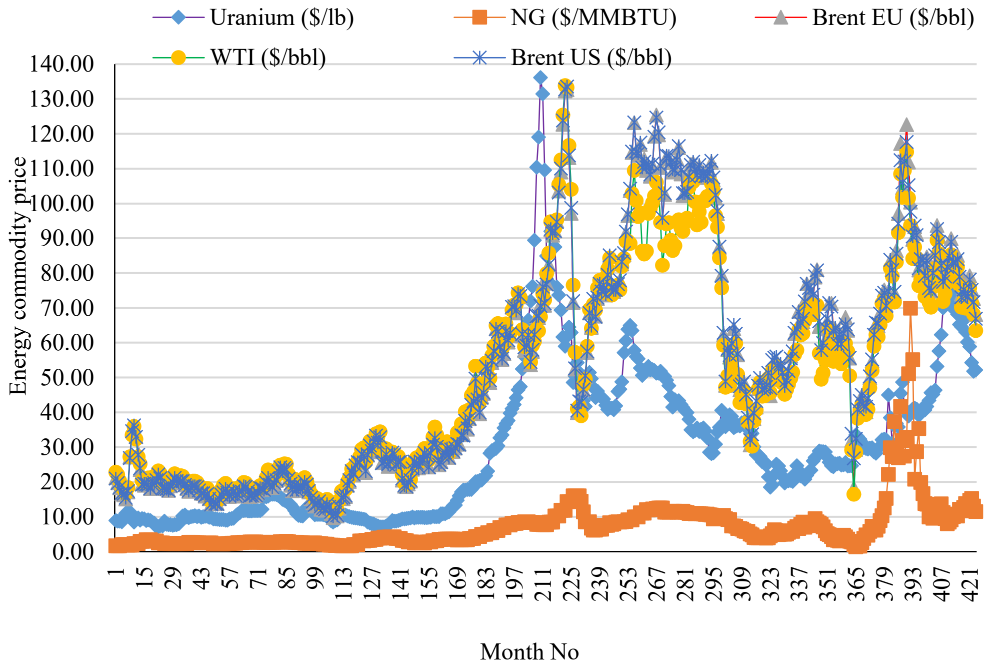

Figure 12. Monthly price data of uranium and other major energy commodity materials (January 1990–April 2025).

	Uranium	Natural gas	Brent EU	WTI	Brent US	Coal
Uranium	1.000	0.454	0.727	0.743	0.727	0.446
Natural gas	0.454	1.000	0.637	0.642	0.630	0.885
Brent EU	0.727	0.637	1.000	0.991	0.999	0.651
WTI	0.743	0.642	0.991	1.000	0.991	0.654
Brent US	0.727	0.630	0.999	0.991	1.000	0.646
Coal	0.446	0.885	0.651	0.654	0.646	1.000

Figure 13. Correlogram of pair-wise linear correlation coefficients of monthly prices of uranium and other energy commodities (January 1990–April 2025).

	Uranium	Natural gas	Brent EU	WTI	Brent US	Coal
Uranium	1.000	0.019	0.027	-0.003	0.039	0.047
Natural gas	0.019	1.000	0.025	0.021	0.022	0.245
Brent EU	0.027	0.025	1.000	0.957	0.972	0.225
WTI	-0.003	0.021	0.957	1.000	0.929	0.214
Brent US	0.039	0.022	0.972	0.929	1.000	0.254
Coal	0.047	0.245	0.225	0.214	0.254	1.000

Figure 14. Correlogram of pair-wise linear correlation coefficients of monthly price changes or log returns of the price of uranium and other energy commodities (January 1990–April 2025).

CONCLUSION

This work is an exploratory evaluation of monthly uranium price data in global markets as a method to analyze global nuclear fuel price trends over the 424-month time frame between January 1990 and April 2025. This time frame covers several business cycles, global financial crises, and exogenous shocks like the COVID-19 pandemic. The time series data for uranium prices analyzed in this work is thus a good signature of the nuclear fuel pricing dynamics under various conditions. The uranium pricing data are seen to follow a right-skewed distribution, while the price change or log returns distributions are more symmetric (but not Gaussian). The tail end or outlier values are found to be more likely to occur than in the case of a normal distribution for prices or returns on prices. It is also seen that uranium prices show heteroscedasticity and respond to global events like other energy commodities. However, its price trends are not very strongly correlated to the prices of coal and natural gas over the same time frame. Thus, nuclear fuel and nuclear power enable energy systems to be diversified and demonstrate enhanced resilience to fuel price shocks.

Caution must be exercised in using the results of this study, particularly for price forecasts, as is done for other asset classes like equity. The available pricing information analyzed in this work represents historic and current demand-supply scenarios for nuclear fuels as well as the impact of major events on the pricing trends (e.g., financial crises, geopolitical instability, and so on).

This study may be further expanded by performing detailed, data-driven modeling of the volatility of uranium fuel prices through approaches like ARCH or GARCH, as has been done for other asset pricing data in financial econometrics, particularly given the time-varying volatility that uranium prices have also exhibited. Nuclear fuel price forecasts can also be made using it. The relation between the stock prices of uranium mining or nuclear fuel manufacturing companies to the price of uranium can also be examined over various time frames to estimate their uranium price risk exposure levels. Price data at higher granularity (i.e., daily or weekly data) instead of monthly data can be used to improve the estimated volatility and price dynamics of uranium.

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