The Market Impacts of US Uranium Import Quotas

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Executive Summary

This study develops an econometric model of the world uranium market to estimate the impacts of quotas on uranium imports into the United States. The econometric model estimates uranium supply and demand in the US and the rest of the world. The model is estimated with data from 1994 to 2016 and yields demand and supply elasticities in line with those reported in the peer-reviewed literature. The demand for uranium is very price inelastic and the supply curves are somewhat more responsive to market prices.

This model is used to estimate the changes in uranium supply, demand, prices, and imports under an import quota that ensures a 25 percent market share for domestic US uranium mining ("25 percent quota"). To provide a sensitivity analysis, the model also estimates the changes in uranium supply, demand, prices, and imports under an import quota that would ensure a 20 percent market share for domestic US uranium mining ("20 percent quota").

Overall, the results of econometric analysis and the model simulations indicate that uranium import controls would provide significant relief for the US uranium mining industry with minimal impacts on domestic electricity prices or the competitive position of nuclear power. Under the 25% import quota, prices to US producers would be expected to increase to levels in line with global production costs, with only a marginal

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impact on the price of electricity to consumers. A 20% quota, which would sustain a smaller US uranium mining industry, would result in a somewhat lesser increase in prices to US producers and electricity prices to consumers.

Under the 25 percent quota, prices increase $21 per pound in 2018 and $32 per pound in 2022 (see Figure ES1), which translate to a 69 and 104 percent increase in domestic prices respectively (see Figure ES2). For the 111 mines operating around the world, the average total cost of production is $40 per pound with a standard deviation of $15. Maximum production costs are $82 per pound. With current market prices of $24 per pound, the 25 percent quota would bring domestic prices back into range with average world production costs.

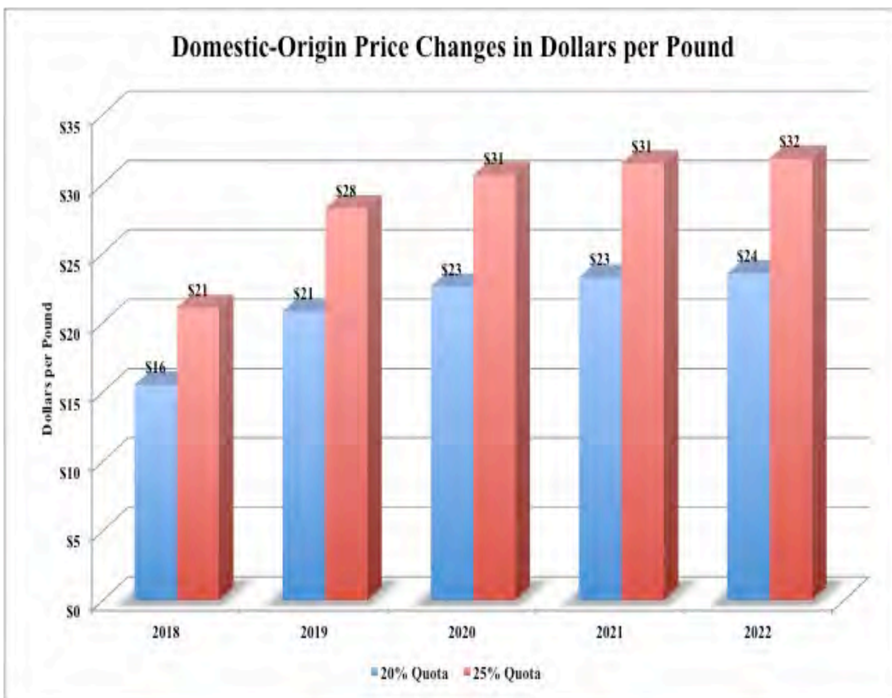

Figure ES1: Price impacts of uranium import quotas

Under a 20 percent quota, prices for domestic-origin uranium would increase somewhat less by $16 per pound in 2018 and $24 per pound in 2022 (see Figure ES1) representing a 61 and a 94 percent increase in domestic prices respectively (see Figure

ES2). Domestic uranium mining revenues increase from $550 to $700 million per year under the 25 percent quota and would increase from $364 to $448 million under a 20 percent quota.

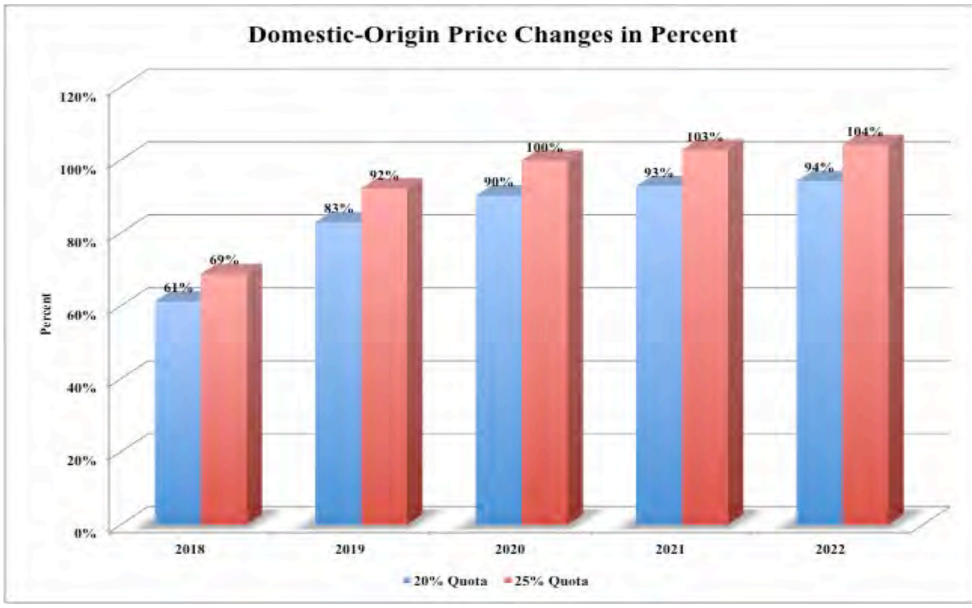

Figure ES2: Price impacts of uranium import quotas in percent

Under this import quota, prices decline for foreign-origin uranium. Even though prices for domestic uranium are higher under the import quota, the small share of domestic production limits the increase in average prices paid by civilian nuclear plant owners and operators (COOs). Average prices for uranium increase between 13 to 21 percent under the 25 percent quota and would increase between 7 and 12 percent for a 20 percent domestic production quota.

In wholesale power markets, the uranium production quota would slightly reduce the margin between nuclear operating costs and the costs of producing power from other sources. To measure how this competitiveness would be affected, the incremental uranium costs due to the quota is divided by nuclear electricity output. These unit incremental costs are from $0.27 and $0.41 per megawatt hour (MWh) under the 25 percent production quota and would be from $0.15 and $0.24 per MWh under a 20 percent production quota (see Figure ES3). These incremental costs are from 0.8 and 1.2 percent of average wholesale electricity prices under the 25 percent production quota. With a 20 percent domestic production quota, the unit incremental uranium costs facing COOs would be from 0.4 and 0.7 percent of the wholesale price of electricity.

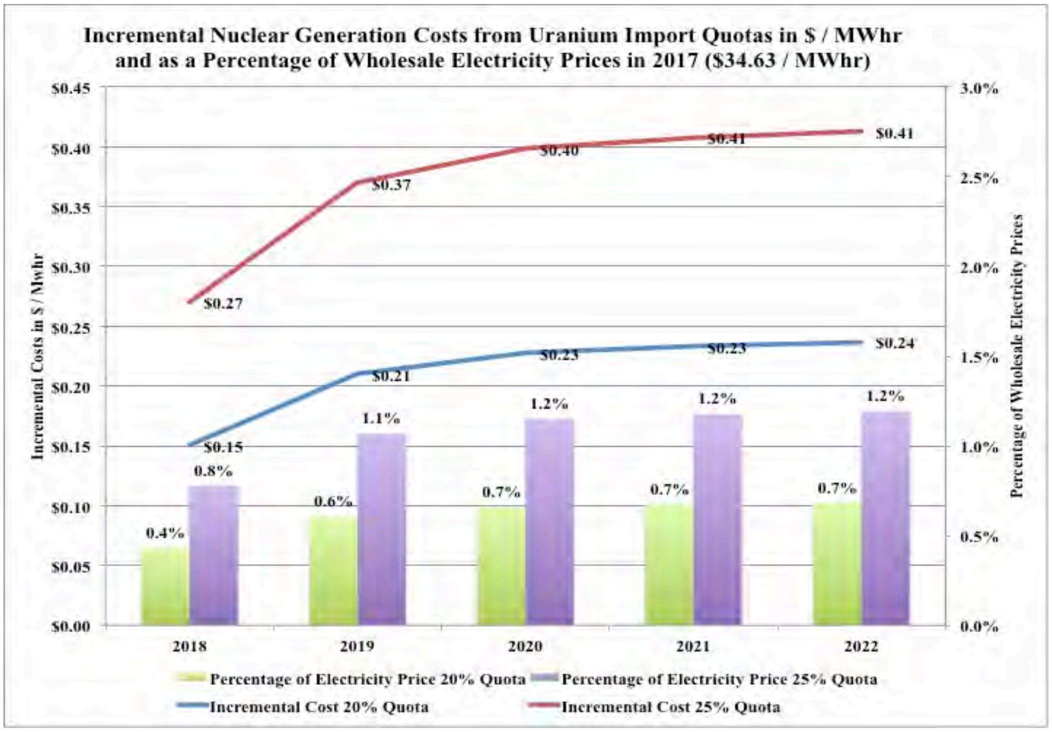

Figure ES3: Incremental costs and wholesale electricity prices

If the proposed domestic production quota was viewed as temporary, prices for future delivery could be lower than prices for spot transactions and buyers would delay purchasing uranium and draw down inventories. This could prevent buyers from entering into the higher-price long-term contracts with US producers that would be required to incentivize increased US production. The econometric model developed in this study allows the estimation of how sensitive uranium inventories are to these spreads between spot and future prices. Average uranium prices paid by COOs across the 25 percent quota increase slightly less than $5 per pound, and somewhat less under a 20 percent quota, which would be the expected price decline in the future once the quota expires. If this is the difference between spot and forward prices, model simulations indicate that the potential supply from inventory drawdowns averages 5.9 million pounds per year from 2.5 to 7.7 million pounds per year (see Figure ES4).

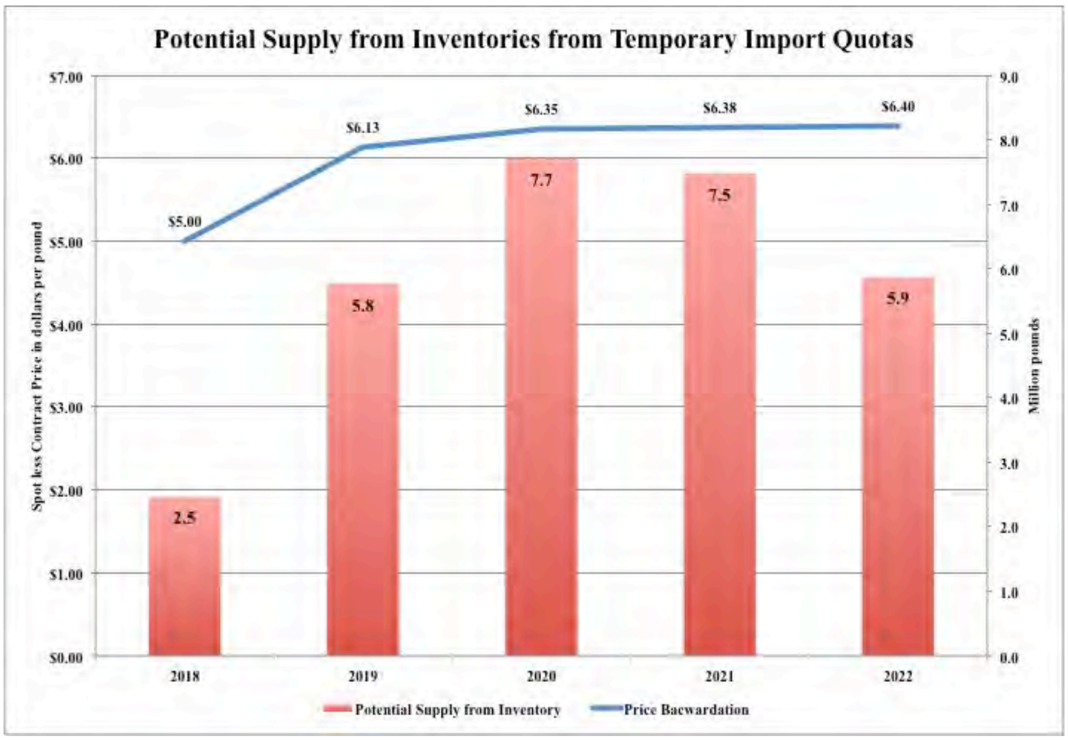

Figure ES4: Price impacts of uranium import quotas in percent

Over the past 20 years, total US commercial inventories were as low as 72.5 million pounds in 1995 and as high as 143.9 million pounds in 2016, which is a difference of 71.4 million pounds. If 5.9 million pounds per year were drawn from this inventory buffer, it would be depleted after 12 years. Hence, if uranium production quotas were adopted, they should remain in place for a minimum of a decade and probably longer. This would encourage US utilities to enter into the long-term contracts with US producers required to support the modeled increase in US production.

1. Introduction

Falling prices, rising imports, and declining domestic production are threatening the economic and financial viability of the US uranium mining industry. Higher production from Russia, Kazakhstan, and Uzbekistan in recent years is contributing to lower prices. Prices for uranium have been falling for the past five years and US production is down nearly 60 percent from the distressed levels more than 15 years ago. Uranium purchases from civilian nuclear plant owner and operators (COOs) in the US fell 10 percent in 2016 to 50.6 from 56.6 million pounds in 2015. The average weighted price of uranium concentrate (U_3O_8) fell 4 percent from $44.13 to $42.43 per pound of U_3O_8 during the same period. During 2016, COOs signed new purchase contracts for 8.7 million pounds of U_3O_8 for an average price of $24.86 per pound, more than 40 percent below the average weighted contract and spot price. Foreign-origin uranium comprises nearly 92 percent of total US purchases of uranium. Falling demand is exacerbating these challenging market conditions for US producers. As a result, commercial inventories of uranium at the end of 2016 were 6 percent higher than 2015 levels.

Lower demand, higher imports, and falling prices are contributing to lower US production of uranium concentrate, which was 2.9 million pounds during 2016, the lowest level since 2005 and substantially below the 6.3 million pounds of production in 1996. During the first half of 2017, production of uranium concentrate fell 14 percent from the first two quarters of 2015. These difficult market conditions have forced uranium-mining companies in the US to propose a quota on uranium imports. The objective of this paper is to estimate the market impacts of this import quota on the uranium market and the price of electricity in the US.

To achieve this goal, this study develops an econometric model of world uranium markets, including the US and the result of the world, which is presented in section 3 below. This regional framework builds upon the studies by Trieu et al. (1994), Auzans et al. (2014), Schneider (2017), and Kahouli (2011). The model determines nuclear power capacity and generation, uranium supply and demand, commercial inventories, and uranium prices in the US and the rest of the world. The parameters of the model are estimated with annual data from 1994 through 2016. An overview of the data sample is discussed in section 2. Given the simultaneous determination of prices, demand, capacity, and generation; the model equations are estimated with two-stage least squares. The econometric estimates for the relationships in the world uranium model are presented in section 4 below.

The model is used to simulate the market adjustments under an import quota that ensures a 25 percent market share for domestic US uranium mining ("25 percent quota"). To provide a sensitivity analysis, the model also estimates the changes in uranium supply, demand, prices, and imports under an import quota that would ensure a 20 percent market share for domestic US uranium mining ("20 percent quota"). Solutions for prices, quantities, and other endogenous variables are compared to estimate the market impacts of the quota. These model simulations are presented in section 5.

The demand for uranium is driven by the operation of highly capital-intensive nuclear power plants that must operate continuously to achieve economies of scale in electric power production. Nuclear power competes with electricity produced from wind, coal, natural gas, and other sources. As a result, COOs hold between 2 and 3 years of uranium requirements in inventory. This suggests that if import quotas are enacted, COOs could simply draw down inventories, especially if the trade restrictions were perceived to be temporary. The response of inventories, therefore, may be an important consideration in determining the duration of the domestic production quotas. To address this issue, the econometric model is simulated under a scenario in which expected uranium prices in the future are lower than current spot prices. This market simulation, which is presented in section 6, indicates that the inventory response is sizable and, therefore, if quotas are adopted they should be for a minimum of 10 years and probably longer.

The paper concludes with a summary of the key findings. Overall, the results of econometric analysis and the model simulations indicate that uranium import controls would provide significant relief for the US uranium mining industry with minimal impacts on domestic electricity prices or the competitive position of nuclear power. Such trade protection may be critical in maintaining a viable domestic uranium mining industry in the United States, see Spencer and Loris (2008), an issue that was previously under consideration circa 1990 by the US Department of Commerce (1989).

2. Overview of Data Sample

The data sample used for the econometric model presented in the next section is from 1994 to 2016 because the two key data series, purchases of domestic and foreign-origin uranium are only available from US Energy Information Administration (2107a) during this period. Developing an accurate market balance for a longer time period is not possible given the lack of data on the significant flows of uranium concentrate coming from the re-processing of spent weapons grade uranium, government stockpiles, and other secondary supply sources. The world data collected by Kahouli (2011) were updated for this study. Data for US uranium markets are collected from the US Energy

Information Administration (2107a, and 2017b). Summary statistics for the endogenous variables are presented in Table 1.

US nuclear capacity on average was 99.5 Gigawatts (GW) over the sample period with a standard deviation of only 1.3. Capacity in the rest of the world is more than twice as large with considerably more variation given its significant upward trend (see Figure 1). Nuclear generation of electric power averaged 757 thousand Gigawatt hours (GWh) in the US and 1,700 thousand GWh in the rest of the world. Uranium requirements or uranium in fuel assemblies in nuclear reactors are roughly twice as large in the rest of the world compared to the US.

Table 1: Summary statistics, 1994 - 2016

	Mean	*Standard Deviation*	*Minimum*	*Maximum*
Nuclear Capacity	*Gigawatts*			
United States	99.56	1.29	97.07	101.89
Rest of World	264.83	14.45	241.26	293.20
Nuclear Generation	*Thousand Gigawatt hours*			
United States	756.96	57.13	628.64	806.97
Rest of World	1,699.08	105.67	1,484.72	1,872.54
Uranium Requirements	*Million Lbs. U3O8*			
United States	49.59	5.96	38.20	62.27
Rest of World	92.74	6.81	76.98	107.03
US Uranium Purchases				
Domestic-Origin	8.00	0.55	7.72	10.81
Foreign Origin	44.41	6.80	30.56	55.73
Uranium Mining Shipments				
United States	4.11	1.26	1.60	6.30
Rest of World	94.99	21.12	69.45	134.50
US Commercial Inventories	110.19	19.17	72.50	143.86
Uranium Prices	*Dollars per lb. U3O8*			
Domestic	28.47	19.08	10.50	59.55
Foreign	27.12	17.98	9.97	55.98
Average	27.36	18.12	10.16	55.61
Spot	29.29	22.31	7.92	88.25
Contract	27.51	18.46	10.58	55.90

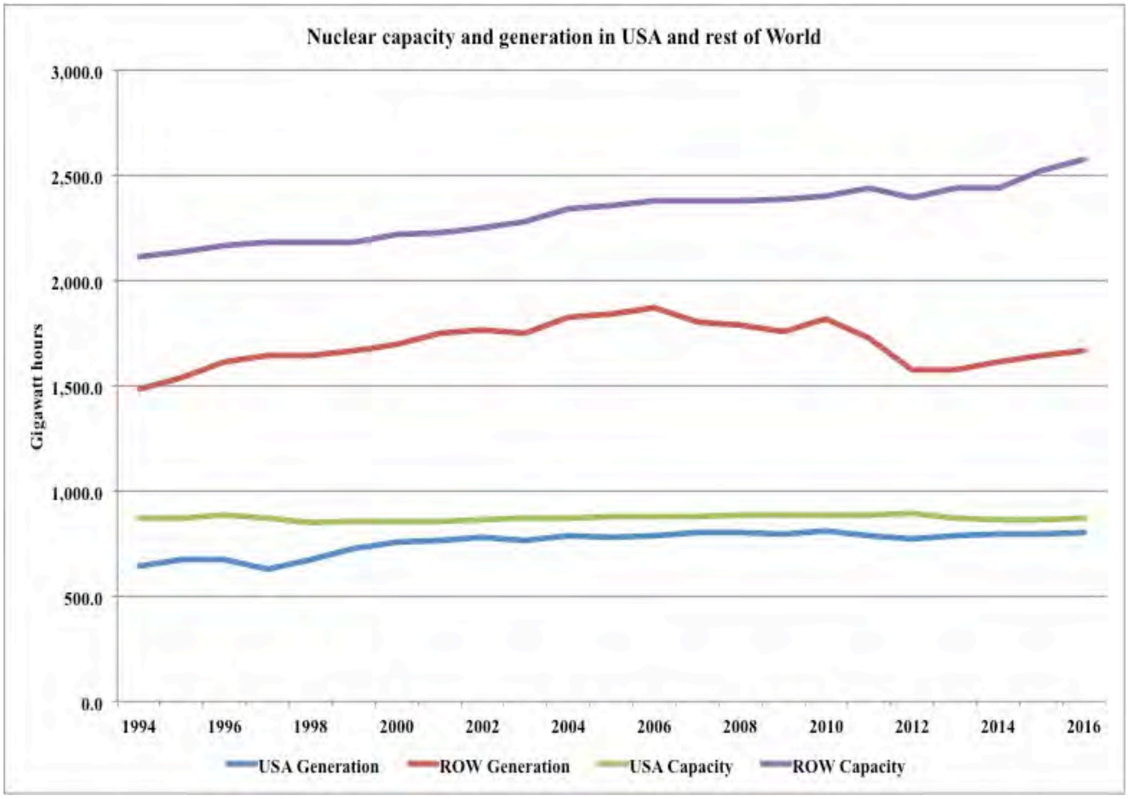

Figure 1: Nuclear capacity and generation

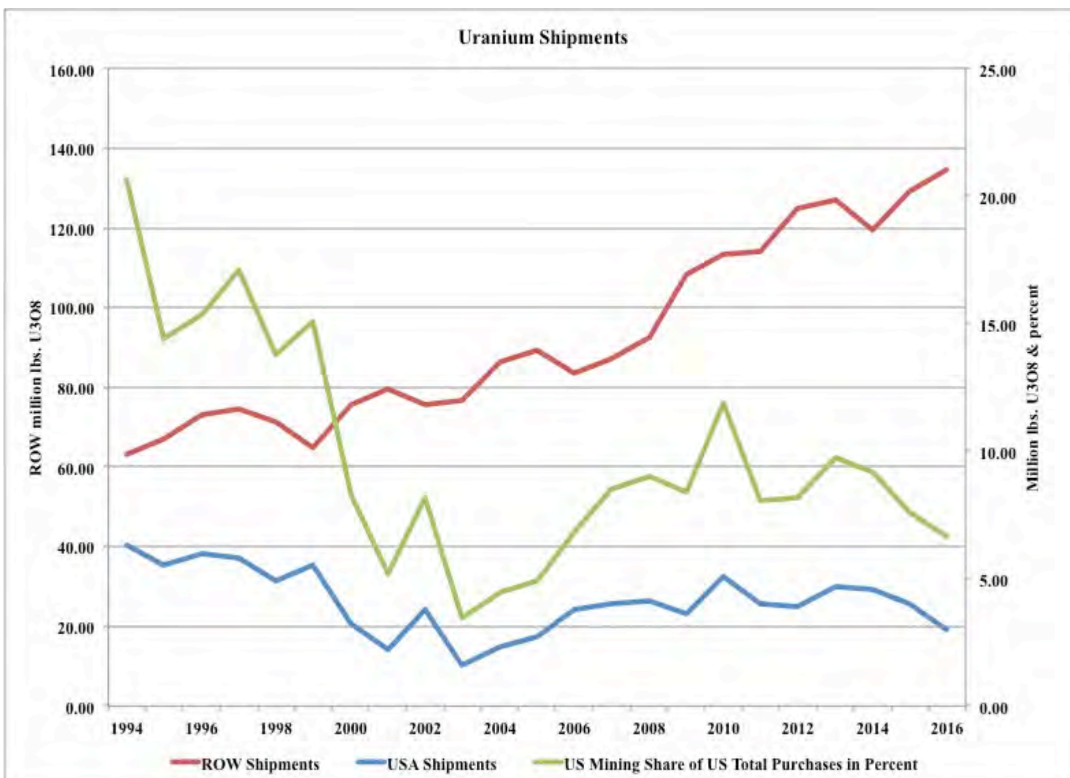

Figure 2: Uranium shipments

Purchases of domestic-origin uranium averaged 8 million pounds per year over the sample period while mining shipments were slightly more than half of this amount at 4.11 million pounds (see Table 1). The difference reflects secondary sources of supply from government stockpiles and re-processors of higher-grade uranium products. The US mining share of uranium shipments in total uranium purchases was over 20 percent in 1994, fell to less than 4 percent in 2003, recovered to nearly 12 percent in 2010 but then fell again to 6.6 percent in 2016. Uranium shipments from mines in the rest of the world more than doubled over the sample period while US uranium mining shipments fell (see Figure 2).

US commercial inventories averaged over 110 million pounds per year, which are more than twice annual uranium requirements (see Table 1). Changes in commercial inventories are also sizable and at times exceed purchases of domestic-origin uranium (see Figure 3). Purchases of foreign-origin uranium averaged more than 44 million pounds per year and peaked at more than 56 million pounds in 2006. Sales of uranium from government inventories are not included in commercial inventories and have been an issue for the uranium industry, see US Department of Commerce (2017) and Meade and Supko (2017).

Spot prices for uranium increased sharply in 2007 (see Figure 4). Contract prices and prices for domestic and foreign-origin uranium also increased and have remained above levels during 1994 to 2005. As previously mentioned, spot prices are currently $24 per pound.

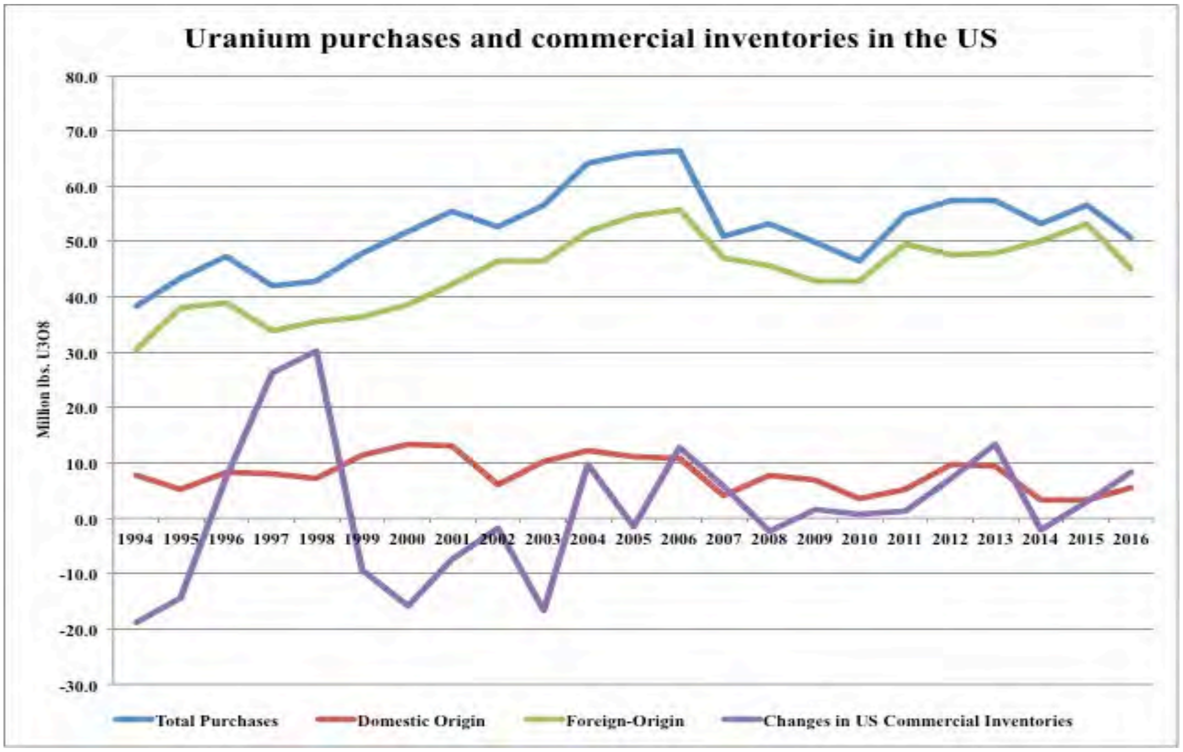

Figure 3: Uranium purchases and inventories

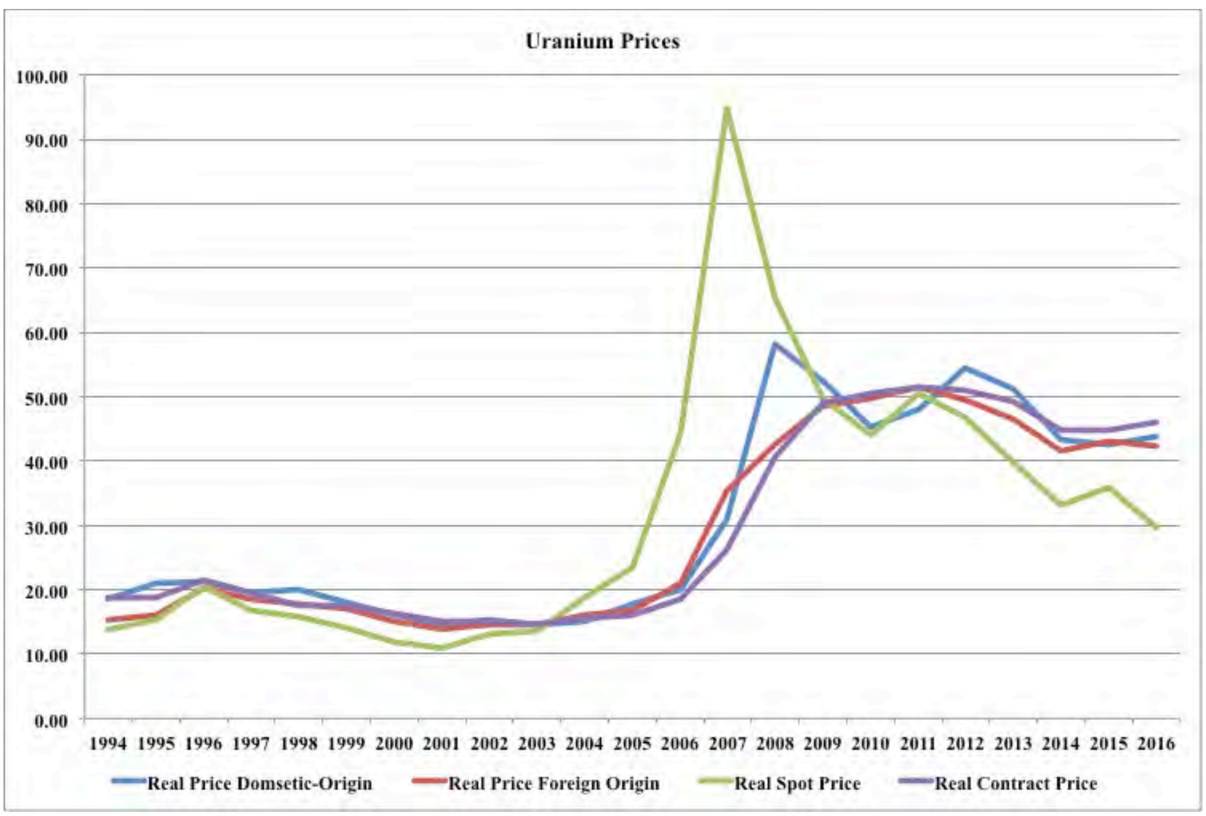

Figure 4: Uranium prices

3. Econometric Model

The econometric model has three blocks representing supply and demand in the U.S. and the rest of the world. Given the small sample available, the supply and demand equations are parsimonious, relating the endogenous variables in Table 1 with each other, lagged endogenous variables, and exogenous factors, such as the producer price index, interest rates, structural shifts, and market shocks. The three sub-sections below describe the behavioral relationships within each block.

3.1 US Demand

The US demand block determines nuclear electric capacity and generation and total purchases of uranium, purchases of foreign-origin uranium, and shipments from US uranium mines. The number of nuclear power plants has steadily declined over the sample period from 109 in 1994 to 99 in 2016. The resulting loss of electric power generation capability, however, has been offset by higher capacity factors due to more efficient management of nuclear electricity generation facilities. Accordingly, US nuclear capacity is hypothesized as a function of the number of plants, lagged capacity factor, and lagged capacity to capture dynamic adjustments. The US nuclear capacity equation, therefore, is as follows:

$$K_t^u = \alpha_0 + \alpha_1 NP_t + \alpha_2 CF_{t-1} + \alpha_3 K_{t-1}^u \quad (1)$$

where K_t^u is US nuclear capacity (the superscript u denotes the region, in this case the US), NP_t is the number of nuclear power plants operating, CF_{t-1} is nuclear capacity factor lagged one period, and αs are unknown parameters to be estimated. US nuclear generation, G_t^u, is simply a function of the lagged capacity factor:

$$G_t^u = \beta_0 + \beta_1 CF_{t-1} \tag{2}$$

where the βs are unknown parameters.

Total purchases of uranium in the US, Q_t^u, are specified as a function of real prices, nuclear generation, and lagged purchases:

$$Q_t^u = \chi_0 + \chi_1 \left(P_t^a / PPI_t \right) + \chi_2 G_t^u + \chi_3 Q_{t-1}^u \tag{3}$$

where P_t^a is the weighted average price of uranium defined below in the supply block, PPI_t is the producer price index, and the χs are parameters to be estimated. The relation for purchases of foreign-origin uranium, Q_t^f, follows the same specification:

$$Q_t^f = \delta_0 + \delta_1 \left(P_t^a / PPI_t \right) + \delta_2 G_t^u + \delta_3 Q_{t-1}^f \tag{4}$$

where the δs are unknown parameters. Uranium in fuel assemblies at nuclear power plants are also specified in a similar fashion:

$$Q_f^b = \lambda_0 + \lambda_1 \left(P_t^a / PPI_t \right) + \lambda_2 G_{t-1}^u + \lambda_3 G_{t-2}^u \tag{5}$$

where the λs are unknown parameters. Nuclear generation with a two-year lag is included to capture lags in fuel loadings, processing, and deliveries.

Uranium shipments from US mines, S_t^u, are determined by the following identify:

$$S_t^u = Q_t^u - Q_t^o - Q_t^f \tag{6}$$

where Q_t^o are other sources of uranium concentrate, such as those from government stocks and uranium fuel processors. This source of uranium supply has dwindled in recent years and is, therefore, assumed to be exogenous in the model simulations presented in section 5.

3.2 US Supply

The supply block determines prices for uranium concentrate by transactions type, either spot or contract, and source of supply, either domestic or foreign-origin. The domestic-origin uranium price is specified as a function of domestic mining shipments and lagged prices. Klingbiel (2017) notes that world in-situ uranium resources peaked in 2007 at around 34 billion pounds and fell to 25 billion pounds by 2015 with increased incremental production cost. Accordingly, the US supply function allows for a structural shift in 2007 as follows:

$$P_t^d = \phi_1 S_t^u + \phi_2 H_t + \phi_3 P_{t-1}^d \quad (7)$$

where P_t^d is the price of domestic-origin uranium, S_t^u is domestic mining shipments, the dummy variable, H_t, is for the pre and post 2007 structural supply shift, and the ϕs are unknown parameters.

The domestic and foreign-origin uranium prices include spot and contract prices so that a weighted average of the former two prices is equal to the weighted average of the latter two prices. To maintain consistency with how market shocks affect US prices, spot and contract prices, P_t^s and P_t^c respectively, are specified as functions of the weighted average price of domestic and foreign-origin uranium, lagged spot and contract prices respectively, and a dummy variable for the speculative spike in uranium and other resource prices in 2007, D_t^{2007}:

$$P_t^s = \gamma_1 P_t^a + \gamma_2 P_{t-1}^s + \gamma_3 D_t^{2007} \quad (8)$$

$$P_t^c = \eta_1 P_t^a + \eta_2 P_{t-1}^c + \eta_3 D_t^{2007} \quad (9)$$

where the γs and ηs are parameters to be econometrically estimated.

Total US commercial inventories are specified as a function of user costs, see Considine (2006), of holding stocks of uranium, U_t, which is defined as follows:

$$U_t = \ln\left(P_t^s / P_t^c\right) + r - \ln\left(PPI_t / PPI_{t-1}\right) \quad (10)$$

where r is the risk free interest rate given by the three-month US Treasury bill rate. The last two terms in (10) represent the real opportunity cost of funds tied up in physical inventories. The first term in (10) is the percentage difference between the spot and contract price. The contract price serves as a proxy for expected prices to prevail in the future. If the spot price is greater than the expected price, which is known as a price backwardation, inventories should decline. Conversely, if the contract price exceeds the spot price, which is a price contango, inventories should increase. Hence, inventories should be inversely related to user costs. Accordingly, the relationship for US total commercial uranium inventories is specified as a function of user costs, sales or, in this case, nuclear power generation, and a two-year lag of inventories, which is consistent with the fuel loading cycles discussed above:

$$I_t = \kappa_1 U_t + \kappa_2 G_t^u + \kappa_3 I_{t-1} + \kappa_4 I_{t-2} \quad (11)$$

where the κs are parameters to be estimated. Inventories are expected to increase with nuclear electric power generation.

3.3 Rest of World

The final block of the model includes equations that determine the price of foreign-origin uranium, average prices for domestic and foreign origin uranium, nuclear capacity and generation, demand, and mining shipments for the rest of the world. The price of foreign origin uranium, P_t^f, is specified as a function of world uranium mining shipments, S_t^w, the dummy variable, H_t, for the pre and post 2007 structural supply shift discussed above, beginning inventories, and lagged foreign prices:

$$P_t^f = \varphi_1 S_t^w + \varphi_2 H_t + \varphi_3 I_{t-1} + \varphi_4 P_{t-1}^f \tag{12}$$

where the φs are structural parameters. With the specification of price for foreign-origin uranium, average prices can be endogenously calculated in full model simulation as follows:

$$P_t^a = \frac{\left[P_t^d \left(S_t^u + S_t^o \right) + P_t^f Q_t^f \right]}{Q_t^u} \ . \tag{13}$$

Nuclear power capacity in the rest of the world, K_t^r, is specified as follows:

$$K_t^r = \pi_0 + \pi_1 \left[\left(P_{t-1}^f / PPI_{t-1} \right) / DI_{t-1} \right] + \pi_2 K_{t-1}^r + \pi_3 K_{t-2}^r \tag{14}$$

where DI_{t-1} is the lagged trade weighted exchange value of the US dollar and the πs are unknown parameters. This dynamic formulation is similar to the model estimated by Kahouli (2011) with a lag in the real price of uranium in foreign currencies. Nuclear power generation for the rest of the world, G_t^r, has a similar specification:

$$G_t^r = \nu_0 + \nu_1 \left[\left(P_t^f / PPI_t \right) / DI_t \right] + \nu_2 K_t^r + \nu_3 G_{t-1}^r \tag{15}$$

where the νs are parameters whose estimates are presented in the following section.

The demand for uranium in the rest of the world, Q_t^r, is also specified as a function of real prices in foreign currencies and nuclear power generation:

$$Q_t^r = \mu_0 + \mu_1\left[\left(P_t^f / PPI_t\right)/DI_t\right] + \mu_2 G_t^r + \mu_3 D_t^f + \mu_4 D_t^{99} \qquad (16)$$

where D_t^f is a dummy variable for 2011 when the Fukushima disaster occurred, D_t^{99} is a dummy variable for an inventory shock in 1999, and the μs are unknown parameters.

The model is closed with identities defining world uranium requirements and shipments of uranium from mining:

$$Q_t^w = Q_t^r + Q_t^b \qquad (17)$$

$$S_t^r = Q_t^w - S_t^u - S_t^c \qquad (18)$$

$$S_t^w = S_t^r + S_t^u \qquad (19)$$

where S_t^c is other sources of uranium supply in the rest of the world, such as processing plants and commercial and government inventories, which are assumed exogenous in the policy simulations of the model.

The nineteen-equation model has thirteen behavioral equations and six identities. Under import quotas, the demand for foreign origin uranium (4) is replaced with an equation that specifies that foreign origin demand, Q_t^f, is equal to the product of the domestic quota share, ψ_i, and total domestic purchases, Q_t^u:

$$Q_t^f = \left(1 - \psi_i\right) Q_t^u \ . \qquad (20)$$

4. Econometric Results

The parameter estimates for the behavioral equations are presented in this section. The equations for US nuclear capacity and generation are estimated with robust or heteroskedastic-consistent standard errors using ordinary least squares because these models contain no endogenous explanatory variables. The estimates for these equations appear in Table 2. All coefficients have the expected signs with capacity increasing with the number of nuclear plants and capacity factors. Generation is strongly related to lag capacity. Both equations have relatively high coefficients of determination, R^2, and the Breusch and Godfrey (BG) statistics indicate an absence of autocorrelation.

Table 2: Parameter estimates for demand side of U.S. uranium market

Dependent Variable / Explanatory Variables	*Estimated Coefficient*	*Standard Error**	*t-Stat.*	*Adj. R^2*	*BG***
Nuclear Generation Capacity					
Intercept	-5.901	9.286	-0.635	0.854	16.460
Number plants	0.308	0.057	5.404		
Capacity factor lagged	0.139	0.019	7.316		
Nuclear capacity lagged	0.618	0.083	7.446		
Nuclear Electricity Generation					
Intercept	114.110	79.590	1.434	0.852	15.168
Nuclear Capacity lagged	7.501	0.889	8.438		
Total Uranium Purchases					
Real average price	-0.089	0.060	-1.483	0.567	10.063
Generation	0.040	0.013	3.077		
Total purchases lagged	0.478	0.208	2.298		
Foreign Uranium Purchases					
Intercept	-10.193	19.500	-0.523	0.670	13.138
Real average price	-0.088	0.062	-1.419		
Generation	0.036	0.062	0.583		
Foreign purchases lagged	0.684	0.699	0.979		
Uranium in Fuel Assemblies					
Intercept	10.931	16.621	0.658	0.559	10.876
Real average price	-0.233	0.085	-2.741		
Generation lagged	0.143	0.042	3.405		
Generation lagged twice	-0.083	0.057	-1.456		

* Standard Errors are heteroskedastic-consistent
** Breusch-Godfrey test for autocorrelation in the residuals, 5% critical value = 5.99

The remaining equations in the model are estimated using two-stage least squares with heteroskedastic-consistent standard errors. The instruments vary by equation but generally included lagged endogenous variables, crude oil prices, and the market shock dummies discussed above. Estimates for the three US demand equations appear in Table 2. The coefficients on real prices have the expected negative signs while the coefficients on nuclear generation have the expected positive signs.

The real price effects for total and foreign uranium purchases are only significant at the 15 percent level, suggesting a 15 percent probability that these effects are insignificantly different from zero. Nuclear power generation is significantly related to total uranium purchases and to uranium loaded into power plant fuel assemblies. All three equations have R^2 coefficients that suggest the models explain more than half the variation in the respective endogenous variable. The Breusch-Godfrey statistics indicate the absence of autocorrelation.

Estimates for the US supply-side equations are presented in Table 3. Prices for domestic-origin uranium are significantly related to US uranium mining shipments so that higher shipments are related to higher prices. Notice that the estimated coefficient for the structural shift after 2007 is large and significant, which is consistent with the view by Klingbiel (2017) that depletion has contributed to higher incremental production costs. The estimates for the spot and contract price equations also appear in Table 3 and have the expected signs and fit the data reasonably well with minimal autocorrelation.

Finally, the two-stage least squares estimation of the inventory equation also has the expected signs and reasonably high levels of statistical significance and goodness of fit statistics, given by the R^2 coefficient and the Breusch-Godfrey statistic. The estimated coefficient for user costs in the inventory equation is -14.4 with a t-statistic of -1.72, suggesting only an 8.5 percent probability that inventories are not affected by user costs.

Hence, US commercial uranium inventories are likely sensitive to user costs and, in particular, the spread between spot and contract prices, which drives most of the variability in the user cost of inventories.

Table 3: Parameter estimates for supply side of U.S. uranium market

Dependent Variable *Explanatory Variables*	Estimated *Coefficient*	Standard *Error**	*t- Stat.*	*Adj.* R^2	*BG***
Domestic Uranium Prices					
Domestic shipments	2.036	0.746	2.729	0.899	16.435
Post 2007 Dummy	24.095	10.099	2.386		
Domestic prices lagged	0.316	0.245	1.437		
Spot Prices					
Average uranium price	0.471	0.156	3.019	0.924	17.091
Spot price lagged	0.467	0.133	3.511		
Dummy 2007	54.401	1.246	43.661		
Contract Prices					
Average uranium price	0.794	0.053	14.869	0.998	17.980
Contract price lagged	0.231	0.056	4.132		
Dummy 2007	-5.535	0.830	-6.668		
US Commercial Inventories					
User costs	-14.443	8.376	-1.724	0.581	10.876
U.S. nuclear generation	0.093	0.037	2.510		
Beg. Inventories	1.072	0.206	5.210		
Beg. Inventories lagged	-0.706	0.317	-2.230		

* Standard Errors are heteroskedastic-consistent
** Breusch-Godfrey test for autocorrelation in the residuals, 5% critical value = 5.99

The parameters estimates for the remaining four-equations in the model for the rest of the world appear in Table 4. World uranium demand is highly significant in the equation for prices of foreign-origin uranium, along with the post 2007 dummy variable for the structural shift discussed above. Lagged US commercial inventories are also statistically significant. Overall, the foreign uranium price equation fits the data very well with an absence of autocorrelation in the residuals.

The estimates for uranium demand in the rest of the world also appear in Table 4. Real prices are highly significant. Dummy variables for the Fukushima nuclear disaster and the 1999 inventory shock are also statistically significant. The remaining two equations for nuclear capacity and generation for the rest of the world indicate that reasonably significant price effects and plausible responses to lagged capacity and generation.

Table 4: Parameter estimates for rest of world (row) uranium market

Dependent Variable *Explanatory Variables*	*Estimated Coefficient*	*Standard Error**	*t- Stat.*	*Adj. R^2*	*BG***
Foreign Uranium Prices					
World uranium shipments	0.139	0.036	3.860	0.969	17.705
Post 2007 Dummy	16.367	2.220	7.372		
Lagged U.S. inventories	-0.038	0.025	-1.519		
Foreign prices lagged	0.411	0.072	5.717		
Uranium demand					
Intercept	75.105	15.276	4.917	0.563	11.594
Real price dollar adj.	-0.386	0.123	-3.138		
Nuclear generation (row)	0.013	0.009	1.401		
Dummy for Fukushima	-11.368	1.868	-6.087		
Dummy 1999	-13.758	1.096	-12.556		
Nuclear Electricity Generation					
Intercept	27.633	167.006	0.165	0.793	14.848
Real price dollar adj.	-2.170	0.867	-2.503		
Nuclear capacity (row)	1.532	0.713	2.149		
Nuclear generation lagged	0.795	0.053	15.008		
Nuclear Capacity					
Intercept	-33.958	24.268	-1.399	0.945	16.347
Real price lagged	-0.091	0.065	-1.402		
Nuclear capacity lagged	0.739	0.218	3.382		
Nuclear capacity lagged twice	0.414	0.272	1.524		

* Standard Errors are heteroskedastic-consistent
** Breusch-Godfrey test for autocorrelation in the residuals, 5% critical value = 5.99

Unlike log-linear models with constant elasticities of supply and demand, the linear equations estimated here have variable elasticities. These elasticities are computed for each point in the sample and are summarized in Table 5 below. The demand elasticities are presented in the top panel of Table 5 and show very price inelastic demand in both the short and long run. The elasticities of demand with respect to nuclear generation are also inelastic in the short-run but are elastic or greater than one, except for uranium requirements in the rest of the world.

The elasticities of prices for domestic and foreign-origin uranium are also inelastic in the short-run and elastic in the long-run (see Table 5). The inverse of these price elasticities are supply elasticities with respect to price. The estimates in Table 5 indicate that the short-run supply elasticities are slightly elastic at 1.4 and 1.1 for the US and the rest of the world respectively. Very price inelastic demand combined with relatively low price elasticities of supply help explain why uranium prices, like many other fuel commodities, are so volatile.

Table 5: Demand and Supply Elasticities

Demand Elasticities		
Total Domestic Purchases of Uranium	*Short-Run*	*Long-Run*
Price	-0.053	-0.101
Nuclear Generation	0.582	1.116
Purchases of Foreign-Origin Uranium		
Price	-0.060	-0.189
Nuclear Generation	0.616	1.953
Uranium in Fuel Assemblies in USA		
Price		-0.153
Nuclear Generation		2.253
Uranium Requirements Rest of World		
Price		-0.079
Nuclear Generation		0.259
Price Elasticities		
Prices for Domestic-Origin Uranium	*Short-Run*	*Long-Run*
US Mining Shipments	0.728	1.062
Prices for Foreign-Origin Uranium		
Rest-of-World Mining Shipments	0.875	1.986
U.S. Commercial Inventories	-0.775	-1.760
U.S. Commercial Inventories		
Spot Prices	-0.128	-0.202
US Nuclear Generation	0.644	1.015

5. Market Impacts of Import Quota

The impacts of the import quota are estimated by simulating the above model under the 25 percent quota with a sensitivity analysis performed using a 20 percent quota. Under the 25 percent domestic production quota, prices for domestic-origin uranium rise between $21 and $32 per pound from 2018 to 2022 (see Table 6), which translate to a 69 and 104 percent increase in domestic prices. According to Ux (2017), for the 111 mines operating around the world, the average total cost of production is $40 per pound with a standard deviation of $15. Maximum production costs are $82 per pound. With current market prices of $24 per pound, the 25 percent quota would bring domestic prices back into range with average world production costs. Domestic mining shipments would increase by 10.34 million pounds in 2018 and by 10.20 million pounds in 2022. Greater shipments at higher prices would result in an increase in domestic uranium mining revenues of $551 million in 2018 and $690 million in 2022. These revenues would provide a substantial stimulus to states with uranium mining facilities and would likely lead to even greater gains to domestic employment, income, and tax revenues.

Table 6: Differences from base simulation under a 25 percent domestic quota, 2018 – 2022

Endogenous Variable	*2018*	*2019*	*2020*	*2021*	*2022*
Nuclear Capacity			*Gigawatts*		
USA	0.00	0.00	0.00	0.00	0.00
Rest-of-World	0.00	0.01	0.03	0.06	0.09
Nuclear Generation			*Thousand Gigawatt hours*		
USA	0.00	0.00	0.00	0.00	0.00
Rest-of-World	0.29	0.79	1.37	1.93	2.39
Uranium Requirements			*Million pounds U3O8*		
USA	-0.93	-1.28	-1.37	-1.38	-1.37
Rest-of-World	0.00	0.01	0.02	0.03	0.03
Commercial Inventories	0.47	0.99	1.07	0.65	0.05
Purchases of Uranium					
Total US	-0.36	-0.66	-0.84	-0.94	-0.98
Domestic Mining	10.34	10.21	10.16	10.16	10.20
Foreign-Origin	-10.70	-10.88	-11.01	-11.10	-11.17
Rest-of-World Mining	-11.27	-11.48	-11.51	-11.52	-11.54
Prices for U3O8			*Dollars per pound*		
Domestic-Origin	21.06	28.22	30.63	31.48	31.85
Foreign-Origin	-0.13	-0.25	-0.33	-0.37	-0.36
Average	4.17	5.83	6.36	6.55	6.64
Spot	1.97	3.67	4.71	5.28	5.60
Contract	3.32	5.40	6.30	6.66	6.82
Commercial Inventories			*Percent*		
User Costs	-3.2	-3.4	-2.3	-1.4	-0.8
Domestic Mining Share	18.9	18.7	18.7	18.7	18.7
Revenues & Costs			*Million dollars*		
US Mining Revenues	551.4	642.3	673.0	684.5	690.4
Total Uranium Costs	218.2	299.1	322.0	329.7	334.0
			Dollars per MWh		
Avg. Retail Electric Rates	0.06	0.08	0.09	0.09	0.09

Incremental uranium costs for COOs are $218 million in 2018 and $334 million in 2022. If COOs pass these costs to consumers, however, electricity rates would rise imperceptibly. The incremental uranium costs due to the import quotas are less than one-tenth of one percent of the average retail price of electricity. Given lower demand for foreign-origin uranium, shipments from uranium mining in the rest of the world declines by more than 11 million pounds per year from 2018 to 2022 (see Table 6). Recently, several overseas producers have announced cutbacks in production due to low prices.

The results from a 20 percent domestic production quota appear in Table 7. In this case, prices for domestic-origin uranium would increase by $15.53 per pound in 2018 and

Table 7: Differences from base simulation under a 20 percent domestic quota, 2018 – 2022

Endogenous Variable	*2018*	*2019*	*2020*	*2021*	*2022*
Nuclear Capacity			*Gigawatts*		
USA	0.00	0.00	0.00	0.00	0.00
Rest-of-World	0.00	0.01	0.02	0.03	0.05
Nuclear Generation			*Thousand Gigawatt hours*		
USA	0.00	0.00	0.00	0.00	0.00
Rest-of-World	0.16	0.44	0.78	1.09	1.36
Uranium Requirements			*Million pounds U3O8*		
USA	-0.52	-0.72	-0.78	-0.78	-0.78
Rest-of-World	0.00	0.01	0.01	0.01	0.02
Commercial Inventories	0.27	0.58	0.64	0.40	0.05
Purchases of Uranium					
Total US	-0.20	-0.37	-0.48	-0.53	-0.55
Domestic Mining	7.63	7.54	7.50	7.51	7.54
Foreign-Origin	-7.83	-7.91	-7.98	-8.04	-8.10
Rest-of-World Mining	-8.14	-8.25	-8.27	-8.28	-8.31
Prices for U3O8			*Dollars per pound*		
Domestic-Origin	15.53	20.82	22.61	23.26	23.55
Foreign-Origin	-0.07	-0.14	-0.19	-0.21	-0.21
Average	2.32	3.29	3.60	3.72	3.78
Spot	1.09	2.06	2.66	2.99	3.18
Contract	1.84	3.04	3.57	3.78	3.88
Commercial Inventories			*Percent*		
User Costs	-1.9	-2.0	-1.4	-0.9	-0.5
Domestic Mining Share	13.9	13.7	13.7	13.7	13.7
Revenues & Costs			*Million dollars*		
US Mining Revenues	364.5	418.1	436.7	444.1	448.3
Total Uranium Costs	121.6	169.9	183.8	188.7	191.5
			Dollars per MWh		
Avg. Retail Electric Rates	0.03	0.05	0.05	0.05	0.05

by $23.55 per pound in 2022. Domestic mining shipments would increase by 7.63 million pounds in 2018 and by 7.54 million pounds in 2022. Greater shipments at higher prices would result in $364 million in additional uranium mining industry revenues in 2018 and over $448 million in 2022. Uranium costs for COOs would increase by $122 million in 2018 and if these costs would be passed through to customers, average retail electricity rates would increase $0.03 per MWh or 0.03 percent.

For electricity supply regions with wholesale pricing of electricity, the uranium production quota would affect the competitiveness of nuclear power in power markets. To measure how this competitiveness would be affected, the incremental uranium cost due to the quota is divided by nuclear electricity output. Unit incremental costs are $0.27 and $0.41 per MWh under the 25 percent quota and would be from $0.15 and $0.24 per megawatt hour (MWh) under a 20 percent quota (see Figure 5). These incremental costs

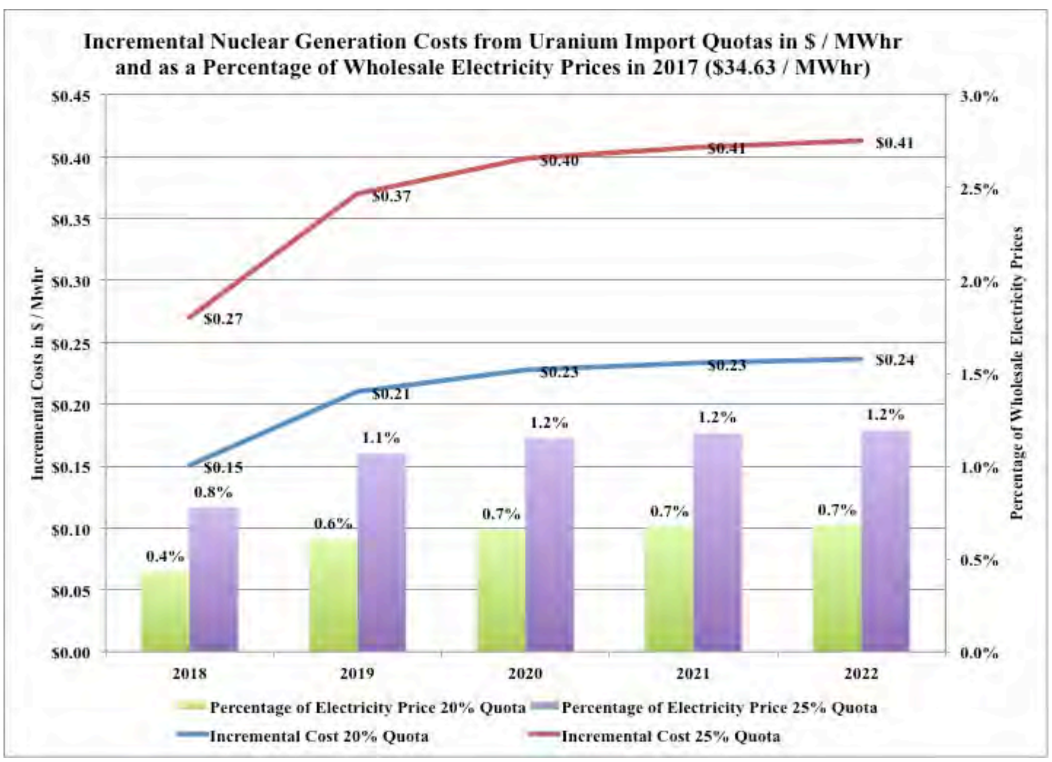

Figure 5: Incremental costs and wholesale electricity prices

are from 0.8 and 1.2 percent of average wholesale electricity prices under the 25 percent quota. With a 20 percent quota, the unit incremental uranium costs facing COOs would be from 0.4 and 0.7 percent of the wholesale price of electricity (see Figure 5).

6. Inventories and the Duration of Quotas

A simulation is also performed to understand the role of price expectations in inventory holding, which has implications for how long production quotas should remain in place to avoid a self defeating drawdown of inventories that would negate the sought after relief for the uranium mining industry. This final model simulation addresses the issue of how long quotas should be imposed if they are enacted. The US uranium industry holds between 1.5 and 3.2 years of domestic sales as inventory. This suggests that there is a considerable amount of supply that could be drawn from inventories. If a quota system were enacted for a temporary period, say two years, then producers would expect prices to decline once the quotas expired. While it would be unlikely for them to completely stock-out to avoid buying higher cost uranium now to re-stock later at a lower price, this does raise the question of how inventories would respond in such a situation. To address this issue, a simulation of a price backwardation is performed.

Under this scenario, contract prices, which serve as a proxy for prices expected to prevail in the future, are assumed to be lower than spot prices on uranium for immediate delivery. A temporary quota program would likely lead to a price backwardation that would provide incentives to meet current supply requirements from inventories because uranium would be cheaper to buy once import quotas are lifted. This could prevent utilities from entering into the higher-price long-term contracts with US producers that would be required to incentivize increased US production.

The increase in average prices paid by COOs under the quota is about $5 per pound. This suggests that once the quota is removed, average uranium prices could drop by this amount. Accordingly, a model simulation that reduces contract prices by $5 per year is performed and the results are displayed in Figure 6. The blue line plots the difference between spot and contract prices or the degree of the price backwardation from 2018 to 2022. For this price backwardation, the potential supply from inventory drawdowns range from 2.5 to over 7.7 million pounds per year. Hence, inventory drawdowns could negate the effects of the import quota.

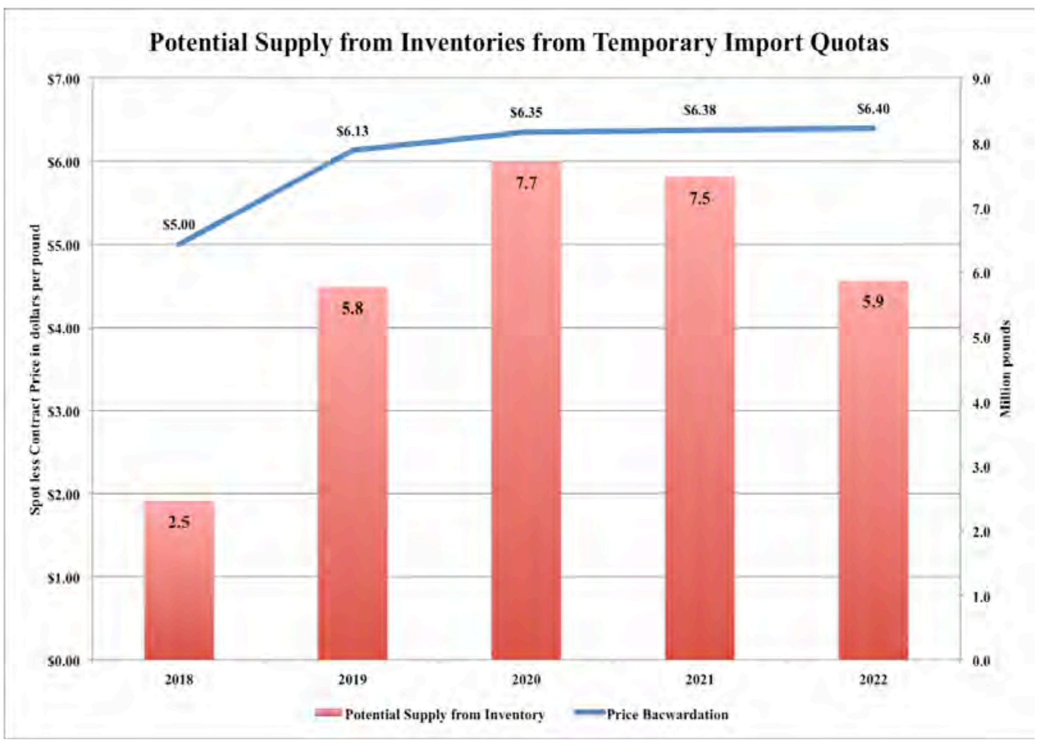

Figure 6: Potential supply from inventories under temporary quotas

Over the past 20 years, total US commercial inventories were as low as 72.5 million pounds in 1995 and as high as 143.9 million pounds in 2016, which is a difference of 71.4 million pounds. If 5.9 million pounds per year were drawn from this inventory buffer, it would be depleted after 12 years. Hence, a domestic production quota system should be adopted for a minimum of a decade and probably longer. This would encourage US utilities to enter into the long-term contracts with US producers required to support the modeled increase in US production.

7. Summary and Conclusions

The Fukushima nuclear accident in 2011 was a watershed event for the world uranium industry, forcing Japan to shutter its nuclear power industry. As a result, world nuclear power generation peaked in 2010 and has yet to recover. Meanwhile, mines developed on the premise of unrealized expectations of robust demand growth have come into production as demand fell and then stagnated. As a result, higher production from Russia, Kazakhstan, and Uzbekistan in recent years is contributing to lower uranium prices. These low prices are forcing US producers to reduce production and this combination is threatening the economic and financial viability of US uranium producers who, as a result, are proposing an import quota. This study estimates the market impacts of the proposed import quota by developing an econometric model of the world uranium market and simulating it out of sample from 2018 to 2022.

The model is estimated with a data sample from 1994 through 2016. The US generates slightly less than a third of world nuclear power production. Despite having the largest number of nuclear power plants, the US imports more than 90 percent of its uranium requirements. In 1994, this import dependency was roughly 80 percent. Uranium prices peaked in 2007 and have been sliding down ever since. Recently, prices are breaking even lower approaching price levels witnessed 20 years ago.

The econometric model developed in this study includes supply and demand relations for the US and the rest of the world. The econometric estimates are consistent with previous peer reviewed studies finding very price inelastic demand. The estimated supply elasticities, however, are somewhat higher than previous estimates, which intuitively is consistent with recent production increases from the world outside the US. The supply elasticities, however, are just barely in the elastic range. The econometric analysis also found that the incremental cost of US production had a sharp break upward after 2007, perhaps reflecting the effects of depletion of low cost sources of uranium.

Under the 25 percent quota, prices for domestic-origin increase by $21 to $31 per pound. Annual domestic uranium production increases over 10 million pounds. As a result, domestic uranium mining revenues increase between $551 and $690 million per year. Prices for foreign-origin uranium decline slightly, which moderates the cost increases facing civilian nuclear plant owner and operators. If these costs are passed completely through to customers, as is likely in regulated electricity markets, retail electricity prices would increase by less than one-tenth of one percent. Even in areas where nuclear power plants operate in competitive wholesale markets, operating costs would rise at most $0.41 per MWh, which is about 1.2 percent of wholesale power prices, hardly a magnitude that would affect the position of these plants in the rank ordering of plants by cost. Under a 20 percent quota, prices for domestic-origin uranium would increase between $15-$23 dollars per pound and retail electricity prices would increase by approximately one-twentieth of one percent.

The model simulation analysis also examines the role of price expectations and inventories under a temporary import quota. The analysis suggests that a modest increase in the difference between spot and contract or long term expected prices would incentivize a substantial drawdown in inventories. Accordingly, if the quotas are temporary, COOs would likely draw down their inventories, waiting for the program to end and lower prices to return. Hence, if an import quota is adopted it should be imposed over at least a decade and probably longer in order to encourage US utilities to enter into the long-term contracts with US producers required to support the desired increase in US uranium production.

In conclusion, this study finds that a 25 percent quota would provide substantial relief for companies mining uranium in the US, with minimal impacts to US electricity prices and costs to consumers. If the US wants a uranium mining industry in the long term, such an import quota may be one option to consider.

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