School of Energy Resources
Center for Energy Regulation
& Policy Analysis

NUCLEAR SERIES PART 3

WYOMING'S NUCLEAR SUPPLY CHAIN OPPORTUNITIES AND CHALLENGES: URANIUM RECOVERY

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A publication of the University of Wyoming School of Energy Resources, Center for Energy Regulation and Policy Analysis (CERPA).

About the School of Energy Resources (SER)
SER collaborates with stakeholders at the state, national and international levels to advance energy technologies and policies to grow and support Wyoming's robust energy sector. SER's mission is to promote energy-driven economic development for the state, and it leads the University of Wyoming's talent and resources for interdisciplinary research and outreach, fulfilling Wyoming's promise to be a global leader in a thriving and sustainable energy future.

Contents

Acronyms

ACF	Autocorrelation Function
ACP	American Centrifuge Plant
AECE	Atomic Energy Commission
AES	Areva Enrichment Services
ARMA	Autoregressive Moving Average Model
BLM	Bureau of Land Management
CERPA	Center for Energy Regulation and Policy Analysis
CFR	Code of Federal Regulations
CPI	Consumer Price Index
DOE	United States Department of Energy
EIA	United Stated Energy Information Administration
EIS	Electromagnetic Isotope Separation
EREF	Eagle Rock Enrichment Facility
FTE	Full-Time Equivalent
GCEP	Gas Centrifuge Enrichment Plant
GLEF	Global Laser Enrichment Facility
GLE	Global Laser Enrichment, LLC
HALEU	High-Assay Low-Enriched Uranium
HEU	Highly Enriched Uranium
HHI	Herfindahl Hirschman Index
LES	Louisiana Energy Services
LEU	Low Enriched Uranium
NEF	National Enrichment Facility
NEPA	National Environmental Policy Act
NPV	Net Present Value
NRC	United States Nuclear Regulatory Commission
PACF	Partial Autocorrelation Function
PLEF	Paducah Laser Enrichment Facility
SRP	Standard Review Plan
SWU	Separative Work Unit
TNE	Tennessee Eastman Company
UF6	Uranium Hexafluoride Gas
WNA	World Nuclear Association

EXECUTIVE SUMMARY

This report quantifies the economic outcomes of the uranium recovery industry in Wyoming. The unique opportunities and challenges of expanding the industry are identified. Additionally, an event study is performed that estimates economic outcomes under a range of potential future uranium price points.

The analysis concludes that uranium recovery operations are expected to increase production in the next few years without any major economic obstacles.

This report is one of a series evaluating the feasibility of developing an integrated nuclear sector in Wyoming. From the uranium recovery mouth to spent fuel processing, each step in the nuclear supply chain has unique economic challenges. To compare the opportunities for Wyoming across the nuclear supply chain, a qualitative scoring system of advantages and obstacles is applied. The summary of these scoring criteria for uranium recovery is provided in Table 1.

Table 1:
Significant Economic Factors Related to Wyoming Uranium Recovery

Uranium Recovery

	Level	Summary
Economic	Moderate Advantage	Uranium prices are near all-time highs, but are sensitive to global trends.
Existing Industries	Moderate Advantage	Uranium operations on standby can be reactivated.
Tax Structure	Minor Advantage	Tax incentives are provided when uranium prices are low.
Location	Major Advantage	Largest uranium reserves in the U.S.
Federal Legal	Moderate Obstacle	High restoration costs required.
State Legal	Moderate Advantage	Wyoming is an agreement state, reducing regulatory compliance costs.
Technology	Minor Advantage	In situ technological growth promotes Wyoming projects.

There are multiple incentives for uranium recovery facilities to increase production in Wyoming. Historic uranium production in the State peaked at 12 million pounds in 1981 (Campbell, 2024), but total U.S. production has decline to less than 50 thousand pounds by 2023 (Bonnar, 2023). Recent increases in uranium price coupled with geologic and State regulatory conditions pave the way to reestablish much of this historic output.

An economic impact analysis was performed for the uranium industry, estimating the total number of jobs created by mines, and the tax revenues that would be generated at different levels of uranium production. The numeric results are derived from an input-output economic model. Table 2 shows the projected economic benefits that uranium mines bring to the State at present production levels, and if production is increased to six million pounds, or twelve million pounds a year.

Table 2:
Wyoming: Total Benefits and Costs of Uranium Recovery

Production Scenario	Current	Middle	High
Production (Thousand Pounds)	146	4,800	12,000
Jobs (Person-Years[1])	147	4,600	17,700
Tax Revenue[2] (Mill. USD)	$0.362	$236	$903
Other Benefits	Reduced contamination risk compared to legacy operations.		
Social Costs	Split mineral and property rights can create competing interests. Potential aquifer contamination.		

The present economic benefits from uranium recovery facilities are constrained by low production levels. Most jobs at uranium recovery facilities are tied to exploration and drilling expenditures. Therefore, if uranium expands in Wyoming, the development will create disproportionally more jobs and tax revenue than current levels. These benefits are accrued directly from the industry as well as through spillover effects on other sectors. Modern recovery technologies require minor surface disturbance, so future development is expected to generate less environmental impact than historic operations. Potential non-monetary costs include conflicts over property rights, and aquifer contamination. Homeowners in other states have expressed concern that uranium recovery operations are required to have access to private property without notice (Board, 2024).

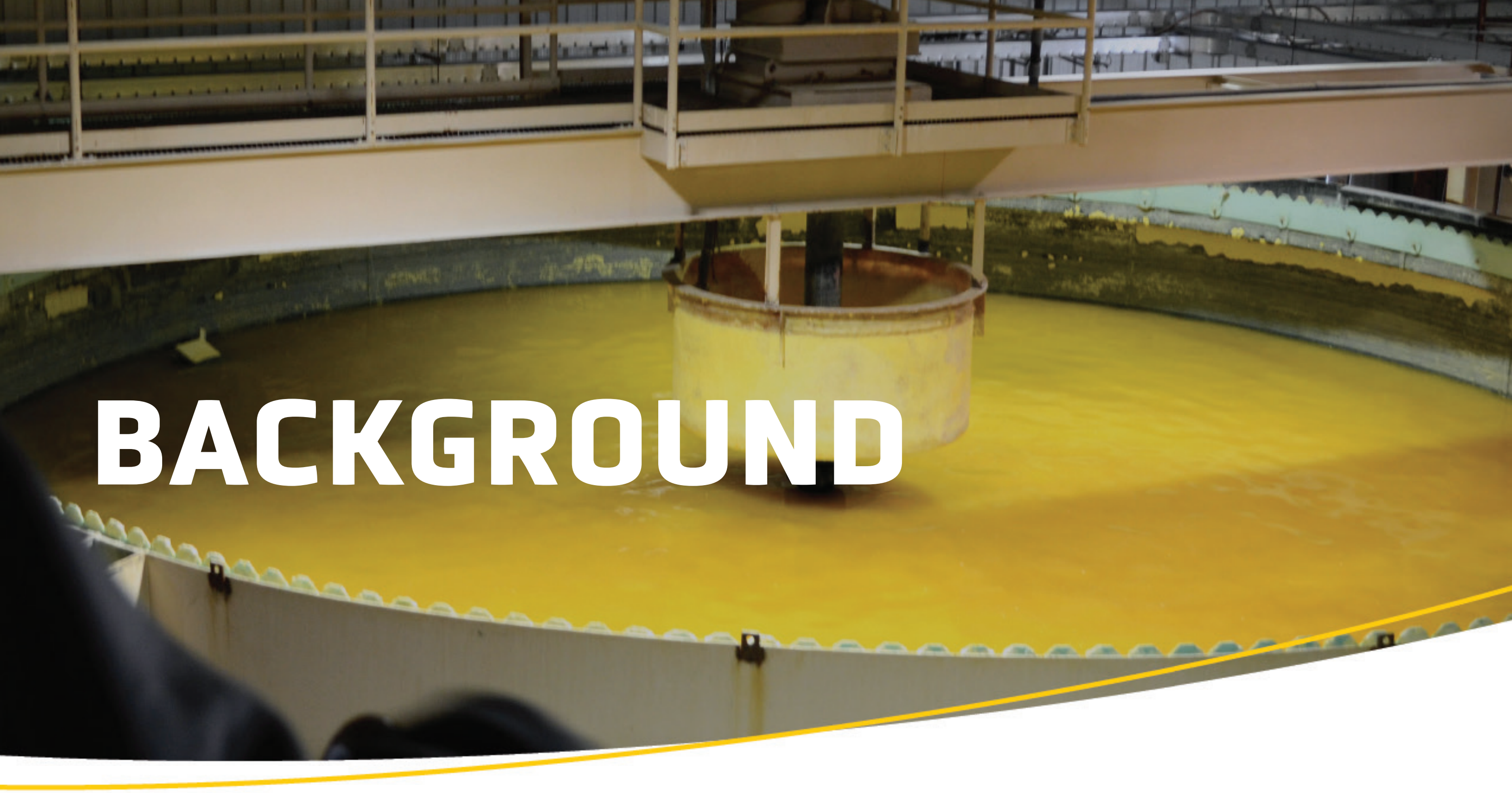
[1] A person-year is the equivalent of hiring a full time employee for one year. For example, adding two half time employees, two contractors hired for six months each, or one full time employee each add one person-year of employment. This metric makes short term projects more readily comparable with long term projects.

[2] Includes State, and County taxes.

INTRODUCTION

The University of Wyoming, School of Energy Resources Center for Energy Regulation and Policy Analysis (CERPA) completed a series of interdisciplinary economic analyses evaluating the opportunities and challenges for Wyoming economic development in the nuclear sector. The series successively evaluates the economic conditions of each segment of the nuclear supply chain, from uranium recovery, all the way to spent fuel storage. This report is the third in the series focused on uranium mining. These economic analyses were produced to provide the Wyoming Legislature, other policy makers, stakeholders, and the general public with objective evaluations of new investment opportunities within the State.

This white paper begins by providing an overview of the uranium extraction process and the contributing factors of Wyoming uranium production. The paper identifies supply-chain market structures that provide opportunities in Wyoming for uranium extraction. Then, an economic impact analysis was created for the uranium recovery industry. Changes in employment, tax revenue, and non-monetary considerations are provided under different market conditions.



BACKGROUND

Uranium recovery facilities generate uranium oxide that is necessary to support the 390 operating nuclear reactors, supplying 10% of the worlds energy (World Nuclear Association, 2024). Uranium not stored as inventories is shipped to a conversion facility to prepare for enrichment. Uranium recovery facilities establish contracts with nuclear power plants to purchase set quantities of uranium in future years (Cameco Corporation, 2024b). Long term contracts typically set an initial delivery date of uranium two years out from the signing period and are active for ten or more years (Combs, 2008). Uranium mines can also sell uranium on the spot market. Spot market prices set terms of delivery within two to three months of the signing date (UxC, LLC, 2024). After enrichment the uranium is deconverted from uranium hexafluoride and prepared for final use in a nuclear power plant.

Most U.S. uranium mines are classified as underground mines, surface mines[3], or as in situ recovery facilities. Wyoming produced uranium entirely with conventional mining methods, until the early 1990s when in situ techniques were adopted[4](EIA, 2023). The first step to establish a conventional uranium mine is to identify target orebodies. Then a shaft is generally sunk in the vicinity of the deposit and workings are excavated to remove the uranium ore (Nuclear Regulatory Commission, 2020). Blasted ore is brought to the surface and sent to a mill, where it is crushed or ground and processed into uranium concentrate. In situ mines are the only type of mines currently operated in.

[3] Open cut or open pit.

[4] See Figure 15 for a diagram of uranium production trends by extraction method in Wyoming.

In Situ (in place) mining recovers uranium from groundwater aquifers. A lixiviant[5] designed to dissociate uranium from the rock is injected into the target formation. For Wyoming in situ mines the lixiviant is a mixture of native groundwater with typical additives such as carbon dioxide, oxygen, and sodium bicarbonate (Gregory & Drean, 2015; Kehoe, 2023), but international mines primarily use acidic lixiviants such as sulfuric acid (World Nuclear Association, 2020). The acid or base dissociates the uranium from a sandstone roll front where a historic oxidation reaction deposited the ore (Wilson, 2015).

The lixiviant within a wellfield is pumped from the recovery wells to a plant that contains an ion exchange process. Vessels inside the plant contain ion exchange resin beads that attract uranium ions in the groundwater. Groundwater from the uranium wellfields is passed through the ion exchange beads, which bind the uranium. Once the groundwater leaves the ion exchange vessels, it is refortified with oxygen and carbon dioxide and reinjected into the mining aquifer within the wellfields. The pressure of the injection wells keep the solution within a closed loop in the aquifer[6]. The resin beads, when fully loaded with the uranium, are transferred out of the ion exchange vessel and then stripped of the uranium in a process called elution. Clean resin beads are then transferred back to the ion exchange vessels for re-use. (D. Wichers, personal communication, June 13, 2024)

This process is repeated, cycling the groundwater between injection and recovery wells until uranium recovery rates becomes subeconomic, and the well grouping is retired. A single recovery facility serves a system of wells. As some wells are retired, others may be added further along the roll front, until all economically recoverable uranium is extracted, and the operation is ended.

The operating cost of in situ mines is lower than underground mines, allowing these facilities to develop low grade uranium deposits. Figure 1 is a diagram of an in-situ operation, showing the processes needed to extract the uranium.

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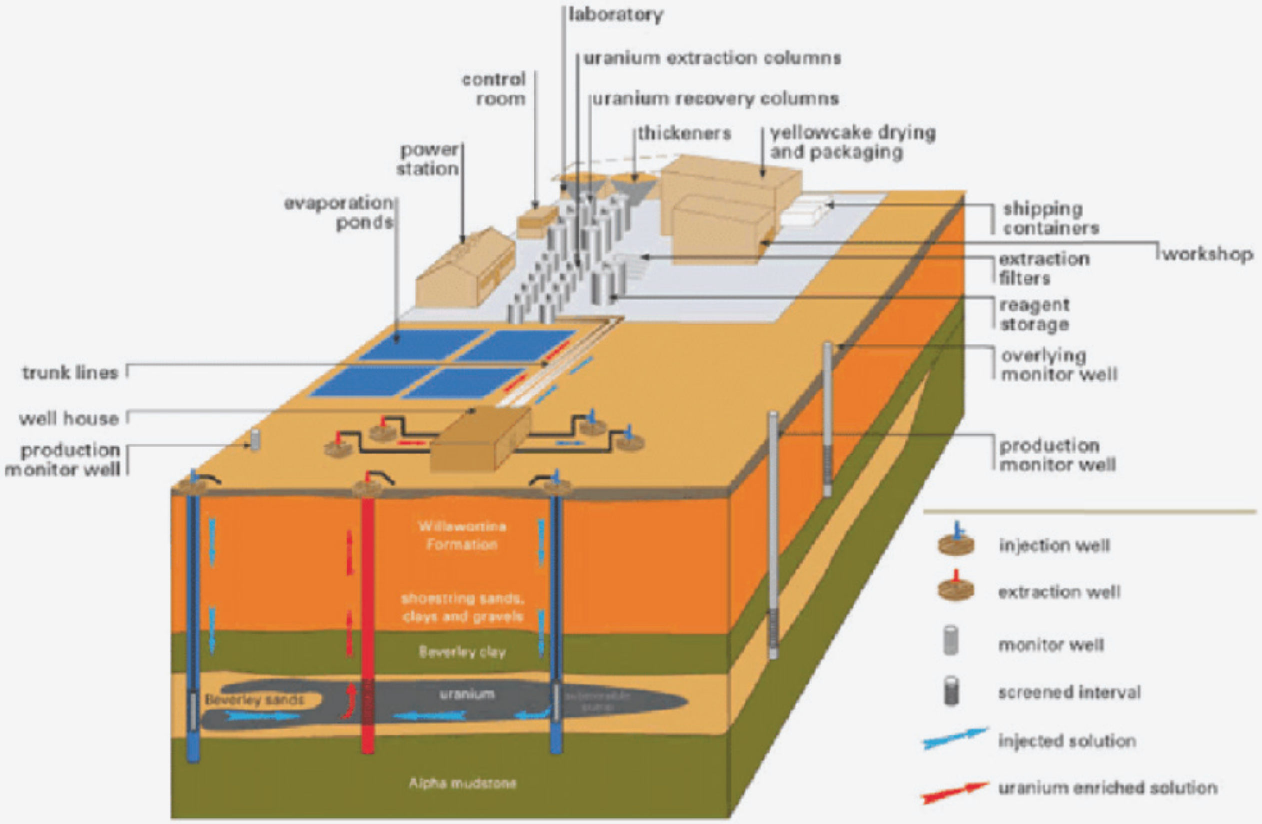
5 A lixiviant is any liquid chemical mixture designed to dissolve a ore concentrate (Wang, 2007).

6 Under normal operating conditions there will be no exchange between the produced aquifer, and the rest of the aquifer. The pressure gradient keeps a constant flow of water within the operation. However, monitoring wells are installed in a ring around the recovery and injection wells, to ensure that the system is fully closed.

Figure 1:
Example In Situ Uranium Recovery Operation (Heathgate Resources, 1998)



During site development, potential mine locations are surveyed to acquire information about the ore quality. This includes drilling exploration wells which are used to assess ore characteristics. Even within the same deposit, the concentration of uranium varies, and zones of rich ore are unevenly distributed. Further localized geochemistry can change operating costs. For example, carbonate mineral content can lead to increased precipitates in the water, eventually blocking the boreholes of recovery wells (Li & Yao, 2024). Carbonaceous material can consume oxidants. These irregularities of Wyoming deposits make exploration an important supply factor in the State.

With this information, operating cost estimates are formed by engineers and production plans are developed. The highest-grade ore is typically produced first, followed by lower grade sources. Production ceases when the head grade of uranium from the wells is too low to extract at a profit. An example of this time path comes from the Cigar Lake Operation in Saskatchewan, Canada. This operation applies jet boring mining to extract ore and has the highest ore grade of any mine (Bharadwaj et al., 2024). The ore grade extracted by the mine, and the price of uranium are plotted in Figure 2.

Figure 2:
Cigar Lake Extracted Ore Grade and Uranium Price[7]

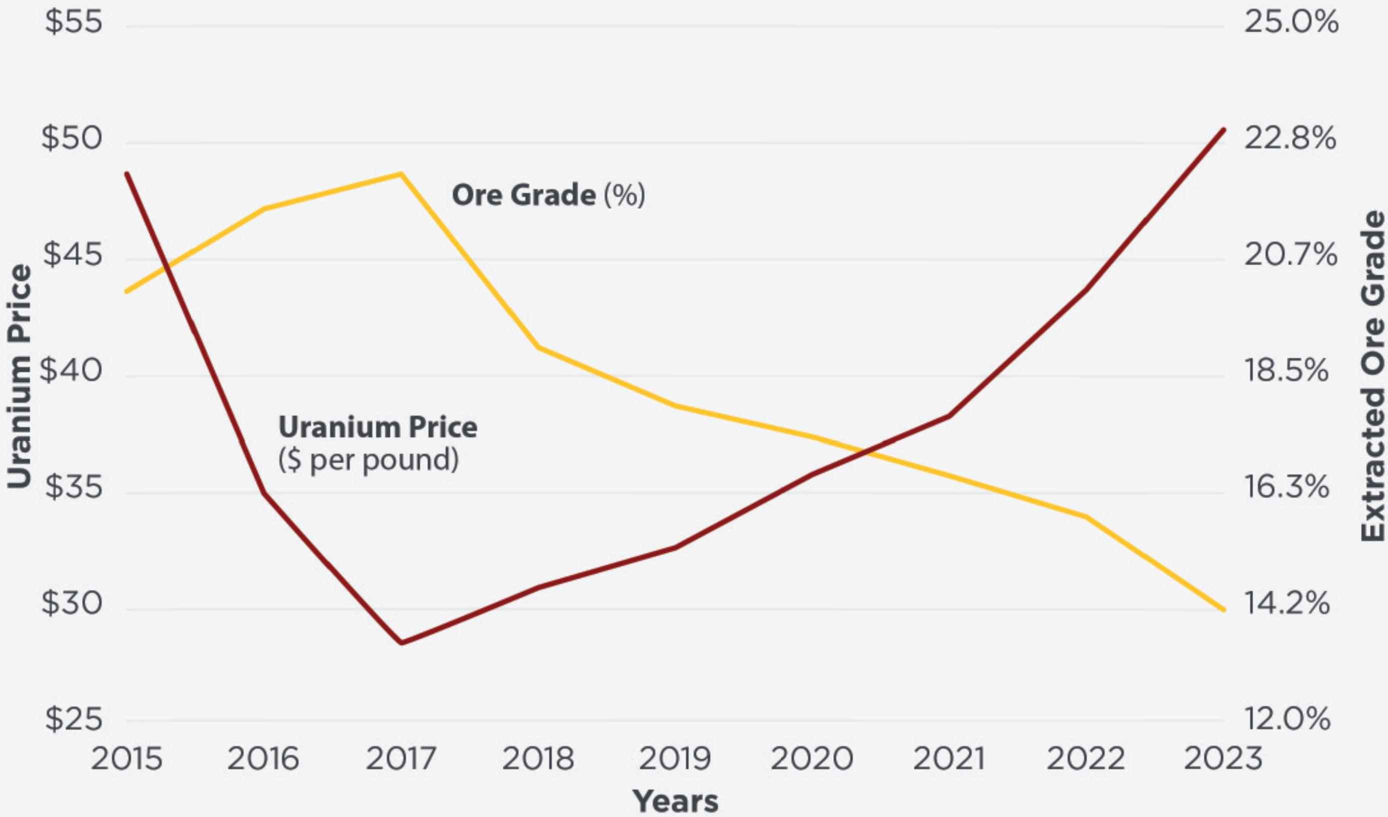
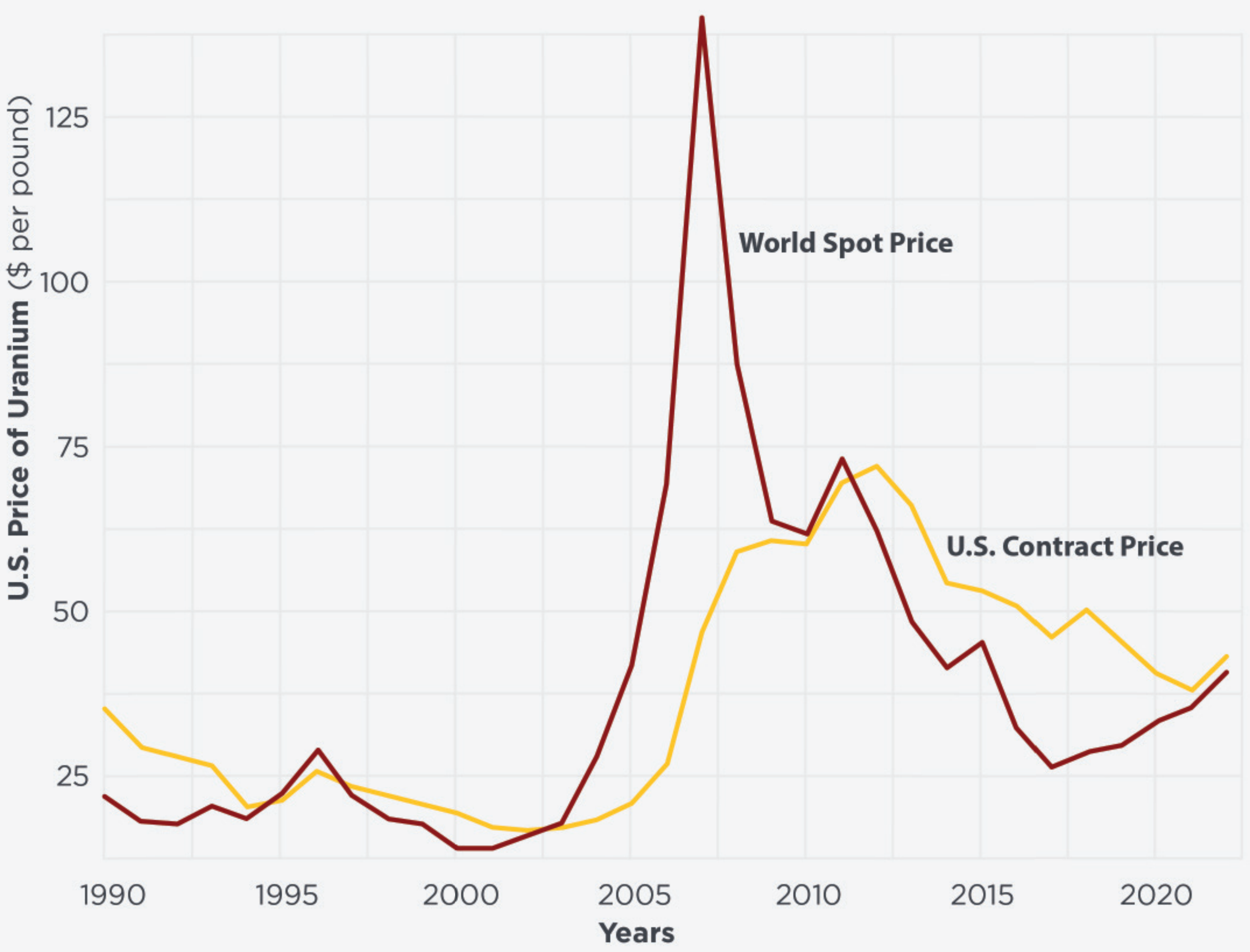


Figure 2 demonstrates an inverse relationship between ore grade and uranium price. As the mine comes online the extracted ore grade is high. The ore grade increases as uranium prices decline in 2016 and 2017. When prices are depressed, the low-quality resources can no longer be recovered profitably, this decreases the total uranium production but raises the average extracted ore grade. Conversely as prices rise from 2018 to 2023, average ore grade declines. These higher prices induce additional recovery lowering the average ore grade. Since prices vary over the life of a project, production plans are modified to account for price shifts

Due to the importance of prices in production decisions, a history of uranium spot price, and contract price is established in Figure 3.

[7] Ore grade data comes from (Bharadwaj et al., 2024). Uranium price data is inflation adjusted using the CPI to 2024 values (International Monetary Fund, 1980; United States Bureau of Labor Statistics, 2023).

Figure 3:
Uranium Contract and Spot Price[8]



[8] World spot market prices come from (International Monetary Fund, 2023). U.S. contract prices are the weighted average contract price of uranium, as reported in each EIA Uranium Marketing Annual Report (EIA, 1994, 1995, 1996, 1997a, 1998, 1999, 2001, 2002, 2002, 2003, 2004, 2006, 2007b, 2008b, 2009b, 2010b, 2011b, 2012b, 2012a, 2014b, 2015c, 2015b, 2016b, 2017b, 2019b, 2020b, 2021b, 2022b). 2017 contract prices are withheld, and a straight-line estimate is used to predict this point. All values are inflations adjusted to 2023 prices (United States Bureau of Labor Statistics, 2023).

The average U.S. contract price for uranium oxide is less volatile than the global spot market price. Nuclear power plants benefit from the long-term contracts by ensuring enough uranium is delivered to maintain operation. The uranium recovery companies benefit by locking in a price high enough to maintain profits. This allows both parties to mitigate long run risks. However, even if uranium operations establish long term contracts, the spot market provides an opportunity for uranium operations to adjust production dynamically. When spot prices rise uranium operations adjust production plans and sell any uranium in excess of their long-term delivery obligations, providing additional revenue.

Uranium could not be purchased by civilians until 1967. Prior to this all uranium was purchased by the US Atomic Energy Commission (AEC)(Neff, 2004). The AEC was the only entity that could purchase uranium, allowing them to set the price of uranium, isolating uranium suppliers from market volatility. The AEC price peaked in 1956 at $118 per pound, gradually declining to $34 per pound by 1968[9](Neff, 2004). Despite the allowance of private purchases of uranium, the AEC extended the organizations purchases of uranium to 1970's providing guaranteed profits to uranium extraction operations, as long as operating costs were lower than $57 per pound (Taylor & Yokell, 1979). This price support of uranium purchases spurred initial exploration.

The spot market price of uranium peaked in 1976 at $220 per pound[10] (Owen, 1985; Price, 2005; United States Bureau of Labor Statistics, 2023). However, the maximum contract price of uranium was only $104.8 per pound, indicating that investors recognized that uranium producers would be able to respond to this short-term price rise by increasing output (Price, 2005)[11]. This price increase in 1976 is attributable to market changes analogous to those influencing the uranium price increases of the 2020's (see Section 3.4). In the late 1970's the U.S. government had an active ban on imports of foreign uranium, there was a global supply shock which halted Australian production in 1975, and a shift in U.S. demand occurred when nuclear power plant operators were required to purchase more uranium inventories[12](Taylor & Yokell, 1979). Figure 4 shows the development of U.S. and Wyoming uranium production, in the context of these historic uranium price changes.

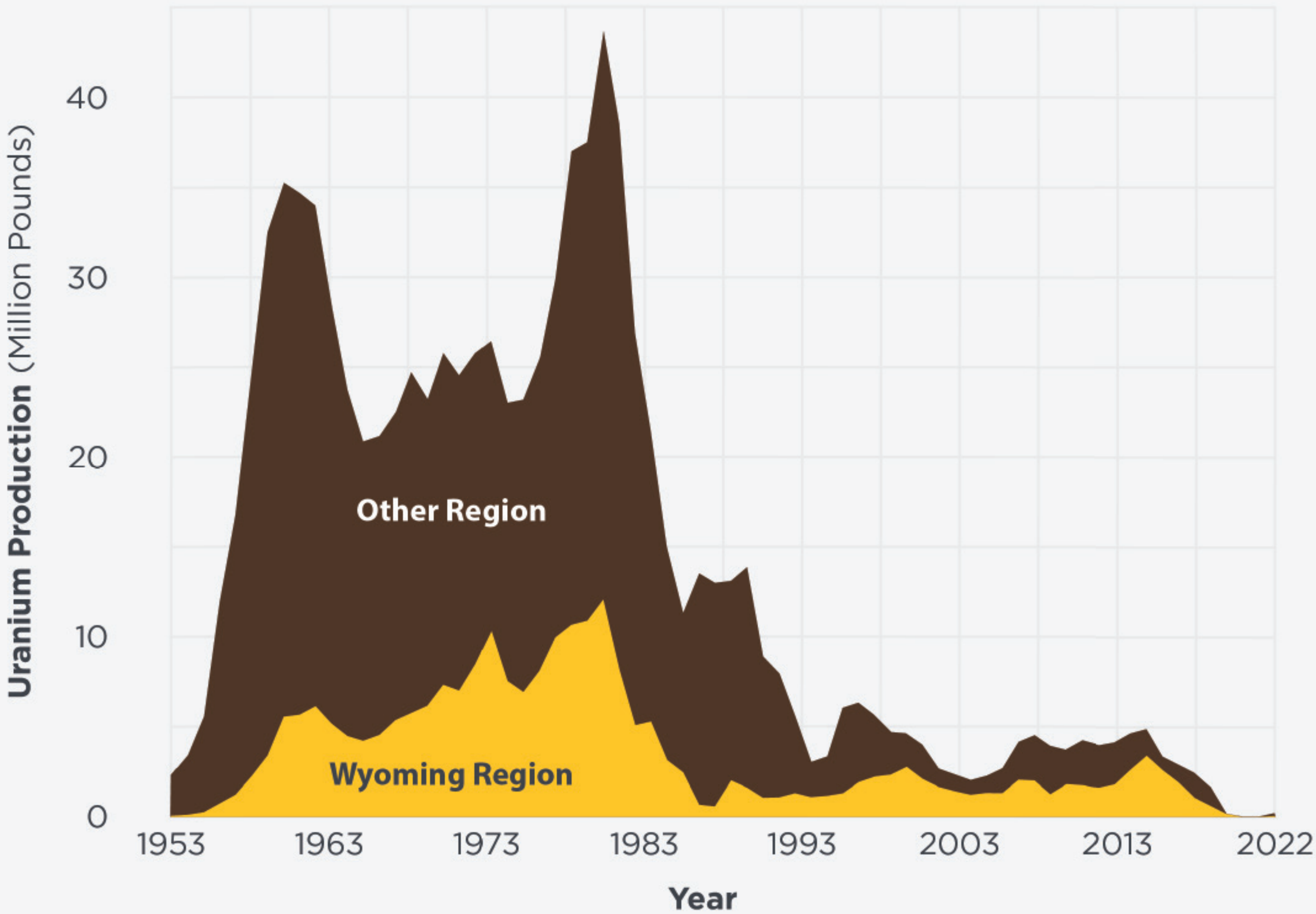
[9] Values were inflation adjusted from the originally reported 2004 values (the date of the publications) to 2024 values (U.S. Bureau of Labor Statistics, 2023).

[10] Price inflation adjusted from $40 in 1976 dollars to 2024 dollar values.

[11] This the long-term price of uranium is not directly provided. A plot of the relative price of short-term spot market and long-term contracts rates is given without units in (Price, 2005). From this graph the maximum short-term price in 1976 is interpolated to be 2.1 times as large as the peak contract price in 1977. $104.76=$220/2.1

[12] The U.S. banned the enrichment of foreign uranium for use in U.S. nuclear power plants until 1977, at this time the embargo was gradually lifted by 10% each year. The Australian government halted all uranium mining in the country following the 1975 election when the newly elected political party required additional safety requirements. The U.S. demand shift occurred due to a requirement that enrichment services be contracted out for ten years, as compared to two years. This in turn meant uranium yellowcake had to be purchased farther in advance, creating a demand for present uranium. (Taylor & Yokell, 1979)

Figure 4:
Wyoming and U.S. Uranium Production[13]

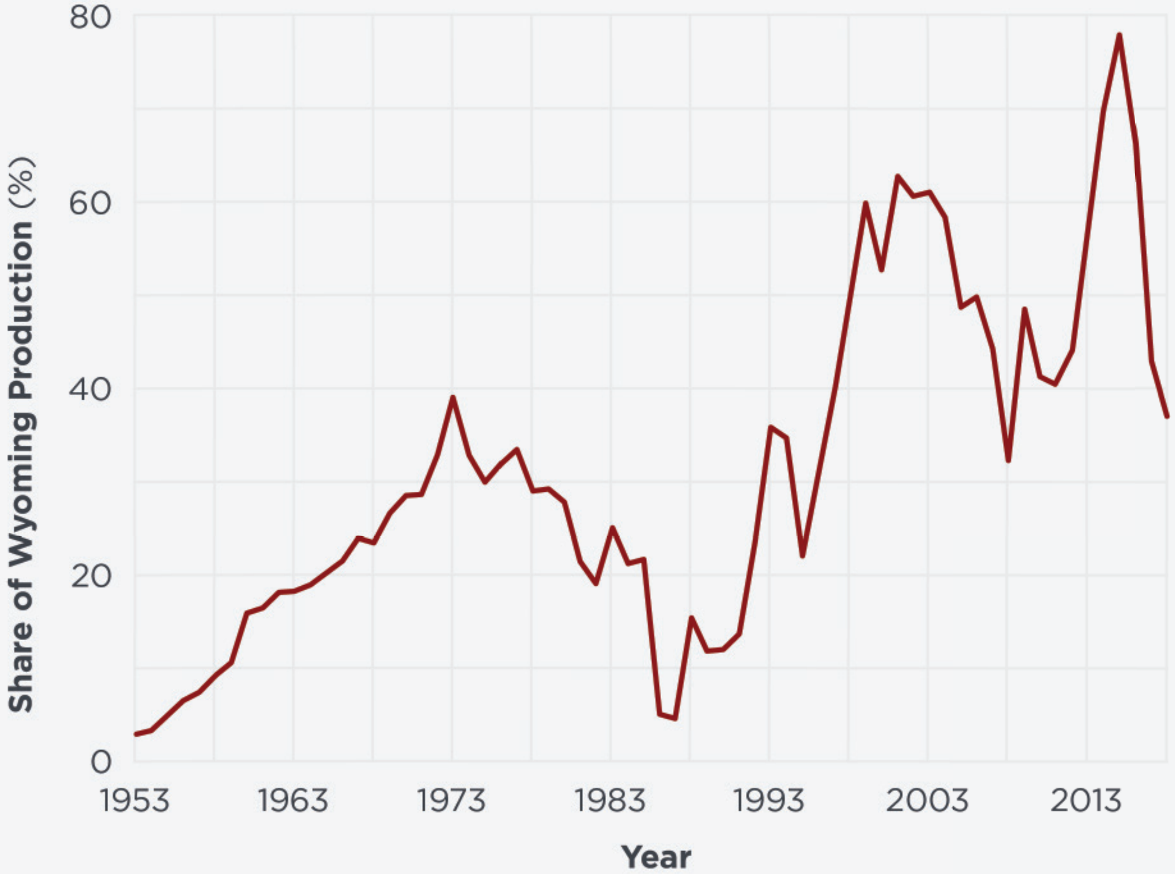


Total U.S. production and Wyoming output both follow market trends in uranium prices, creating significant correlation. The elevated AEC prices drove early investment, with production peaking in 1980. Sixty-seven U.S. nuclear power plant projects were canceled following the three-mile island incident in 1979 (EIA, 2017c). This shift in expected future uranium consumption led to price decline and consequently the decreased uranium production observed in Figure 4. These macro trends in the uranium market influenced U.S. and uranium production. However, there are factors which distinctly influenced the Wyoming uranium recovery industry.

[13] U.S. values are total uranium concentrate produced in a year from (EIA, 2023, 2024b). Wyoming production data is reported mine production from the Wyoming State Geologic(Campbell, 2024). The values reported were interpolated using optimized software, from the uranium production figure (Rohatgi, 2022).

The development of in situ mining and Wyoming geologic exploration have contributed to Wyoming producers gaining increased market share. Figure 5 plots the percentage of U.S. uranium contributed by Wyoming facilities over time.

Figure 5:
Percent of U.S. Production Sourced in Wyoming[14,15]

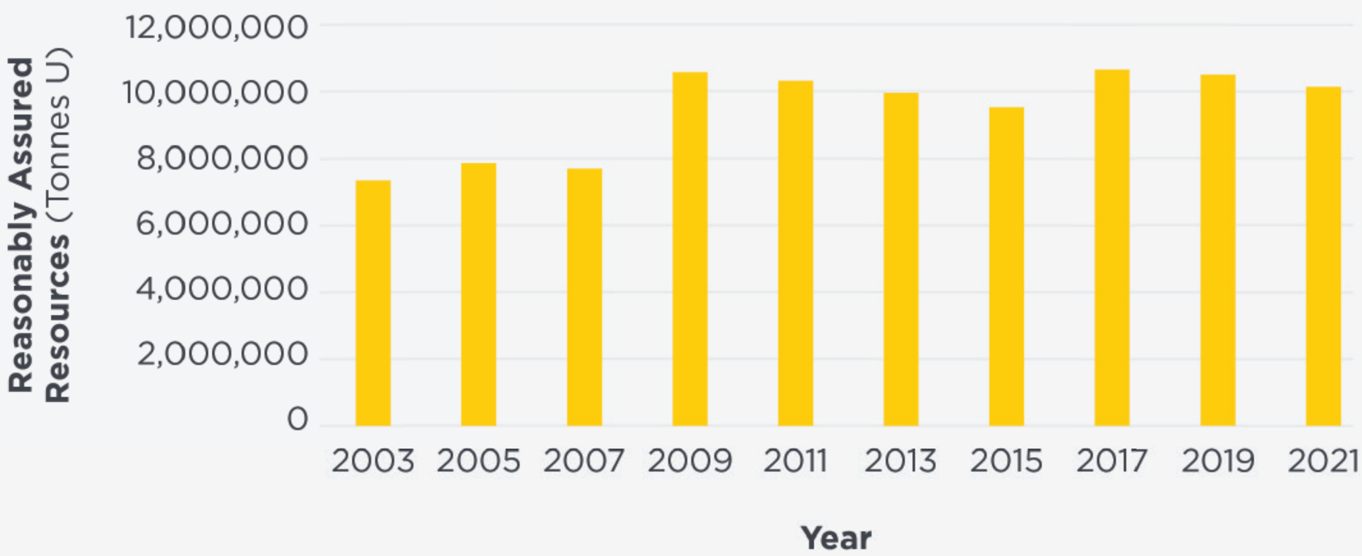


[14] Data from (Campbell, 2024; EIA, 2023, 2024b). Some measurement error is expected as the Wyoming data is interpolated using graphical software (Rohatgi, 2022), and the reporting methods of the Wyoming Geologic Survey, and EIA are different.

[15] Note that U.S. quantity of uranium produced, is decoupled from the consumption from U.S. reactors, due to exports and imports. Only 4.6% of uranium used in U.S. reactors was supplied by U.S. operations in 2023 (EIA, 2024a).

Another factor of uranium production is resource availability. However, there is an economic element to establishing the total geologic reserves of uranium. Uranium reserves are defined as the volume of uranium that can be technically and economically recovered (NEA, 2020). Uranium prices directly affect the level of estimated reserves. When prices are suppressed, low grade uranium ore cannot be recovered economically thereby reducing reserves. This price effect interplays with technological and geological limitations. For example, low grade ore bodies in shallow aquifers could not be economically recovered with open pit mines. The development of in situ technology provided a route to add this existing uranium into reserves estimates. Finally elevated uranium prices promote exploration for uranium, leading to new deposits being discovered. Estimated world reserves of uranium at $130 per kg is provided in Figure 6

Figure 6:
Reasonably Assured Uranium Resources at $130 per Kg[16]



Due to improved geologic knowledge, and advances in recovery technology, total uranium reserves have increased between 2003 and 2021. This is despite the continuous consumption of uranium by nuclear power plants. This is notable because the geologic limitations in Wyoming reserves are not a strict limit on uranium production and market factors affect the total reserves in the State. Also with a significant enough price rise, alternative methods of extracting uranium become economic. For example, the most recent estimates of the cost to produce uranium from sea water is between $200 and $390 per pound (Lindner & Schneider, 2015; United States Bureau of Labor Statistics, 2023). This threshold acts as a backstop price where a very large reserve of uranium becomes available limiting future price growth.

[16] Data used for Figure 5 was collected iteratively from all Nuclear Energy Agency and International Atomic Energy Agency Uranium Resources, Production and Demand series. See (NEA, 2003, 2005, 2007, 2009, 2011, 2011, 2014, 2016, 2018, 2020)

ADVANTAGES AND BARRIERS IN WYOMING

A set of empirical and qualitative analyses are applied to contextualize the opportunities and challenges related to fostering investment in Wyoming extraction. A scoring system ranging from *severe obstacle* (red) to *major advantage* (green) is given to each category of development (see Gebben & Peck, 2023). The following six sections identify this score for the categories of: 1) economic factors, 2) existing industry in Wyoming, 3) the State tax structure, 4) location specific effects, 5) legal consideration, and 6) available technology. At the beginning of each section, the *Scoring Criteria* subsection provides the score and rationale. For those seeking a more thorough explanation, a detailed discussion of the steps used to identify the score is provided in the *Analysis* sub-section.

On net, these factors promote uranium recovery in Wyoming. The qualitative scores range from a *minor advantage* to *major advantage* for five of the six categories. The only identified *moderate obstacle* is federal aquifer remediation rules which add unique costs to U.S. in situ operations. An empirical analysis is used to support these results. The uranium supply elasticity is estimated through regression analysis. This result is used to demonstrate that current price trends will lead to the expansion of uranium mining in the State, that the Wyoming severance taxes minimally slows uranium production, and that aquifer remediation costs effect uranium recovery operations most when uranium prices are low.

ECONOMICS

Economic Barriers: Scoring Criteria

The market price of uranium has increased by 150% between 2020 to 2024 (Cameco Corporation, 2024a; International Monetary Fund, 2023)[17]. This provides a significant advantage to Wyoming uranium projects that make production decisions based on uranium prices. Time series analysis is used to estimate the U.S. uranium supply curve. The results predict that for every 1% rise in uranium price Wyoming producers will increase output by 0.66%. If prices remain stable, the recent uranium price rise to $90 per pound will double uranium production in the State[18].

Contributing factors to the recent uranium price increase are identified. These include a decrease in global uranium supply due to mine closures in Kazakhstan and federally imposed quotas on Russian uranium (Kazatomprom, 2024; Rep. McMorris Rodgers, 2023). On the demand side nuclear power growth in Asia, and international agreements to increased nuclear power have driven expectations that more uranium will be purchased in the next decade (NEA, 2020; United States Department of Energy, 2023).

However, the dynamics of nuclear power plant uranium demand leads to volatile uranium prices. This contributes to uncertainty in future long run uranium prices. While contemporary trends are likely to drive uranium production growth, such price shifts need to be maintained to sustain development.

Taken together, economic factors are identified as a *moderate advantage*. Current uranium contract prices are above the threshold required to reestablish uranium operations in Wyoming, but long run prices are variable and a sudden decline in uranium prices would dampen this growth.

Economic Barriers: Analysis

The profitability of uranium operations in Wyoming is driven by the price of uranium. In turn, this price is set by the unique attributes of supply and demand of the uranium market. This section provides background information about the structure of this market and applies this knowledge to explain the advantages Wyoming has in this sector. Before turning to global supply and demand factors, the decisions made by operators to develop uranium resources in Wyoming are explained which places the States industry in context of the global market.

[17] Based on the May 31st 2024 price of $90.38 per pound (Cameco Corporation, 2024a), and an average 2020 price of $29.43 which is inflation adjusted to $35.65 in 2024 dollars (International Monetary Fund, 1980; United States Bureau of Labor Statistics, 2023). 153.5%=$90.38/$29.43-1

[18] 1.535*0.66=1.01 *increase from 2020 levels.*

The choice to operate a uranium extraction facility depends on the facilities operating cost, uranium yield, and the price of uranium. Where uranium revenues exceed operating costs uranium extraction continues. Ore grade affects this decision primarily through increasing revenue. A higher ore grade means that the same operating expenditure yields more pounds of uranium, all else equal. The distribution of global supply at any given uranium price is therefore a function of the operating costs relative to uranium yield. When uranium prices are low only operations with equally low costs, or with elevated ore grade can support production leading to market concentration[19].

This is evident in the global trade of uranium. Kazakhstan, Australia, and Canada supplied 80% of global uranium in 2020 when prices were $35.65 per pound[20] (NEA, 2020). The Canadian Cigar Lake Operation has the world's highest ore grade with average grade ranging between 14%-28% (Bharadwaj et al., 2024; Bishop et al., 2015). This lowers the average total cost per pound of uranium to $20.58 (Bharadwaj et al., 2024). Both Kazakhstan and Australia uranium extraction facilities have low operation costs due to geologic and legal factors (see Section 3.9 for further discussion). While Kazakhstan in situ operations have a much lower ore grade than the Cigar Lake Operation, the cost of extraction is also lower than the hard rock mine. This reduces the total average cost to $23.43 per pound in Kazakhstan[21](Clark et al., 2018). This explains how these operations continued to produce uranium while prices were at $25 per pound, in both cases the revenue per pound of uranium exceeded the operating costs when averaged by total output[22,23]. During this period of low uranium price, global supply was concentrated in countries where geologic and legal factors produced the highest returns. Most resources in Wyoming were subeconomic at these prices, preventing the industry from expanding. The median total costs of production for Wyoming projects evaluated were $51 per pound[24].

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[19] The term high and *low* ore grade is used flexibly. One reserve of uranium may have a lower geologic concentration of uranium but yield better economics. For example, reservoir geochemistry can affect operating costs. It should also be noted that in situ operations have reduce operating costs, meaning the cutoff grades of in situ sites are not comparable to traditional mining methods.

[20] Prices inflation adjusted to 2024 values.

[21] Operating costs are inflation adjusted to 2024 dollars.

[22] Note that averaging the operating costs by production, allows the value to decrease by either decreasing costs or increasing the production. This makes the operating cost units the same as the units of returns ($/lb).

[23] A good heuristic to identify the cutoff price required for a facility to operate is to assume that the uranium price per pound must exceed the average operating cost. However, the actual cutoff price of uranium is dependent on how the firm discounts cash flows and assess risk premiums. If a firm will only invest is a project if it is profitable with a 12% discount rate, then upfront project costs add proportionally more to the cost per pound in present value terms than a company assessing profitably with a 5% discount rate. Also if uranium prices increase lower grade resources will be produce, which in turn increases this average operating costs. This means the cost estimate is dependent on the final operation plan. This metric is only used a first approximation of comparative profitably across mines.

[24] Cost inflation adjusted to 2024 dollars. Reports reviewed include (Malensek et al., 2022; Moores & Western Water Consultants, Inc, 2021a; Western Water Consultants, Inc, 2024a, 2024b)

At higher uranium prices, other countries, and Wyoming, have ore that can be extracted profitably. This leads to a diversification of the global supply chain and an increase in Wyoming uranium output. The range of geologic conditions across the State impacts the expected uranium output. The first movers have the most amenable geologic factors, but as price increases more marginal resources can be developed, and existing operations can expand production into lower quality areas of the field. Defining ore quality as a combination of geologic factors that affect yield (ore grade) and costs (geochemical properties, and depth) the distribution of ore quality sets how much uranium can be produced in Wyoming at specific market price.

The recent price upticks in uranium have revealed the supply dynamic of Wyoming's uranium industry. For example, the Christiansen Ranch Project now called Willow Creek announced it would re-open operations, selling all produced uranium on the spot market (World Nuclear News, 2024). This suggests the ore quality at the operation was too low to be profitably extracted at the previous prevailing prices[25]. Future well field development was halted in 2014 when uranium spot prices averaged $40.50 per pound (International Monetary Fund, 2023; United States Bureau of Labor Statistics, 2023)[26]. With the prices increasing to $100 per pound at the time of reopening, the projects could develop the existing wells with the option to drill wells farther along the roll front (Cameco Corporation, 2024a; Uranium Energy Corp, 2024). This indicates that the minimum price threshold for any Wyoming sites to be globally competitive is around $50. It is also important to note that this price threshold may change over time. As a resource is depleted revenues at the site are reduced increase the minimum uranium price threshold needed to operate. On the other hand, improvements in technology (Section 3.4) can reduce operating costs, thereby lowering the minimum uranium price threshold.

This uranium price threshold is not the entire story for the State. Existing operations such as the Willow Creek and Lost Creek Project benefit from past investment. Most site permitting, geologic surveys, and construction costs were previously completed during site development (see Section 3.5). The cutoff price to reactivate an existing uranium project, is lower than the price necessary to induce a new project[27]. For new projects to be developed uranium prices must be sustained above that project's cutoff price, which accounts for upfront site development costs. While this cutoff price varies by project, historic production trends suggest a price in the range of $70-$150 will promote some new development in Wyoming.

[25] Holding operation costs fixed, at the site.

[26] Inflation adjusted to 2023 dollars.

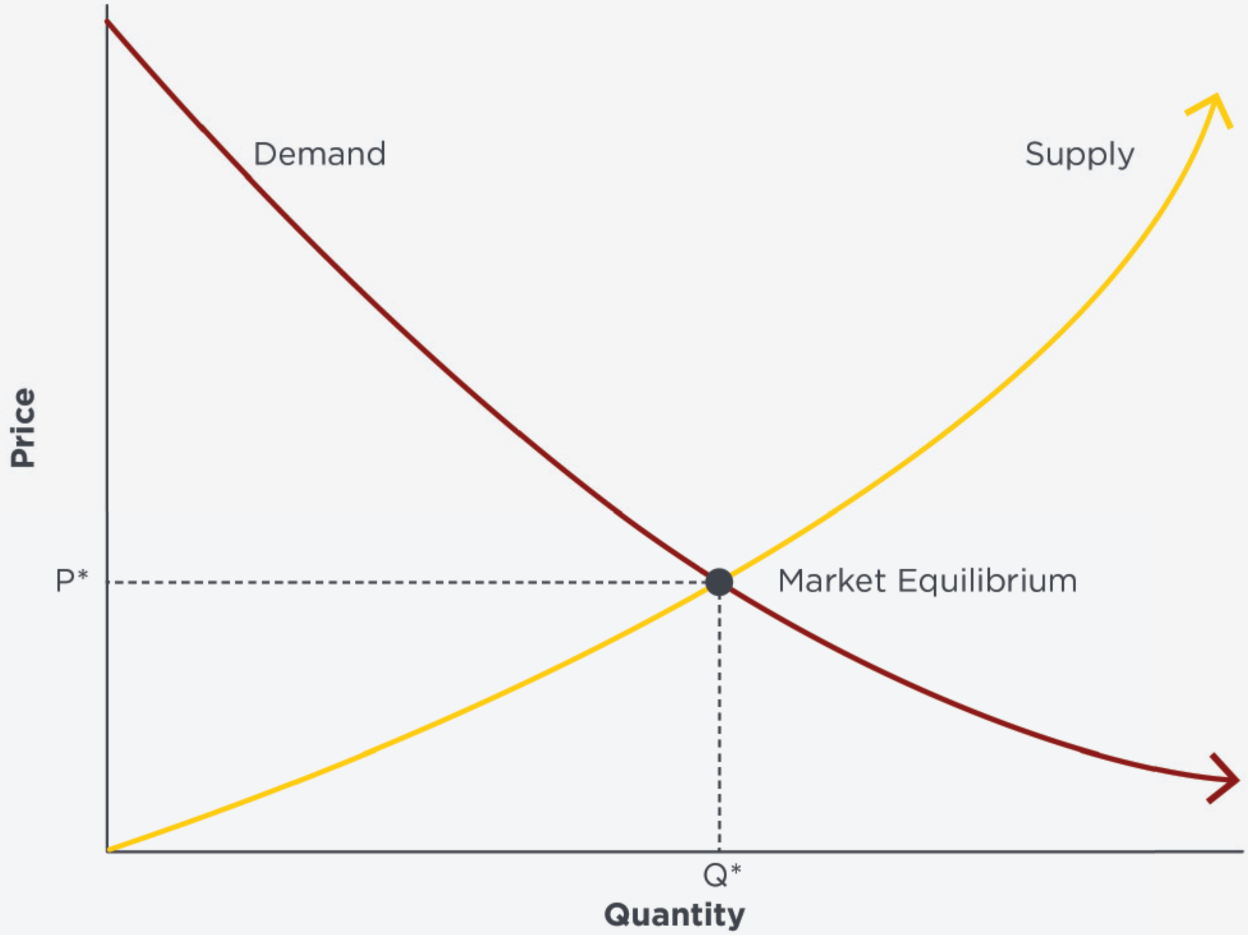
[27] all else equal

From a policy perspective, ore quality in the State cannot be changed, but policy can change operating costs. The tax rate (Section 3.6) and remediation requirements (Section 3.9) change the operating cost and can be modified to lower this minimum price threshold.

Uranium Supply

To understand the uranium markets, it is necessary to know how the supply and demand of uranium differ from other markets. A demand curve is a function that identifies how much of a product would be purchased at every possible price. The demand explains not only the current quantities purchased in the market, but also the outcomes under a range of future scenarios. Similarly, supply functions show how much of a good will be produced for sale at every possible price. These two functions work together to establish the market price and quantity of a good. A generalized supply and demand curve is shown in Figure 7.

Figure 7:
Concept of Supply and Demand



As price increases, less product is purchased by consumers. However, rising prices make it so that more products are produced for sale. The market price of any goods is set where these two lines intersect[28]. If a company raises prices above this point, the product will be left unsold and if prices decrease below this point, companies can maximize profits by raising prices. This leads to convergence on this equilibrium point over time. In Figure 7, the yellow line shows how a supply curve slopes upwards, with firms producing more at higher prices. The red line shows how demand slopes down as consumers purchase less as prices rise. The final market price in the supply curve is labeled as “p*” on the y axis, and the market quantity sold is labeled as “q*” on the x axis.

Changes in market price occur when either the supply or the demand curve shifts. An example of a supply shift in uranium is the development of in situ technology. In situ mining reduced the cost of producing uranium, in amenable reserves. As a result, the yellow supply curve in Figure 7 would shift to the right, and more uranium is supplied at each market price.

An approximation of the U.S. uranium supply curve is provided in Figure 8 which shows evidence of a supply shift occurring in 2008. Price and quantity data cannot typically be used to plot a supply curve, because shifts to both supply and demand affect the market price and quantity. However, the uranium market has unique features that allow the quantity and price data to estimate a supply curve.

The U.S. uranium suppliers are a relatively small portion of global supply, so supply shocks in the U.S. have a minimal impact on global price. Additionally, very few potential supply shifts are identified since the 1980’s. While globally supply shifts have occurred in this period, a supply shift in another country is a demand shift for U.S. sourced uranium. If the supply curve does not shift than price and quantity changes occur only because of shifts in demand, and these changes can be used to estimate supply[29]. The uranium market is sufficiently close to this situation, that a simple graph of quantity produced vs price, generates a quasi-supply curve.

Figure 8 plots the quantity of uranium concentrate produced in the U.S. (EIA, 2023, 2024b) against the U.S. average contract price of uranium. The U.S. average price includes long term contract prices for U.S. firms representing the actual received payments. Producers respond to these realized prices more directly than spot market prices, which are more volatile. Price data is collected iteratively from EIA marketing reports[30]. This simple estimate matches the expectations of a constant slope supply curve with a single shift occurring in 2008.

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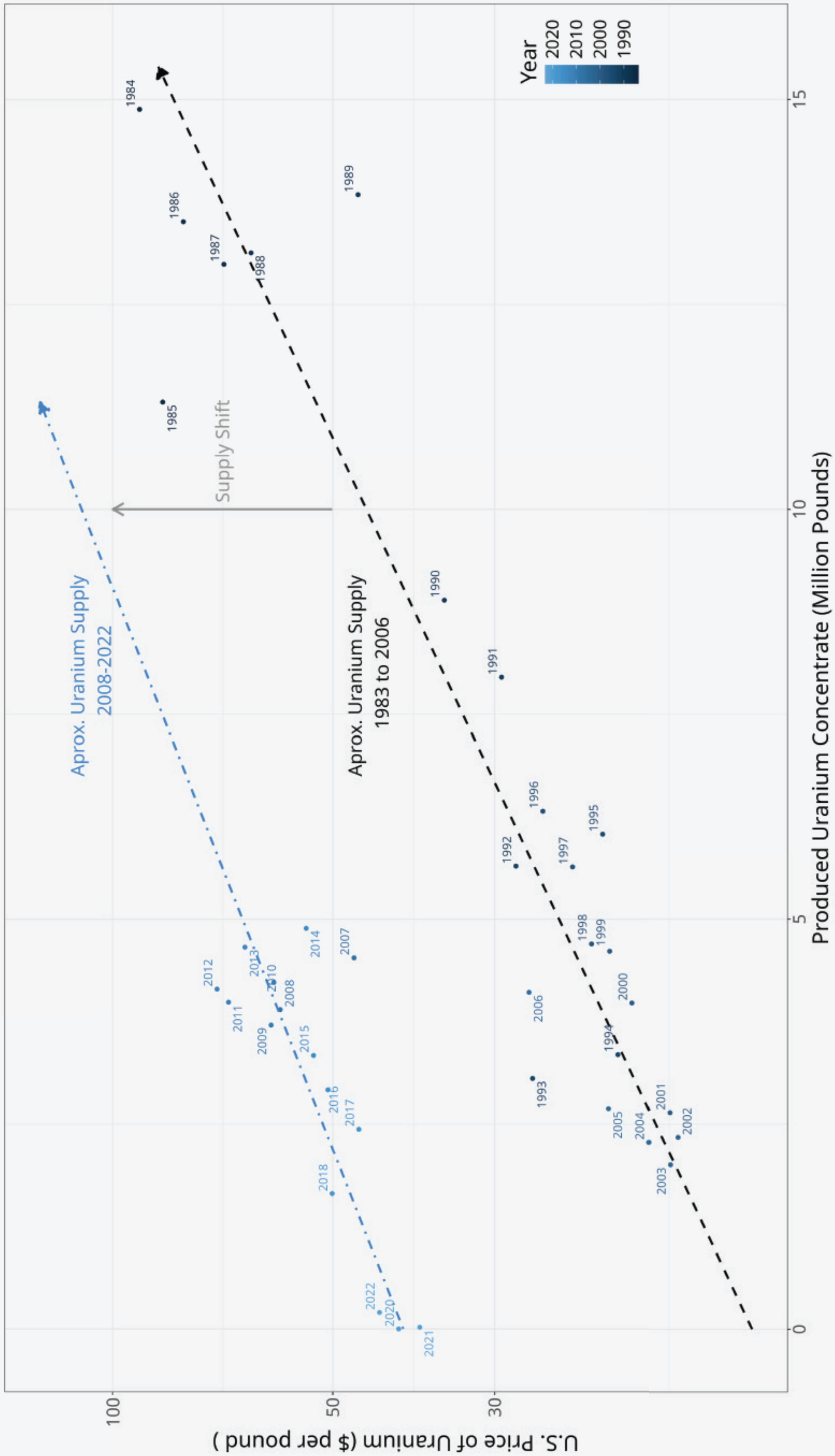
[28] This assumes a competitive market structure. In a monopoly or monopsony, the price will deviate from this point of intersection, being based on marginal profit rather than marginal revenue.

[29] But not demand. For demand to be estimated in this manner, demand must remain constant.

[30] See reports (EIA, 1994, 2004, 2005b, 2006, 2007b, 2008b, 2009b, 2009b, 2010b, 2011b, 2012a, 2012b, 2014b, 2015b, 2015b, 2016b, 2016b, 2017b, 2019b, 2020b, 2022b).

Figure 8: Approximate U.S. Uranium Supply Curves[31]



[31] Ibid

The apparent change in supply corresponds with the removal of a quota on Russian sourced uranium which was announced in 2007 and initiated in 2008 (International Trade Administration, 2008). This shift reduces the amount of uranium produced at each price[32]. The removal of the quota can affect the relationship between U.S. production and contract price. One explanation is that the U.S. price decouples from long run expectations. The quota removal occurred gradually, with limit reductions based on forecasts of U.S. nuclear power plant use (International Trade Administration, 2008). Consequently U.S. contract prices are purchased at a premium, compared to the uranium price expected to be paid once the quota is fully removed. Further the quota lowers the average expected long run U.S. uranium prices[33]. On March 2024 the U.S. congress passed a ban on low enriched uranium imports from Russia which subsequently was approved by the president on May 13th, this may again shift supply (Rep. McMorris Rodgers, 2023).

Figure 8 provides a simple visualization of uranium supply but is not a robust statistical estimation of U.S. supply. To provide this information, a time series regression analysis is used. For this procedure a model of the uranium recovery industry is necessary.

The model predicts the total quantity of uranium concentrate produced in the U.S. each year. Uranium operations make decisions about expanding capacity in stages. First, existing projects respond to prices immediately, by increasing exploration rates and extraction at operating wells. Next, the exploration expenditures lead to new production wells. It takes time for the in situ wells to reach full capacity, so the response in uranium production caused by a uranium price shift is expected to occur over time. Further, operators factor in the available uranium inventories of nuclear power plants when making investment decisions. If uranium stockpiles are large, then powerplants will augment newly produced uranium with these reserves.

[32] Since supply curves are plotted with quantity on the x axis. A movement of the supply curve up on the y axis is a reduction in quantity produced at each price. This can be counter intuitive because the commonly used term “upward” or “increase” in supply may imply a downward movement in the supply curve.

[33] In scenarios where the uranium prices significantly rise, a quota on Russian uranium allows U.S. prices to rise faster than global averages. This possibility raises the expected present value of U.S. extraction operations, even if the current world and U.S. price are comparable. Removing this upside for uranium mines, shifts supply inward.

The change in uranium production is estimated as a response to uranium price, using yearly lags in uranium production, a one-year lag of total uranium inventories, and a time trend. The time trend prevents a spurious regression that attributes correlated trends with casual changes to supply (Granger et al., 1998). It also incorporates long run trends in mineral depletion due to extraction. Two lags in uranium production are included in the final model[34]. One difficulty in estimating uranium supply is that prices are affected when uranium supply shifts. For example, if a new mining technology lowers operating costs, the quantity of uranium produced by mines will increase, which in turn lowers the market price of uranium. Consequently, a simple linear regression can incorrectly estimate that uranium projects increase production in response to lower prices. To avoid this an instrumental variable method is applied. This procedure identifies a variable correlated with changes in demand but not with changes in supply. We apply the West Texas Intermediate price of oil as an instrument, following past literature (Kahouli, 2011; Mason, 1985). A change in the demand for energy will affect both the price of oil and uranium, but a change in the price of oil does not plausibly change the operating cost of uranium recovery operations. The estimate from these models is provided in Table 3.

[34] This selection is based on the Akaike information criterion (Akaike, 1974). Two lags minimize the AIC score.

Table 3:
Uranium Supply Estimate

Dependent Variable:	U.S. Uranium Production		
	Two lags	One lag	IV Regresion
Model:	(1)	(2)	(3)
Variables			
Ur. Price	0.3711***	0.4962***	0.6417***
	(0.1151)	(0.0997)	(0.1932)
Ur. Prod: One year lag	0.8083***	0.4829***	0.4744***
	(0.1531)	(0.0282)	(0.0252)
Ur. Prod: Two year lag	-0.3715**		
	(0.1625)		
Inventories: One year lag	-0.1795	-0.4540**	-0.4439**
	(0.1801)	(0.1874)	(0.1993)
After 2007	-0.0457	-0.2380	-0.3734
	(0.2137)	(0.1775)	(0.2903)
Year	-0.0264*	-0.0168*	-0.0165
	(0.0133)	(0.0093)	(0.0122)
Fit statistics			
Observations	37	38	34
R^2	0.93651	0.95482	0.94304
Adjusted R^2	0.92381	0.94777	0.93286

Heteroskedasticity-robust standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Abbreviations: Uranium (UR.), Production (Prod)
Each continuous variable has been transformed with a natural logarithm.
Uranium price is the average U.S. contract price in a given year.
For the Instrumental Model: F-test (1st stage), Ur. Price: stat = 14.4, p = 7.359e-4
Wu-Hausman: stat = 0.071057, p = 0.791829

The results from Table 3 provide insights into the production decision of Wyoming operations. Each coefficient can be interpreted as the percentage change in production due to a 1% increase in the respective variable. For example, in model one a 1% increase in uranium price increases the amount of uranium produced by 0.37% in the same year as the price increase. A 1% increase in the previous year's production accounts for an additional 0.8% increase in production[35].

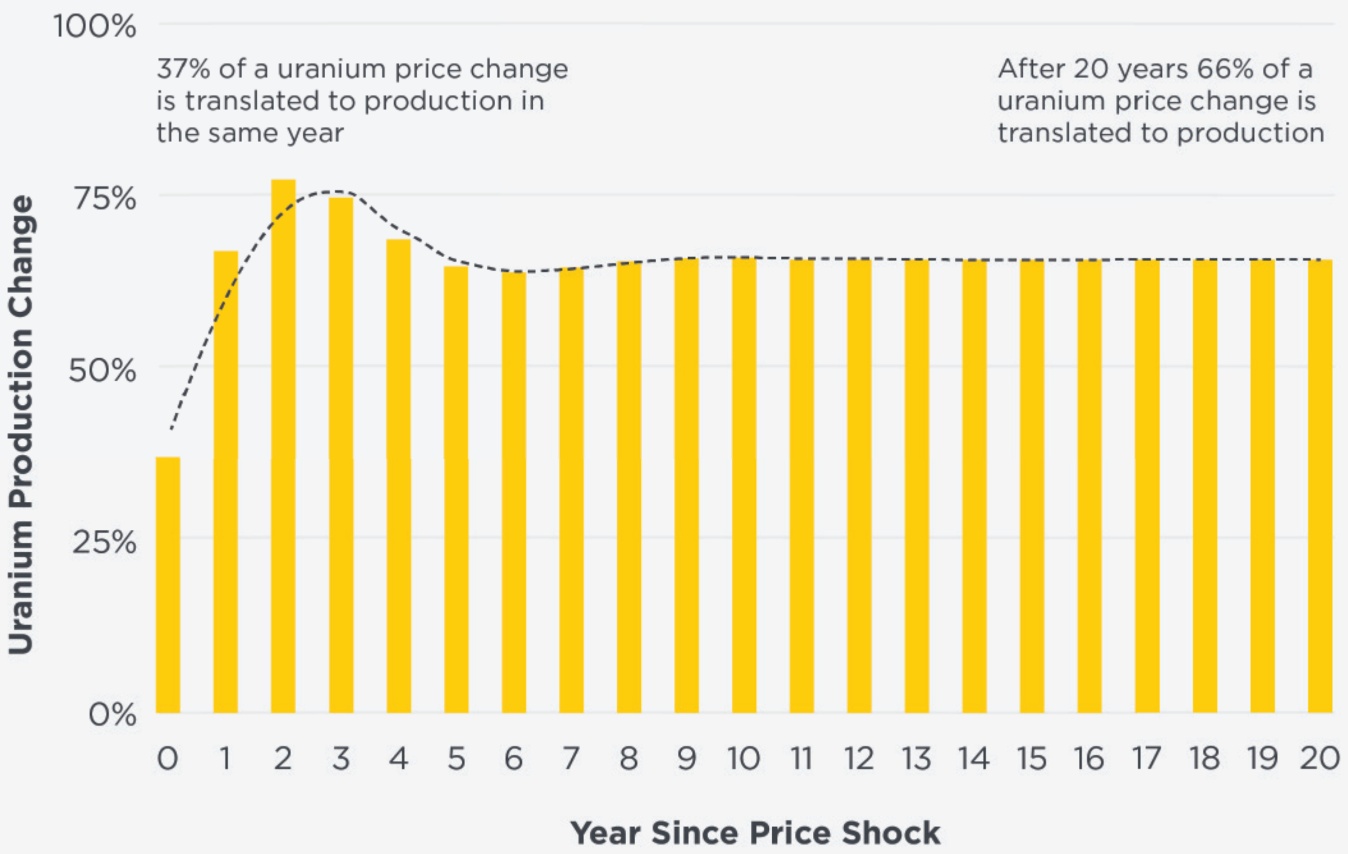
The effect on production over time matches the dynamics expected from uranium recovery operations. Based on model one[36], uranium companies can add to production in the same year that prices increase. However, the largest effect occurs two years following the price change, as exploration from the previous year leads to new production wells becoming operational. Finally, after three years existing production declines as resources are extracted. The previous years inventories levels reduce current production as an alternative source of mined uranium.

Because the response of uranium production to price shocks is dynamic, the cumulative effect over time is provided in Figure 9. The value on the y axis is the percentage of a price increase that translates to production. For example, if a 1% increase in uranium price expands production by 0.7% this value is 70%.

[35] Therefore a 1% increase in price one year ago would induce 0.296% more production in the present year (0.296=0.371*0.8).

[36] Model one is preferred over the instrumental variable method. While oil prices are found to be a strong instrument for uranium prices a Wu-Hausman test cannot reject that the IV model is the same as the simple time series regression (Durbin, 1954; Wu, 1973). This suggest that U.S. supply shocks are rare, and unlikely to create significant bias in the model.

Figure 9:
Dynamic Production Response to a Uranium Price Shocks



When an increase in uranium price occurs, uranium producers increase output with a peak extraction rate two years after the price change. A sustained 1% increase in uranium price translates to a 0.66% increase over the long term.

From these results it can be concluded that uranium market price is the most important economic factor affecting Wyoming uranium operations. Spot prices must be high enough that uranium revenues of uranium projects exceed operating cost to start production. These prices must be sustained to establish mining output. Recently, uranium prices have surged, going from $35.65 per pound in 2020, to $90 in 2024[37]. The model estimates this will lead to a doubling of Wyoming uranium production[38]. If these prices are sustained, then Wyoming uranium production can be reestablished without any additional State support, placing the economic score as a major advantage. However, prices are unlikely to be stable as is explored in the following evaluation of uranium demand.

[37] Based on May 31st 2024 prices (Cameco Corporation, 2024a) and inflation adjusted IMF price (International Monetary Fund, 1980; United States Bureau of Labor Statistics, 2023)

[38] Almost a perfect doubling is estimated. +100.32%=($90-$35.6)/(%35.6)

Uranium Demand

In addition to providing a quantitative estimate of Wyoming uranium supply, the various factors affecting operation decisions are developed. The market structure of uranium demand is found to lead to volatile prices, which can create uncertainty for uranium producers.

A unique element of the uranium market comes from the demand curve. The rate at which consumers reduce the quantity purchased due to a price increase defines the slope of a demand curve. A major contributor to the willingness to reduce consumption when prices rise is the substitutability of the good with other products. Take for example the Wyoming beef market. If the price of beef rises, consumers may substitute beef with bison, chicken, or other foods. This makes the demand curve elastic, meaning a small change in price will reduce the amount purchased significantly.

Uranium, however, is one of the most inelastic demand markets in the short run. Most uranium is purchased by nuclear power plants, and these power plants consume the same amount of uranium per day with little adjustment based on uranium price. The only substitute of mined uranium for nuclear power plants comes in the form of alternative sources of uranium, such as using saved inventories of uranium, under feeding enrichment faculties, or processing existing depleted uranium to extract additional low enriched uranium[39].

Due to the design of nuclear power plants, they operate as a baseload energy source. The average cost of a nuclear power plant is $20 billion[40] (Stewart & Shirvan, 2022). This large initial cost is recovered over time with low marginal operating costs. On the other end of the spectrum, natural gas power plants have relatively low upfront investment costs, but fuel operating costs are higher and variable. A typical nuclear power plant costs a total of $24.38 per megawatt, while a gas turbine costs $31.76 per megawatt (Energy Information Administration, 2021). However, the fuel cost of a nuclear power plant is only $7.47 per megawatt, with gas turbines costing $26.48 per megawatt (Energy Information Administration, 2021). The rest of this operational cost difference comes from maintenance and labor, which are not sensitive to fuel costs.

To compare these two different types of energy supplies, Figure 10 provides an estimate of the levelized cost of natural gas electricity power plants and nuclear power plants under different uranium prices. Levelized costs divide all capital costs over the total amount of electricity generated. This allows the price per Megawatt hour (Mwh) to be compared across energy sources.

[39] Which is dependent upon the cost of Separative Work Units (SWU)

[40] These costs may decline as additional power plants are developed, since the costs include the recent overrun Vogtle project.

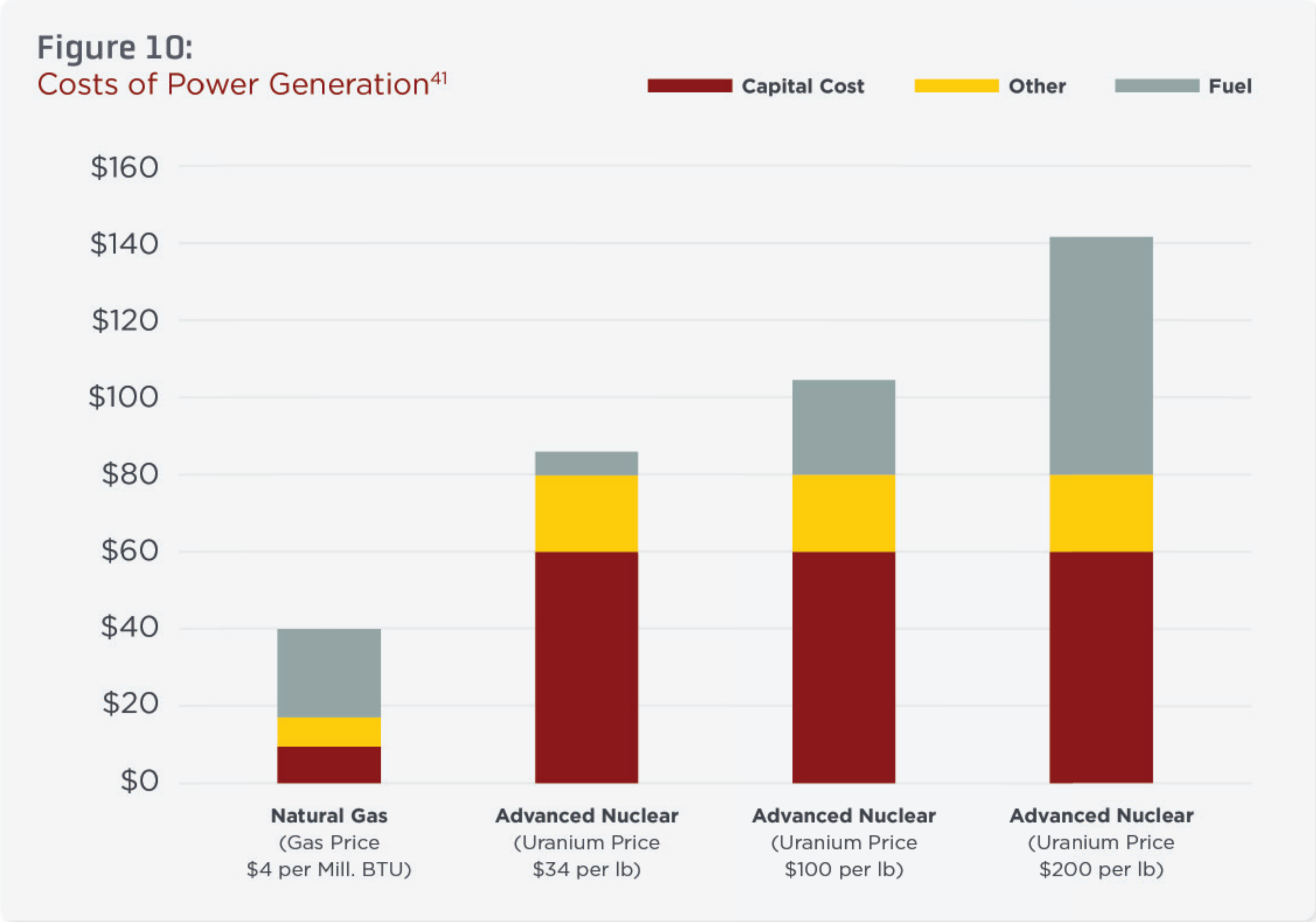


Figure 10 demonstrates that recent nuclear power plants are more costly than natural gas power plants overall, but the cost distributions are significantly different. For natural gas, the capital costs, labeled in red, are very low, with high fuel costs labeled in grey. However, nuclear power plants have a relatively high capital cost, and low fuel costs.

[41] Major costs are taken from EIA estimates of levelized costs (Energy Information Administration, 2022b). Based on the average variable cost estimates from EIA reports, fuel costs are assumed to make up 30.6% of variable costs for nuclear, and 83.4% for natural gas(Energy Information Administration, 2021). Nuclear fuel costs include both raw uranium and enrichment costs. Uranium enrichment costs are assumed to follow the same trend as uranium price, see (Gebben & Peck, 2023) Appendix F for further details. This is separated using the cost estimate that 51% of variable costs come from uranium purchases, and 24% from enrichment (World Nuclear Association, 2022). The estimates based on 2021, numbers so a $33.91 lb price of uranium is used, with $3.91 per million BTU as a natural gas price (International Monetary Fund, 2023; U.S. Energy Information Administration, 1997).

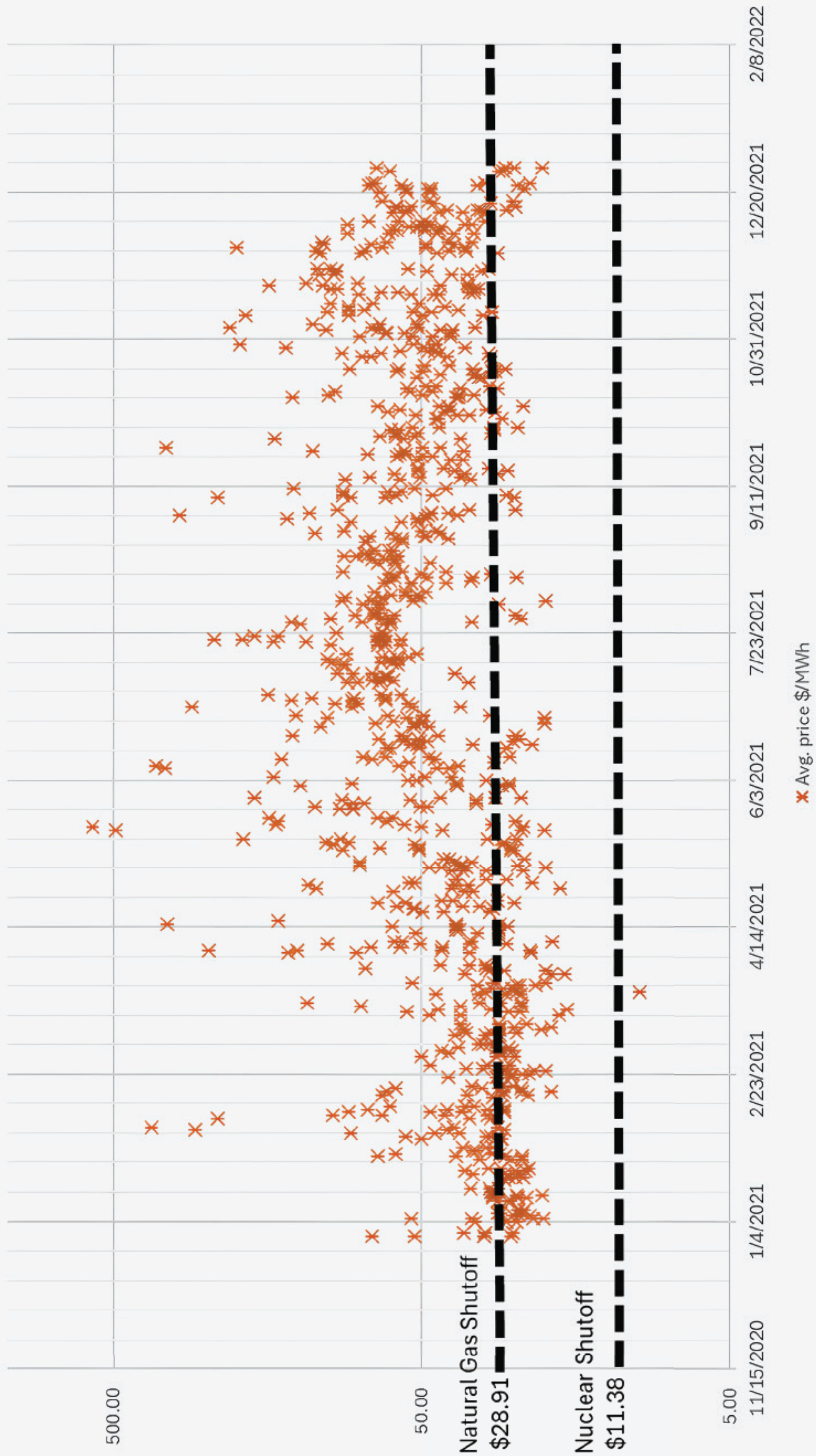
The capital investment of nuclear power is a sunk cost[42], which is not considered in operational decisions. If the fuel and enrichment costs (grey) are below the whole sale price of electricity, nuclear power plants continue to have an economic incentive to operate. Even if overall profits are negative, operating the power plant decreases total losses. The daily returns cover the operating costs of the nuclear power plant, with enough extra yield to cover a portion of the sunk upfront costs. In contrast, natural gas power plants are more sensitive to electricity prices.

Figure 11 uses this fact to demonstrate that the amount of uranium consumed is highly inelastic to uranium price. Approximately 75% of the U.S. is served by a deregulated energy market, referred to as Independent Service Operators (ISO) or Regional Transmission Organizations (RTO) (EPA, 2024). An ISO runs an auction to fill electricity consumption. Power generation firms bid to supply electricity in the region (Federal Energy Regulatory Commission, 2022). The ISO selects the market clearing price needed to fill the electricity sales of consumers. ISO electricity market prices were collected for 2021 (Intercontinental Exchange & Energy Information Administration, 2022) . Other States, including Wyoming, implement a regulated energy market where electricity production is vertically integrated (a monopoly). However, these ISO prices provide information about the value of electricity to consumers and the operating choices of energy producers.

Based on the estimates outlined in Figure 10, the price at which each power source would choose to shut down are plotted as horizontal lines. Any point below this line is a weekly period where the respective energy source would choose to shut off. Operating costs are based on the Henry Hub natural gas market price, and the spot market for uranium for 2021 (International Monetary Fund, 2023; U.S. Bureau of Labor Statistics, 2023; U.S. Energy Information Administration, 1997). Notably, only one data point is estimated to be below the operating costs of nuclear power plants. But many weekly periods are below the operating costs of natural gas. This makes nuclear power a cost-effective base load energy source, similar to coal power plants in operational choices. Nuclear power plants produce large amounts electricity and do not adjust output. Natural gas on the other hand is an adjustable source of electricity, running when prices are high, but turning off during periods of low prices.

[42] A sunk cost is any cost which cannot be recovered. For example, the labor cost of constructing a nuclear power plant is sunk. If a powerplant project is over budget, the money spent on labor cannot be recouped. However, the land cost is not sunk, because the land purchased for the power plant can be sold.

Figure 11:
Market Price of Electricity and Cut Off Levels of Nuclear Power Plants in 2021[43]



[43] Price data taken from (Federal Energy Regulatory Commission, 2022).

Based on this analysis, nuclear power plants would shut off production only two days a year[44] while natural gas plants would choose to shut off 75 days of the year. When only accounting for variable costs, the marginal profit of nuclear power plants averages $44.8 per MwH compared to $28.11 per MwH for natural gas power plants. However, when including the large upfront costs of nuclear power plants, the average profit of natural gas is $19.37 per MwH while nuclear power plants sustained an average loss of $31.7 per MwH. Actual profits of nuclear power plants may differ from this estimate. Regulated energy markets can set electricity prices based on an allowable rate of return. Additionally, some ISO's have implemented a capital market where power generators are paid for having capacity available in the future[45]. However, this model shows the important distinction between the short run and long run costs. Fuel costs set operation choices on a day-to-day basis, while long-term profitability informs the construction of new facilities.

A key point resulting from this analysis is that nuclear power plants do not adjust total uranium consumption based on the price of uranium. This makes the market highly inelastic. Therefore, minor shifts in the amount of uranium supplied can have major effects on the uranium price.

Figure 12 provides a conceptual diagram of the uranium market. The left-side figure shows a demand curve for a typical market. Here, the demand curve has a shallow slope, showing that a small change in price can significantly affect the quantity purchased. In the diagram, a supply shock is shown. Starting at an initial supply labeled as SS an outward shock in supply is shown in SS1. An outward supply shock is created by any change that increases output at all prices. For example, a supply shift in the wheat market could include good weather in a major growing region. SS2 represents an inward shift of the supply curve such as a year with heavy frost in a wheat growing region. The changes in price due to these shifts can be seen in P1 and P2, respectively. This price change is small because a commodity like wheat has many substitutes, including other grains.

The right most diagram in Figure 12 represents the uranium market, facing the same total supply shifts as shown in the left diagram. The slope of short-term uranium demand is steep. Notice that the same shift in supply produces a substantial change in uranium spot market prices. If a new resource of uranium is discovered, the supply shifts out and prices drop. Conversely, a retraction of expected production creates a much larger increase in price than is seen in the more elastic market.

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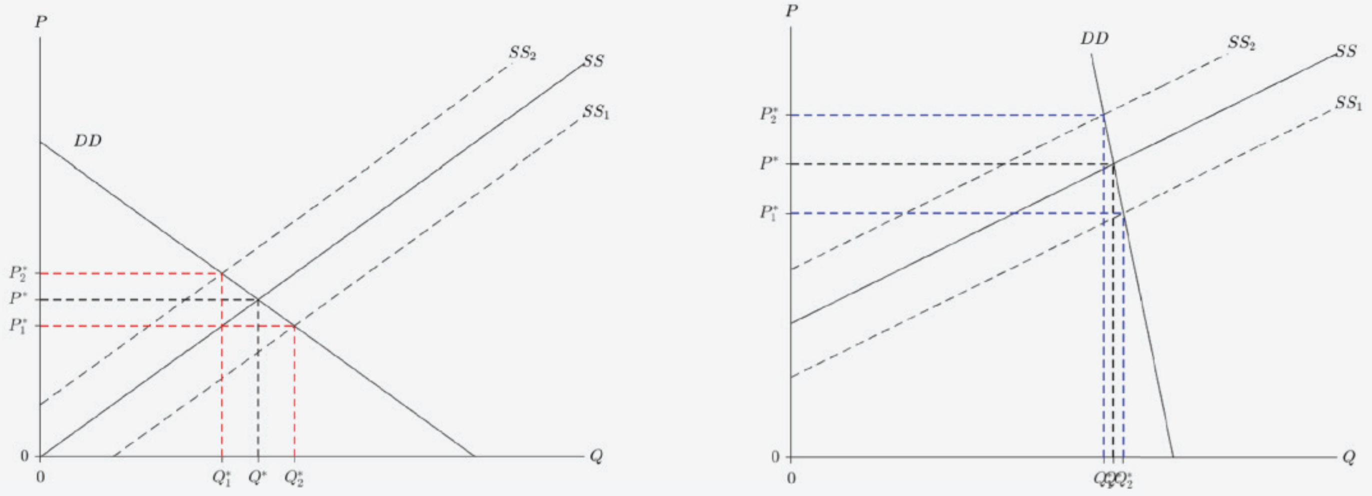
44 Although they are unlikely to do this due to notable costs of shutting on and off.

45 In this system the ISO estimates the amount of additional capacity they wish to add to the grid in the future. Then companies bid for obligations to supply this capacity at the selected date. The companies are paid the market clearing price to fill this capacity. This obligation can then be bought or sold by the companies before the capacity is required to come online. This provides an additional source of revenue for nuclear power plants other than electricity sales.

Figure 12:
Stylized Supply Shift of Uranium



This analysis explains the recent market trends in uranium. Uranium prices have high volatility because of this inelastic demand. Demand for uranium includes both deliverable markets for nuclear power plants and futures markets based on long run expectations. Changes in expectations of nuclear power plant needs have significant impacts on price. For example, after the Fukushima incident in 2011, uranium prices dropped from $63 to $18 per pound by 2018 (International Monetary Fund, 1980). The incident moved up the expected retirement of nuclear power plants, shifting the demand inward.

In the present year, uranium prices have rallied, increasing from $35.65 per pound in 2020 to $90 in 2024 (International Monetary Fund, 2023). Such a large change in price is made possible by this market structure and provides some caution in estimating long run uranium prices. One factor was the COP28 conference, where 20 countries agreed to triple nuclear output by 2030 (Meredith, 2023; United States Department of Energy, 2023). Nuclear power growth has stalled in the U.S. partially due to decreasing costs of renewable energy, an alternative low carbon fuel. However, in Europe, locations with economic wind and solar projects are limited, making nuclear power more economical in comparison. This policy shift changed the long run expectations of nuclear power plant growth in Asia and Europe. This shift in long run demand has an immediate effect on prices since uranium purchased today can be stored for future use.

Coupled with this demand shock, a supply shift occurred in January 2024 further increasing prices. Kazatomprom, the world's largest uranium producer, announced that shortages of hydrochloric acid and unexpected geologic issues would curtail production from the previously announced increase of 20% (Kazatomprom, 2024). Another supply shock occurred due to the Russo-Ukraine War. Russia accounted for 6% of all uranium production in 2020 (International Atomic Energy Agency, 2023). Conflict in the region leads to the potential of restricted Russian supply directly and indirectly through sanctions. Neighboring Kazakhstan produced 40% of all uranium in 2020 (International Atomic Energy Agency, 2023). While uranium supplies were not immediately affected, the U.S. implemented a Russian import ban in 2024 (Rep. McMorris Rodgers, 2023)[46]. Combining these supply and demand shifts, in an inelastic setting, produced more than a doubling of uranium prices. Since long term expectations of industry output are tied to uranium prices, this shift is significant for Wyoming uranium projects. Future supply or demand shifts could counteract this increase in price, but if sustained, many of the stagnate Wyoming uranium projects will be profitable under these market conditions.

Considering both the Wyoming uranium supply factors, and the global market for uranium, the overall score of economic factors is places as a *moderate advantage*. Prices have recovered to a level where uranium extraction operations are profitable, and the most likely outcome of this is continued growth in Wyoming uranium production. However, the sensitivity of the uranium market makes long-term uranium price predictions tenuous. A shift inward of uranium demand will result in a steep reduction in uranium prices. Based on the elasticity of the market, such a shift is not improbable, and Wyoming uranium operations are dependent on uranium prices being maintained above operating costs, typically above $50[47] a pound. For these reasons, Economic factors are scored as a *moderate advantage* for Wyoming uranium production but would be scored as a *major advantage* if long run uranium prices were more stable.

[46] This is a ban on importing low enriched uranium, which is expected to have a similar effect to a ban on yellowcake imports. Russia produced 4% of the global enrichment in 2021(NEA, 2022). This will raise the domestic price for enrichment, and uranium prices are linked to enrichment prices due to the ability to underfeed centrifuges (Gebben & Peck, 2023).

[47] Here operating costs refer to the average total costs of new extraction facility.

EXISTING INDUSTRY

Existing Industry: Scoring Criteria

Existing Wyoming industries in the mining and extractive sectors are found to provide a *moderate advantage* for developing uranium operations in the State. Wyoming uranium production has accounted for more than half of total U.S. output since the 1990s (see Figure 4). The exploration and operating experience from these facilities provide future Wyoming uranium recovery operations with a cost advantage when compared with undeveloped uranium plays. Further, Wyoming uranium operations that were placed on standby can be reopened quickly, while avoiding some development and regulatory costs. These cost savings are typically many millions of dollars compared to a new extraction facility. However, only a portion of Wyoming facilities are on standby, so the ability for the States output to expand based on this advantage is capped. These existing facilities provide a *major advantage* to development in the short run, but the score is constrained to a *moderate advantage* over the long-term horizon.

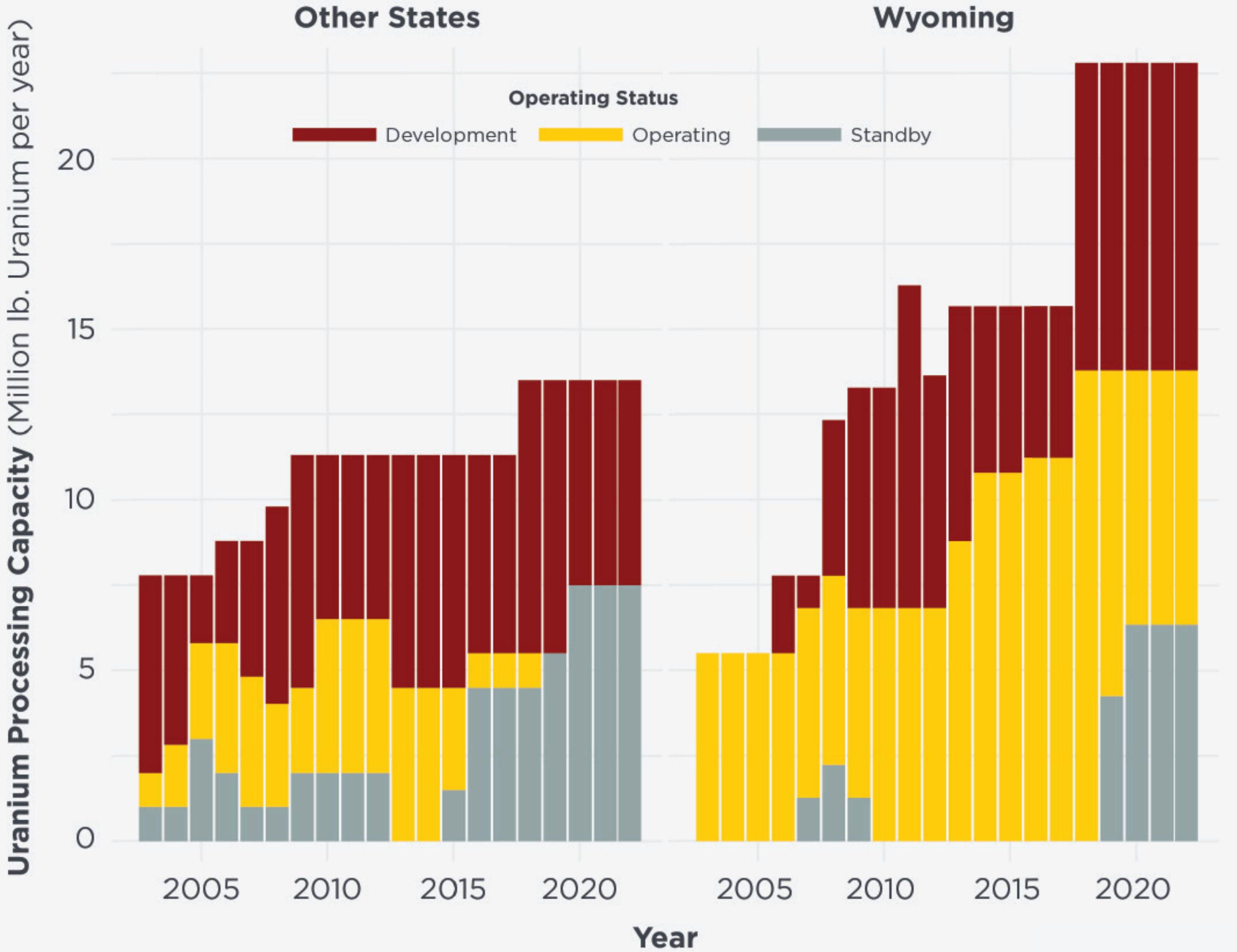
Existing Industry: Analysis

Existing industries improve the viability of Wyoming based uranium operations. Operating and stand-by facilities have more price flexibility than new facilities and have established geologic information, reducing uncertainty. A recent example of this occurring is the reactivation of the Christensen Ranch Project in Johnson and Campbell counties. The uranium project plan is to sell on the spot market rather than seeking long term contracts (World Nuclear News, 2024). Given the gap between spot and long-term contracts, established Wyoming producers rapidly took advantage of the spot market prices. As discussed in Section 3.4, the uranium market is volatile because of the inelasticity of nuclear power plants. Short term price spikes are a common occurrence, so this ability to expand production into lower quality ore provides a distinct advantage to Wyoming operators.

To compare the flexibility of uranium operations, the status of licensed in situ processing facilities was collected from each EIA uranium production report going back to 2003[48]. The total licensed capacity and the status of the processing facilities is provided in Figure 13.

[48] See reports (EIA, 2005a, 2005a, 2007a, 2009a, 2010a, 2011a, 2014a; Vest, 2012, 2013; EIA, 2008a, 2015a, 2016a, 2017a, 2019a, 2020a, 2021a, 2022a, 2023, 1995, 1994, 1997a, 1999, 2000, 2001, 2003, 2002, 2003, 1997b).

Figure 13:
In situ Processing Capacity, in Wyoming and the U.S.[49]



Notably, Wyoming has more in situ processing capacity than all other states combined. The existing operating capacity allows operating mines to expand in response to price increases without being constrained by capital. The standby capacity and developing capacity have lower barriers to entry than undeveloped fields. Based on a finer review of the data, it was determined that most of the developing capacity in Wyoming was initiated during exploration phases, but the project was never completed. These potential development locations have established geologic data, and preliminary feasibility reports, providing a cost advantage from restarting the project.

Further, the concentration of uranium mining promotes efficient policy and industry wide collaboration. Groups such as the Wyoming Mining Association provide a mechanism by which uranium producers can collaborate and advocate for policy changes.

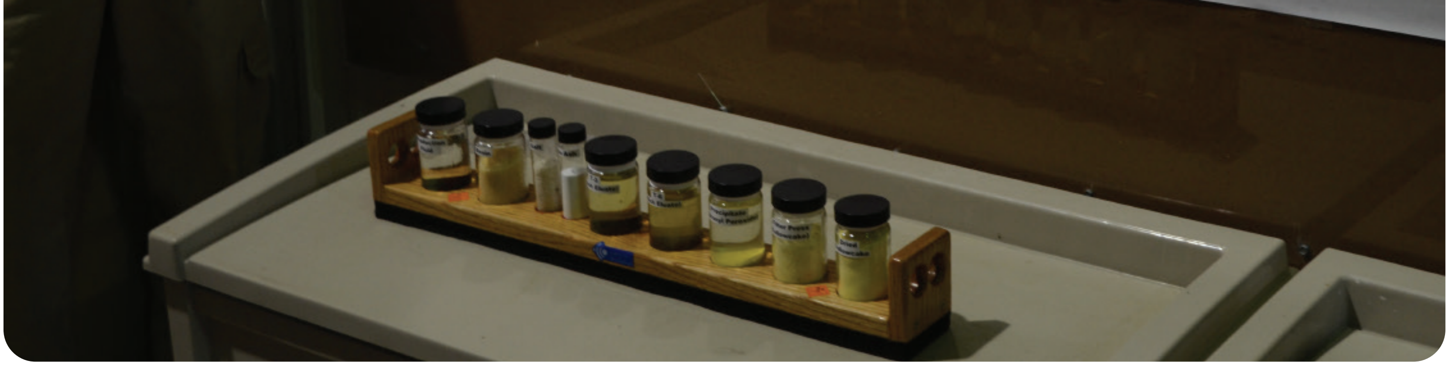
[49] Ibid.

There are also spillover benefits from the existing oil and gas industry. An obvious comparison is in the management of wells for in situ uranium recovery and oil extraction. However, the extraction methods have significant differences, with uranium operators targeting shallow aquifers, while oil and gas wells require advanced deep drilling. Nevertheless, there are complementary practices between both industries. Uranium in-situ mines are required to restore groundwater of aquifers after operations cease (see Section 3.4). As part of this process, an injection well is drilled to a lower depth than the production aquifer and completed in a non-potable geologic zone, to inject wastewater from the in situ restoration operations. This UIC Class I injection well requires more advanced drilling operations than the production wells so access to oil and gas drilling rigs can assist in this process. This Class III well requires more advanced drilling operations than the production wells so access to oil and gas drilling rigs can assist in this process.

Wyoming produced 10% of the country's coalbed methane in 2022, making the State the third highest producer in the country[50] (Energy Information Administration, 2022a, 2023a). In this extraction process, shallow wells are drilled into a coal field. The removal of water from the aquifer reduces ambient pressure allowing natural gas to escape from the coal. Since this process targets shallower aquifers, drilling rigs used for coal bed methane can be used to install uranium in situ wells. Previous investigations of the oil and gas market have shown that drilling rates are more responsive to price than production, and that access to the same drilling equipment creates inter market connections between oil and natural gas (Anderson et al., 2018; Roberts & Gilbert, 2016). The ability to use coal bed methane drilling equipment creates a similar effect in the uranium market. Typically, access to drilling equipment is not a binding constraint. However, during times of major price increases, existing operations expand production into less profitable regions of the field, and new operations begin construction. This restricts access to drilling rigs capable of providing in situ production wells. However, Wyoming CBM drilling rigs can be relocated for use in uranium in situ drilling when capital is scarce. This makes Wyoming producers more responsive to price shifts and provides additional economic benefits to locating in the State.

However, the value to companies from increased capital is reduced when labor availability is insufficient to utilize the equipment (Cobb & Douglas, 1928). The stagnation in uranium drilling from 2016 until 2020, reduced the number of experienced operating crews. As a result, current uranium operations in Wyoming have found it necessary to hire Nevada based firms (D. Wichers, personal communication, May 6, 2024). The advantages of the available drilling rigs are currently limited by this constraint on labor. If the uranium industry can regain this experience the existing industries' advantages will increase.

[50] 2022 is the most recently reported year of data.



The existing uranium recovery industry also promotes growth through acquired knowledge. Early in situ operations in Wyoming struggled with mineral control and the selection of the proper lixiviant. These experiences inform future projects that can operate more efficiently by applying the data acquired from exploration (McDowell et al., 2016). Further, exploration provides information to future operators in the State. The knowledge gained from exploration provides a social benefit above the private operation profits (Mason, 1985, 2014).

TAX STRUCTURE

Score

Moderate Advantage

Tax: Scoring Criteria

The structure and level of Wyoming uranium severance taxes are found to be a *minor advantage* to uranium recovery facilities operating in the State. Wyoming has a graduated tax rate that adjusts with uranium price, minimizing tax burden when operations are marginally profitable. After accounting for tax deduction, the maximum uranium severance tax rate in Wyoming is comparable to nearby states. The severance tax does not prevent facilities from opening, but operating facilities slow production by an average rate of 1.3% per year. Since this effect does not delay facility opening, the tax structure score is placed in the *minor advantage* range.

Tax: Analysis

Non-renewable resources have a distinctive set of profit incentives not prevalent in other industries. These unique attributes change which tax structures are optimal in states like Wyoming that manage large reserves of natural resources.

Taxation of non-renewable resources can be structured to avoid significant market distortion (Ricardo, 1819). In most industries, raising the rate of taxation reduces long run profitability, which limits entrance into the market. As a result, raising taxes reduces output and affects relative prices. Scarce resources are unique in that the natural reserves place a physical limit to market entry. Even if taxes are increased, the total number of uranium projects is restricted by geologic factors. This means that state taxes on uranium recovery can be set so as not to affect total production.

For example, assume a state imposes a fee of $5 million to start a uranium recovery operation. Assume also that the company expects to make a total profit of $10 million dollars over the life of the project. The fee to open the facility still leaves the firm with $5 million of potential profits, so they will choose to pay the fee and open it. If this operation fee was raised to $9 million, the facility owner would still choose to pay the fee and operate, but their potential profits decrease from $5 million to $1 million. In this example, raising the entrance fee does not affect the choice of the operator, but it shifts profits from the operation to the State. If the start-up fee does not make the operation unprofitable, the total number of facilities in operation is unaffected by the fee rate.

This phenomenon can be compared to other sectors of the nuclear integrated industry evaluated in this white paper series. In an earlier white paper, nuclear component manufacturing was found to be advantaged by Wyoming's low tax rates. Unlike uranium recovery, manufacturing firms have a wide range of possible locations and will produce less when taxes increase. However, uranium operators are limited by geology and the location of their orebodies and are less sensitive to tax rates.

This concept is important to determine whether the Wyoming tax structure is an advantage to uranium producers. The tax rate is not a burden so long as it does not eliminate the expected profits of uranium operations in the State. Yet the profitability of uranium operations is contingent on the ore grade quality of individual operations and the price of uranium, which is accounted for in the Wyoming tax structure. In 2020, the Wyoming Legislature voted to establish a graduated severance tax structure dependent on the spot price of uranium (Brian et al., 2020). Table 4 provides the Wyoming severance tax rate on uranium which scales with the market price of uranium until 2026.

Table 4:
Wyoming's Uranium Severance Tax Rate (Brian et al., 2020)

Market Price	Tax Rate
Less than $30.00	0%
$30.00 to $36.67	1%
$36.68 to $43.34	2%
$43.35 to $50.00	3%
$50.01 to $60.00	4%
$60.01 or more	5%

This tax structure benefits the State by accounting for firm profitability. The total severance taxes collected by Wyoming are set by the number of units extracted, not the firm's profit. When the price of uranium decreases, expenses remain the same, but revenues decrease[51]. If this reduction in profit margins is high enough, a severance tax will lead to premature abandonment of existing operations or prevent new facilities from operating. Since the Wyoming tax rate drops to 0% during periods of low prices, the total number of operating uranium operations in the State are not reduced by tax rates. At higher prices, the State acquires higher tax revenue, but the higher taxes are paired with higher profits so the decision of operators to maintain or close is unaffected.

At a price of $60 or more, Wyoming has one of the highest severance tax rates of any major uranium producing state including New Mexico 3.5%, Colorado 2.35% (Colorado State Auditor, 2021), Texas 0% (Reed, 2000), and Nebraska 2% (Nebraska Department of Revenue, 2022). However, after tax deductions, this rate ends up being closer to 2% for Wyoming operations (Malensek et al., 2022). Further, the structure of natural resources markets makes this difference a minor factor in production. The tax rate each state can set without decreasing production is dependent on the quality of the resource in the state and the scarcity of uranium (Maniloff & Manning, 2018). Since uranium reserves are highly geologically constrained, see Figure 19, and Wyoming has operable in situ recovery operations, the difference in tax rate between Wyoming 5% and the rates in neighboring states of 2.35% in Colorado, and 2% in Nebraska is likely a minor factor. Overall, the realized tax rate of 2% in Wyoming is expected to decrease the production rate by 1.32% based on the results from Table 3, independent of the price of uranium[52].

While the total number of operating facilities is not affected by the Wyoming severance tax rate, it is likely that year-to-year production choices will change. In order to maximize profits, operations account for future revenue streams. Extracting a unit of uranium today increases the future cost of extraction because the lower cost production unit has already been removed,

The severance tax rate reduces the profitability of these marginal resources so fewer wells are drilled. When price increases, these resources become profitable. The effect is that severance taxes reduce the rate of production, extending it over a longer period. Economic theory predicts that the extraction rate from operations is set by interest rates, and that adding a 1% severance tax is equivalent to a 1% increase in interest rates (Hotelling, 1931).

[51] For example, if a State has a fixed 5% severance tax a 10% decrease in uranium prices will decrease revenues of miners by 10% and decrease tax costs by 0.5%. Other costs stay the same so profits are reduced by 9.5%.

[52] Unlike the added restoration costs discussed in Section 3.6, the cost of the tax remains constant in percentage terms. The restoration costs are fixed and are a higher percentage of revenues when prices are low. In comparison the severance tax is increased in absolute terms when prices are higher, and decreased when uranium prices are lower.

The link between interest rates, severance tax rates, and uranium production is driven by the economic concept of the time value of money where money received in the future is worth less than the same amount received today. For example, a company that receives $100 in revenues today can invest it and within one year receive a return of investment. If, for example, a bond returns $110 within one year, then the time value of money to that company is 10% per year. If given the choice between receiving $100 today or $105 in the future, that company will select to have the $100 today.

Bond rates set the time value of money for companies making investment decisions. If the bond rate is 1% per year, they can borrow money to invest in production. If the expected returns on uranium mining are higher than 1% per year, they will expand production until the next set of wells returns less than 1% per year. For this reason, mining companies produce more if interest rates are low and less if interest rates are high. From the company's perspective, receiving a 1% tax on revenues is the same as increasing the cost of capital by 1% through increased interest rates. This means the rate of extraction of uranium mining is linked to the combination of bond rates and severance taxes. The uranium severance tax slows the rate of uranium extraction. This reduces the amount of taxes the State receives today but increases the expected tax returns in the future.

Since the number of Wyoming facilities in operation is not reduced by the graduated severance tax structure, and the predicted delay in production is less than 2% this year, this tax score is a *minor advantage*.

TECHNOLOGY

Technology: Scoring Criteria

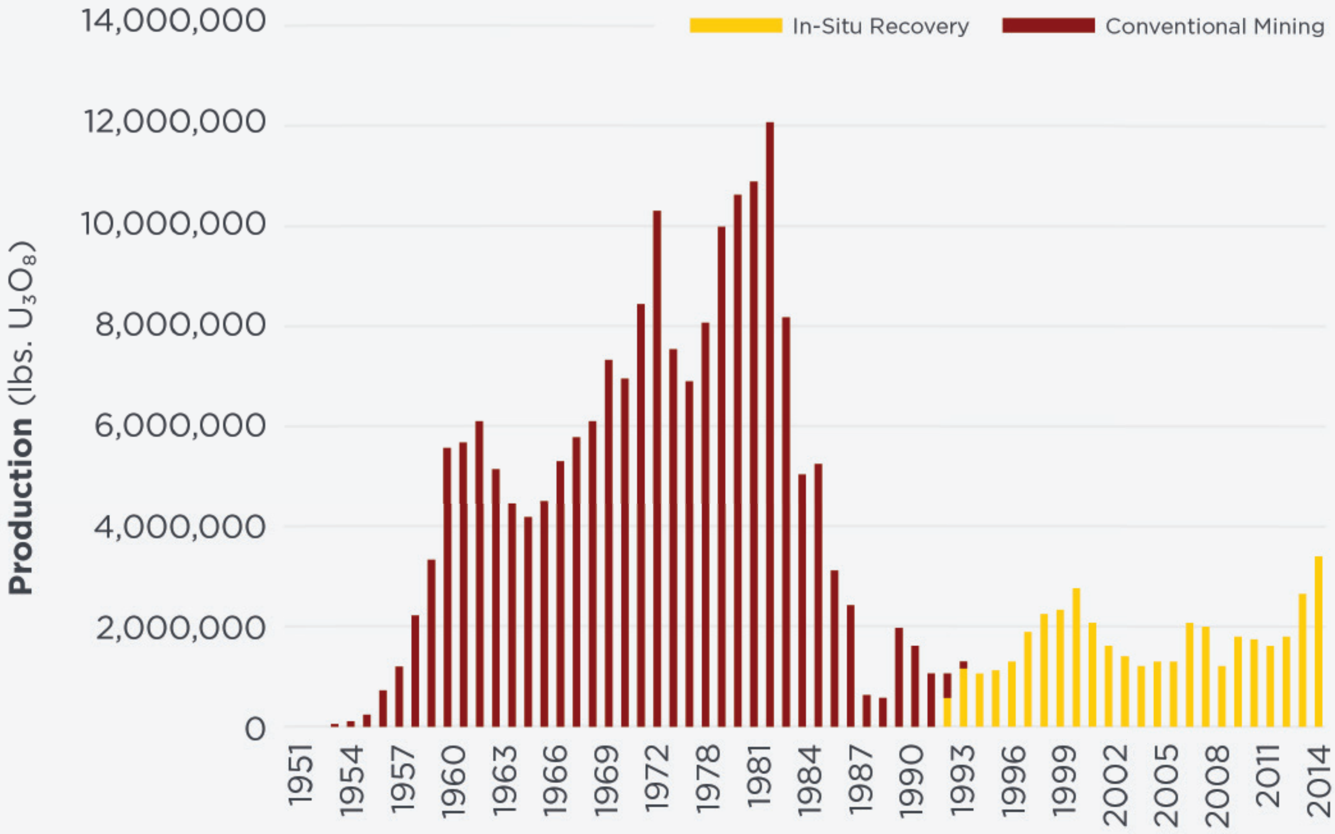
Technological developments are found to be a *minor advantage* for uranium extraction in Wyoming. The development of in situ recovery has opened new uranium resources in the State. Over time, in situ methods have become more refined, providing operators with more knowledge of optimal parameters to extract Wyoming reservoirs, and increasing cost effectiveness. Due to these innovations, Wyoming was able to continue uranium extraction at lower cost points and continued production, even as uranium prices reached all-time lows in 2018. This technologic innovation is applied in other regions, thereby not making Wyoming operations significantly more cost effective than in other regions.

Technology: Analysis

The first ever in situ uranium operation was tested in Wyoming at the Shirley Basin uranium project during the 1960's (Mudd, 2001; World Nuclear Association, 2020). Wyoming is well suited to in situ recovery due to fluvial (river) sandstone deposits. These uranium resources are deposited in natural aquifers allowing for wells to extract the uranium through chemical interactions with the reservoir. Since this point, in situ uranium recovery has grown to account for 55% of global production (World Nuclear Association, 2020).

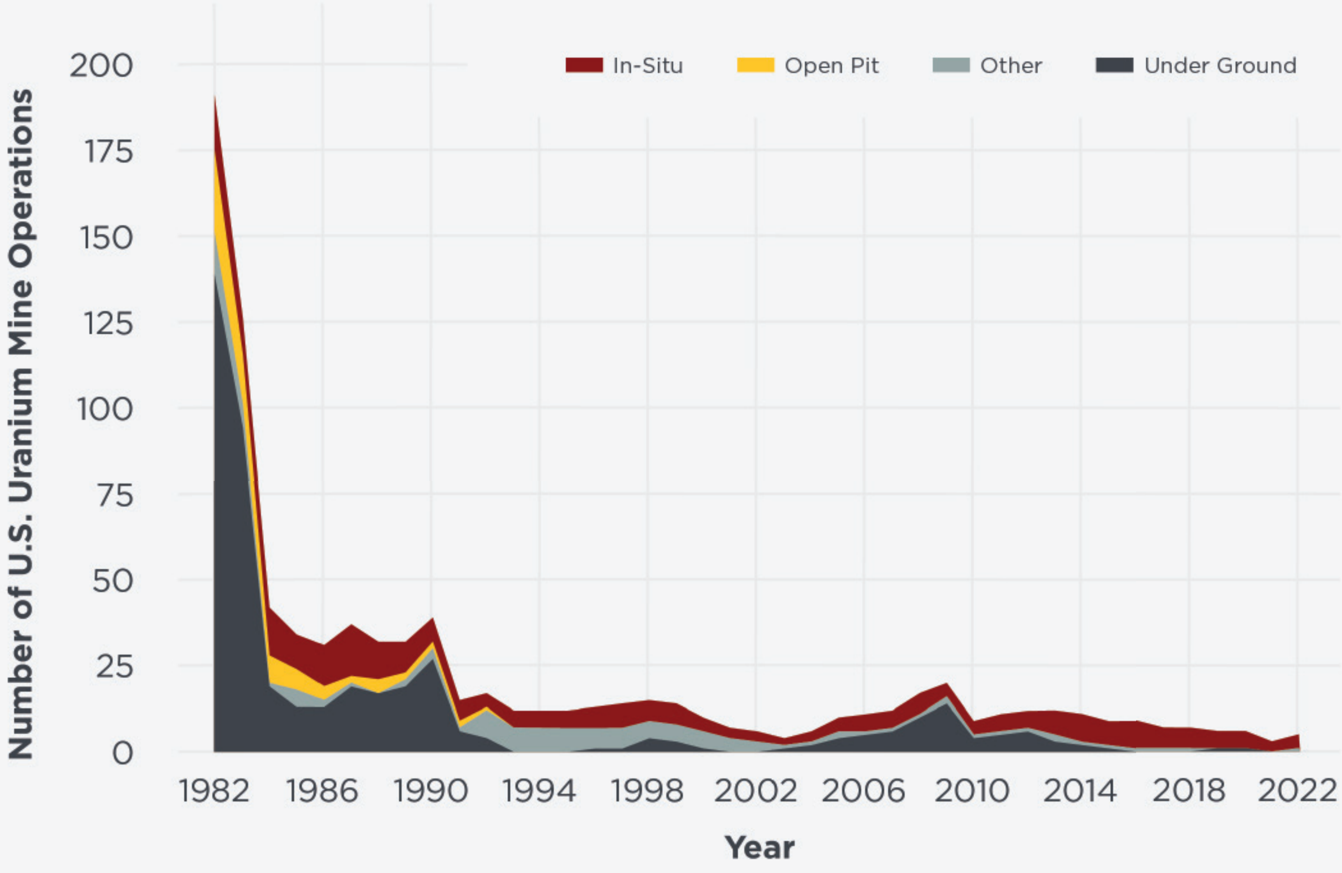
This shift in extraction methods has changed the Wyoming uranium industry, since 1993 all Wyoming produced uranium has come from in situ operations. Figure 14 presents the total production of uranium in Wyoming, with separate values for in situ and conventional operations.

Figure 14:
Wyoming Uranium Production and Technology Used (Wilson, 2015)



Notably, Wyoming operators rapidly adopted the ISL technology, following low production in the 1980's. This adaptability allowed Wyoming operations to grow in U.S. market share jumping from 4% of U.S. production in 1984 up to 37% in 1993 (see Figure 5). Figure 15 shows the number of active uranium operations in the U.S. by mining method. While underground operations did reopen in the mid 2000's during a period of high uranium prices, these operations were subsequently retired, leaving only in situ operations. Having already switched to in situ methods, Wyoming operations grew in market share.

Figure 15:
Number of Operating Uranium Operations by Technology Used[53]

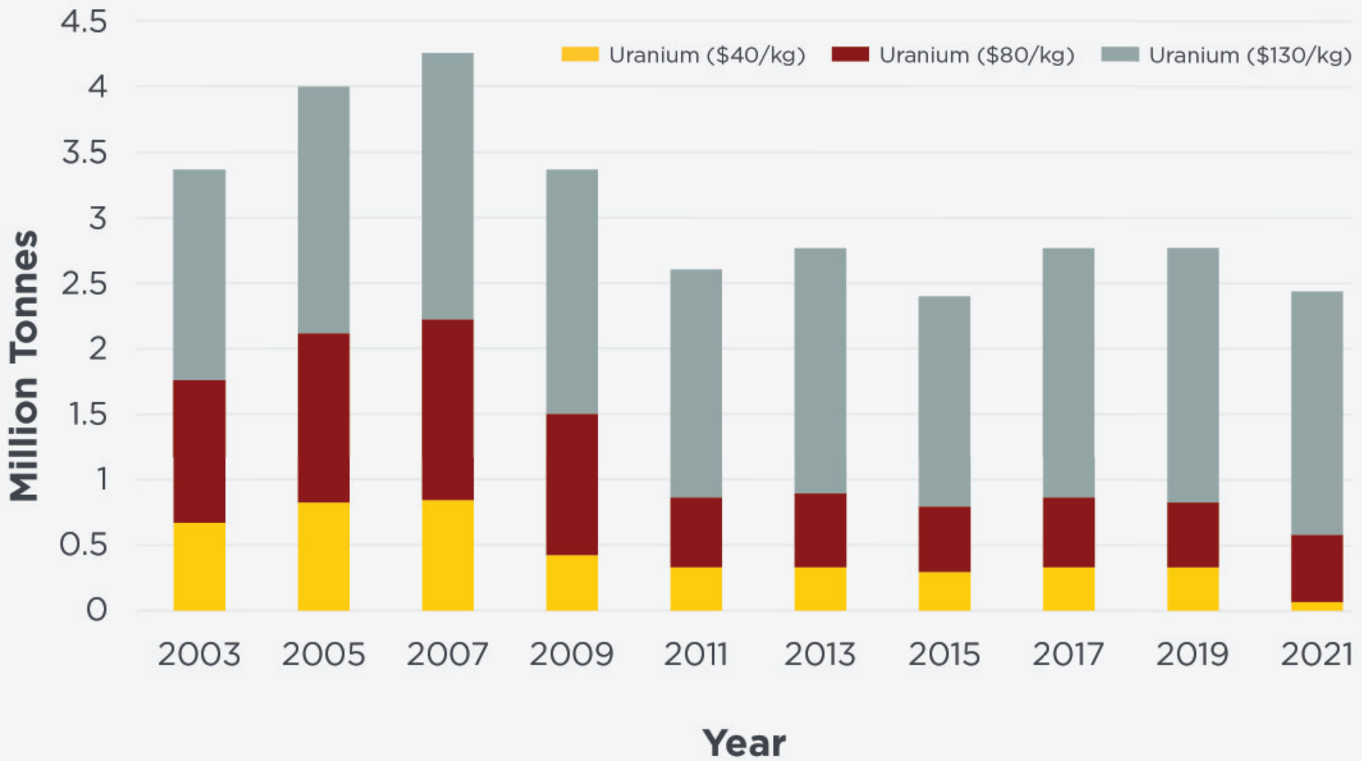


[53] Data collected from reports (EIA, 2005a, 2005a, 2007a, 2009a, 2010a, 2011a, 2014a; Vest, 2012, 2013; EIA, 2008a, 2015a, 2016a, 2017a, 2019a, 2020a, 2021a, 2022a, 2023, 1995, 1994, 1997a, 1999, 2000, 2001, 2003, 2002, 2003, 1997b)

Much of the technological innovation of ISL mining comes from localized acquired knowledge. The optimal dissolving agent used to maximize production depends on the geochemistry of reservoir. For example, carbonate is basic reducing the effectiveness of acids. Restoration costs are affected by characteristics such as surrounding aquifer PH, the sandstone composition, and even the mixture of microorganisms (Borch et al., 2012; Hu et al., 2011; Yang et al., 2023; Zammit et al., 2014). Early ISL operations in Wyoming suffered from a lack of information about these characteristics resulting in additional operating costs and reduced output. However, with increasing data and geologic understanding, the range of technologies available to mitigate issues developed, improving productivity and resulted in cost reductions. (McDowell et al., 2017)

Total reserves of uranium are estimated by calculating the reasonably expected volume of uranium that can be recovered economically at a target price, meaning that price and technology play a key role. Figure 16 provides estimates of uranium reserves from traditional operations at different prices across time and Figure 17 provides the same information for in situ mining.

Figure 16:
Global Mined Reasonably Recoverable Uranium[54]



[54] Data for figures iteratively collected from The Nuclear Energy Agency uranium Redbook reports (NEA, 2003, 2005, 2007, 2009, 2011, 2011, 2014, 2016, 2018, 2018, 2020)

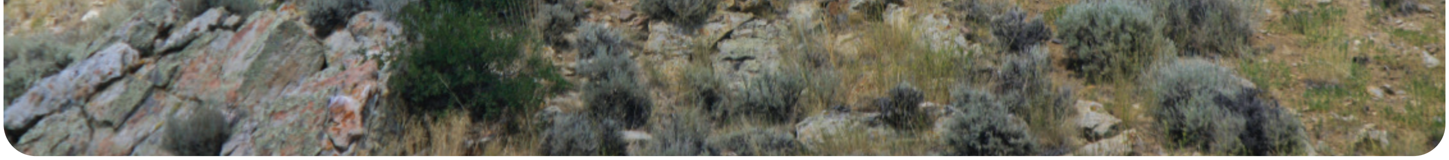
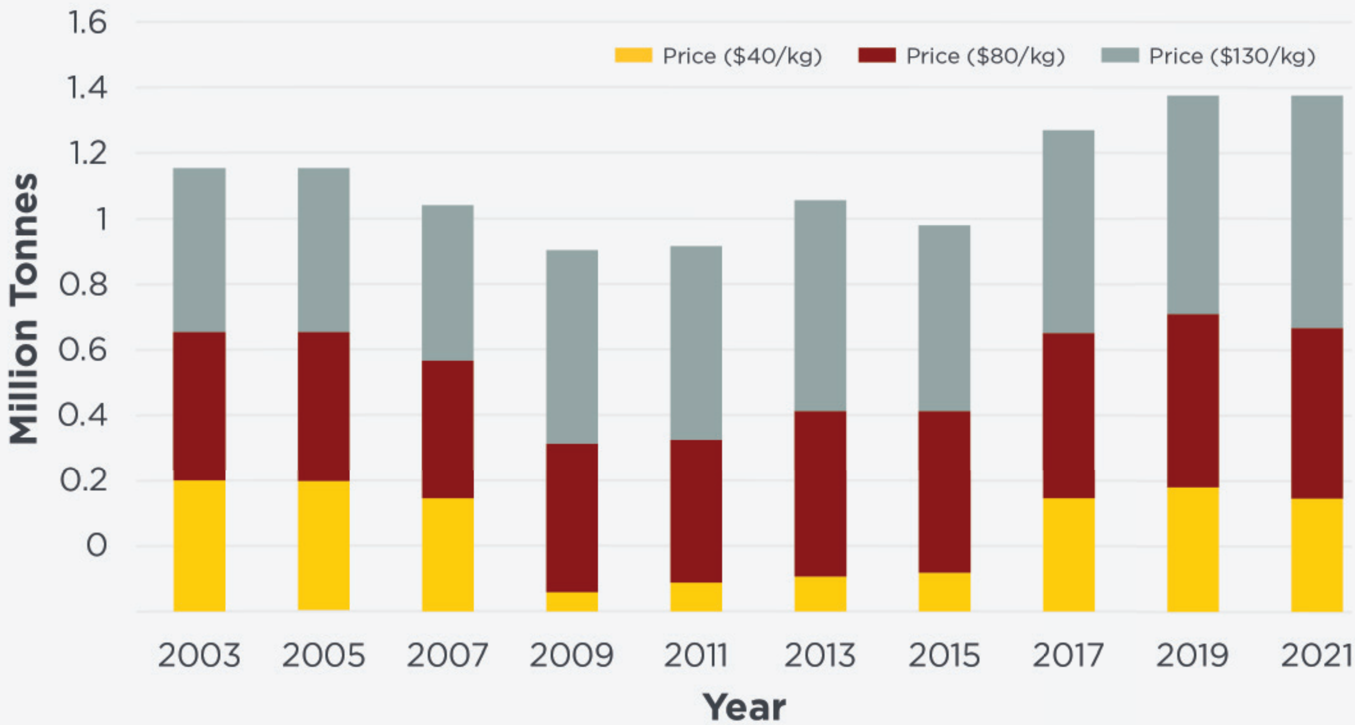


Figure 17:
Global In-Situ Reasonably Recoverable Uranium



Over time, the dynamic of uranium mining has evolved. At the $130 per kilogram price threshold, in situ mining represented 25% of estimated reserves in 2003, with a slight uptick to 32% in 2021. However, at the lower price thresholds, in situ mining has become increasingly relevant. In 2003, at the $80 price, in situ made up 32% of uranium reserves, but by 2021 this climbed to 57%. At the $40 per kilogram threshold, in situ mining makes up nearly all known extractable resources.

To mitigate remediation costs, Wyoming has innovated alkaline ISL methods, which dissociate fewer particulates into the groundwater. This method only recovers between 60-70% of uranium ore compared to an 80-90% recovery rate when using acid (McDowell et al., 2017). For Wyoming operations with high initial water quality and carbonate levels above 2%, this methodology reduces restoration cost improving operation profitability. Other technological developments have the potential to further reduce restoration costs by targeting uranium more directly with the leachant in conjunction with new well spacing configurations (Krumhansl et al., 2009)

These continued innovations in ISL mining provide an advantage for uranium operations in the State by increasing access to Wyoming deposits. However, this innovation has been adopted globally, and is, therefore, not unique to the State. The current state of uranium recovery technologies places the technological score as *minor advantage*.

LOCATION

Location: Scoring Criteria

Location is the most foundational factor of the uranium mining industry. Without uranium ore deposits, the industry cannot be developed no matter how favorable the other economic conditions are. Wyoming has a *major advantage* in location due to the accessibility of uranium ore in the State. However, some location factors interact with legal requirements, reducing the advantage of operations in Wyoming.

Location: Analysis

Three location factors were identified as affecting uranium mining production: 1) Ore characteristics; 2) Geochemistry; 3) Water quality. Of these factors, ore characteristics and geochemistry directly affect operating efficiency. Water quality, population, and geochemistry affect profitability indirectly through policy interactions. Notably, geochemistry falls into both categories of costs, affecting regulatory compliance costs, as well as direct operation expenditures. Infrastructure and electricity grid limitations were not found to limit uranium extraction in the State.

The starting point for the location analysis is the geologic distribution of uranium. The identified global uranium reserves are shown in Figure 18.

Figure 18:
World Reserves of Uranium (International Atomic Energy Agency, 2023)

(<USD 130/kgU as of 1 January 2021)

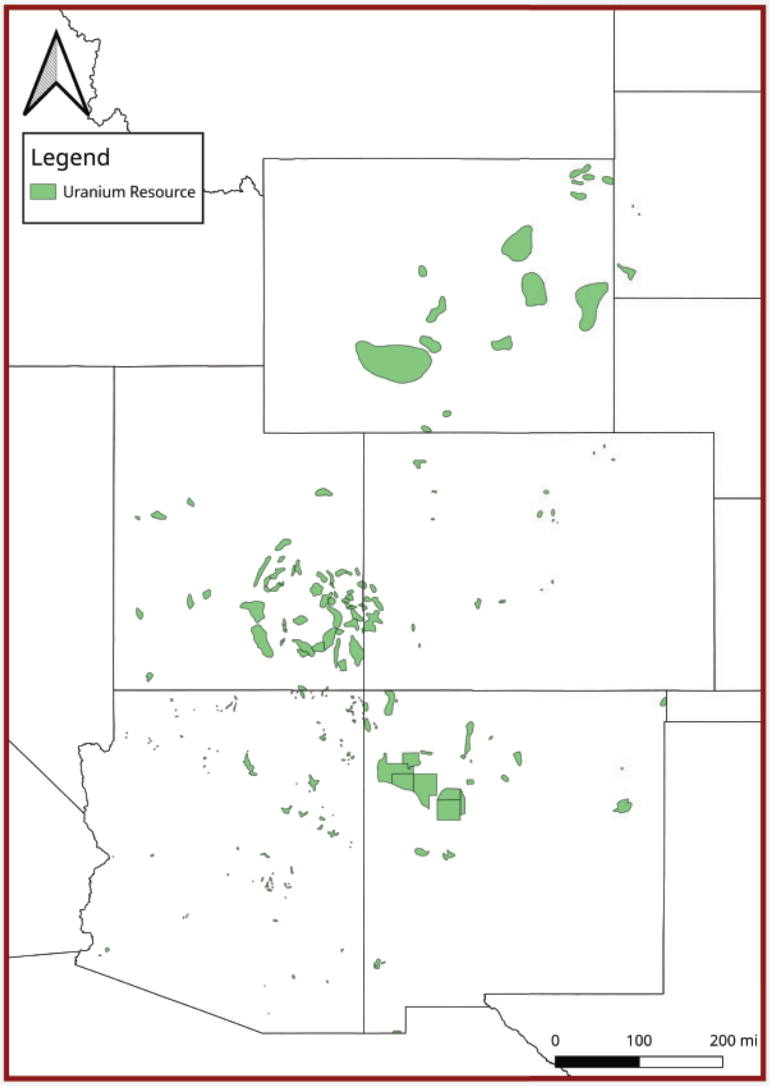
*Secretariat estimate or partial estimate.
The global distribution of identified recoverable conventional uranium resources in the <USD 130/kgU cost category among 15 countries, which are either major uranium producers or have significant plans for growth of nuclear generating capacity, illustrates the widespread distribution of these resources. Together, these 15 countries are endowed with 95% of the global resource base as specified above (the remaining 5% are distributed among another 24 countries). The widespread distribution of uranium resources is an important geographic aspect of nuclear energy inlight of security of energy supply.

As discussed in Section 3.4, reserves are driven by total exploration and cost estimates, making them an imperfect measure of geologic availability. Nevertheless, Figure 18 provides important context for global resource availability. The U.S. has the 14th most uranium resources[55] but due to the heterogeneous distribution of uranium, this accounts for only 1% of all world reserves.

[55] At $130 per kilogram of uranium

However, U.S. uranium reserves are themselves unevenly distributed. The most recent estimates of U.S. uranium reserves at $100 per pound places Wyoming at 36.35% of all U.S. reserves (Energy Information Administration, 2010a). Since Wyoming ore has a lower-than-average uranium grade, the percentage of total reserves is higher than this at 52.7% of all technically recoverable uranium in the U.S. (Energy Information Administration, 2010a). The development of in situ recovery technology has improved the economic viability of lower grade ore present in Wyoming, leading to a trend of increasing reserves in the State. Taken together, Wyoming is estimated to contain 0.36% of global uranium reserves, which is significant for such a small region. Wyoming has 7.3 times more uranium reserves than an average area of the same land mass[56].

Figure 19:
Location of Regional Uranium Reserves[57,58]



[56] 7.31=0.36% • (197•10^6 sq miles of land on earth)/(97•10^3 sq miles in Wyoming)

[57] Data sources for the map provided as shape files by the EIA (EIA, 2020c) .

[58] Texas and Virgina reserves excluded for clarity. The Coles Hill Deposit is not extractable due to a uranium mining moratorium in the Virgina. Texas has developed uranium resources.

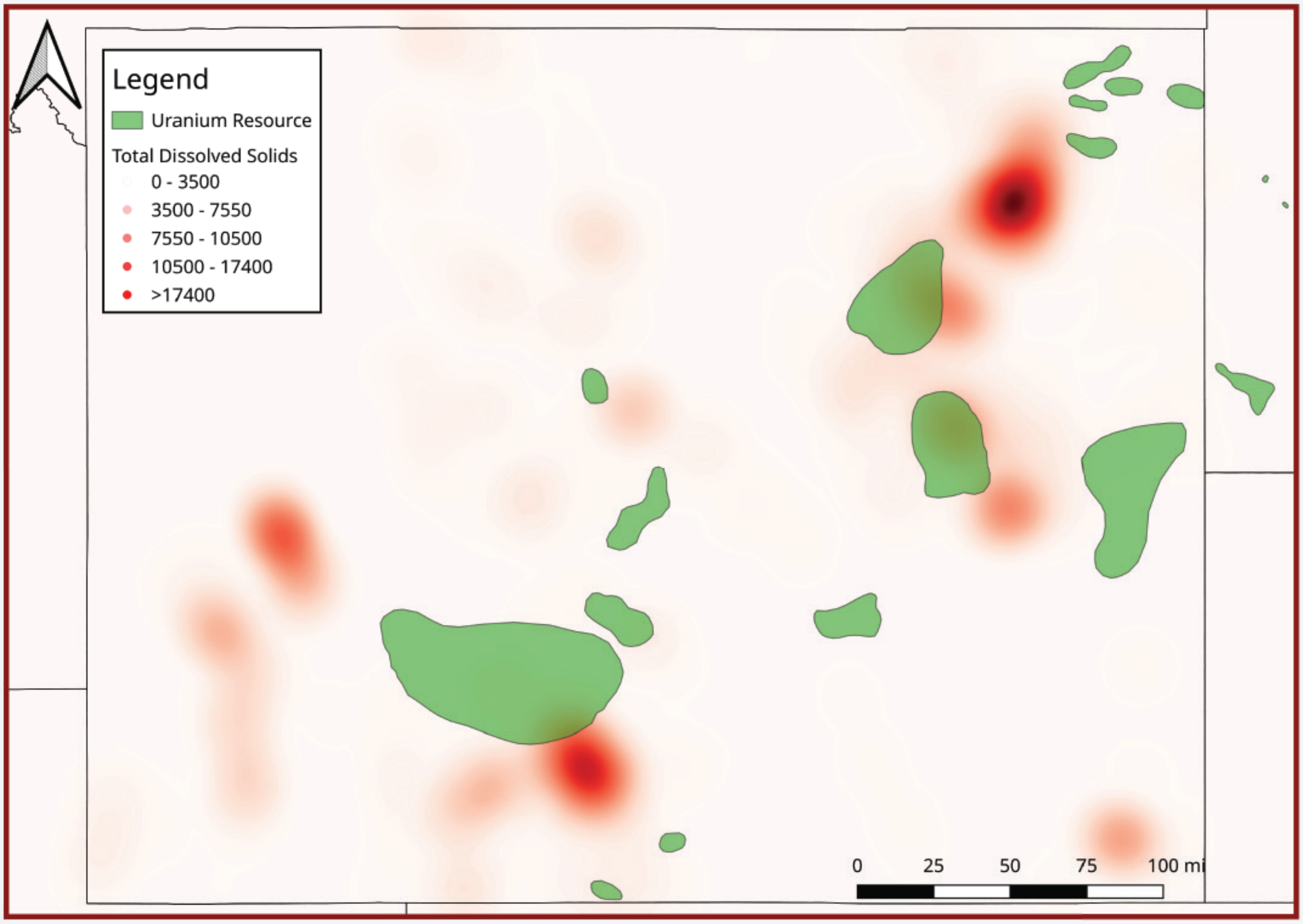
Legal obligations of uranium recovery operations, discussed in Section 3.9, include restoring the groundwater to a pre-mining state, meaning that higher initial groundwater quality increases production costs. Wyoming has high average water quality and all uranium operations in the State were drilled in areas with potable water or water usable for agriculture. Other nations with uranium operations, such as Australia and Canada, have uranium sources located in aquifers with high total dissolved solid (TDS) levels (Commonwealth of Australia & Lambert, 2010; Fyodorov, n.d.). This creates a disadvantage to Wyoming operators that must expend more resources restoring groundwater after production ends than their competitors in Australia and Canada. Interestingly, if Wyoming was located over lower quality groundwater, this would provide a location-based advantage for the State.

To see how water quality levels can affect uranium production in Wyoming, a heat map of dissolved solids in groundwater is overlayed with uranium reserves in Figure 20. Groundwater samples from wells less than 2000 feet deep are used to predict the average TDS solid in between wells (Wyoming State Geological Survey, 2020). Areas in red have aquifers with elevated TDS levels. Uranium reserves that overlay a red region, can be produced at a lower cost, because less restoration is necessary to reach pre-mining dissolved solid levels.

Most uranium bearing aquifers in the State are in a low TDS area as estimated in Figure 20. This reduced the location advantage of the uranium resource.

To determine if Wyoming infrastructure places a limit on uranium production, managers of in situ projects in Wyoming were contacted. Neither access to electricity nor access to reliable roads were reported as creating operation constraints for Wyoming uranium recovery.

Figure 20:
Wyoming Uranium Reserves and Water Quality[59]



These location factors provide a *major advantage* for the uranium mining industry in Wyoming. Most importantly, the State possesses the natural resources necessary to establish industry. Further, most of these resources can be extracted due to the low population density of the State. Counteracting these benefits are the additional operation cost for operations because of the States high water quality levels. Despite the high-water quality in the State, Wyoming remains one of the few States with the resources necessary to maintain a uranium mining sector placing the score in the *major advantage* category.

[59] Data sources used to create Figure 17 come from (EIA, 2020c; Wyoming State Geological Survey, 2020)

LEGAL

Legal: Scoring Criteria

Federal regulations are scored as a *moderate obstacle* for uranium operations in Wyoming. This contrasts with State rules which provide a *moderate advantage* for Wyoming uranium operations. A significant challenge to the uranium extraction industry is the legal standards of aquifer remediation. At low uranium prices such rules are a severe obstacle, placing operating costs above potential mining revenue leading to operation shut ins. At higher uranium market prices such as are present in 2024, this obstacle is reduced to a *moderate obstacle*. Assuming prices of $90 per pound, the average effect of federal rules is a reduction in uranium mining output of 3%.

The State of Wyoming acquired regulatory authority over uranium operation management beginning in 2016. Based on operation cost data, this resulted in lower licensing costs for Wyoming projects. Compared to a baseline uranium operation in another state Wyoming operations have $2 million lower costs. This Wyoming specific cost advantage places the State legal score as a *moderate advantage*.

Legal: Analysis

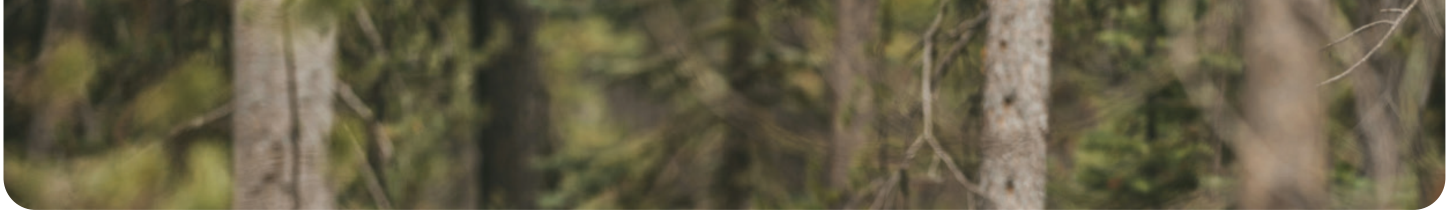
Legal barriers are identified as the most significant obstacle to developing uranium operations in Wyoming. The legal costs are primarily driven by the application of the Safe Drinking Water Act (SDWA), which adds significant restoration costs to uranium mining projects in Wyoming. Legal costs can also be impacted by 40 CFR Part 61 Subpart W which regulates both tailings and fluid retention impoundments.

The regulation restricts the use of injection wells, such as those used for in situ mining, from operating without enrollment into an underground injection program.

> "Any underground injection, except into a well authorized by rule or except as authorized by permit issued under the UIC program, is prohibited." 40 CFR §144.11

Further the regulation states that

> "No owner or (well) operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water."



Based on these restrictions, uranium mining companies in Wyoming must establish Class III injection wells for solution mining pursuant to the appropriate UIC program (US EPA, 2015a). In order to develop a Class III well, operations must receive an aquifer exemption (US EPA, 2015b). An aquifer exemption identifies the proposed aquifer for in situ mining as not a potential drinking water source. This requirement can be met by either demonstrating the aquifer is not a safe drinking source due to natural occurring minerals or that it is unlikely to become a drinking source for economic reasons.

Wyoming has been granted primacy by the EPA over the aquifer exemption process. The relevant definition:

1. An aquifer which contains fresh and potable water may be exempt from the definition in Chapter 1, Section 2(a), if the Commission by order, after due and legal notice and public hearing, determines any of the following criteria exists:

   A. It is mineral, hydrocarbon, or geothermal energy producing;
   B. It is situated at a depth or location which makes recovery of fresh and potable water economically or technologically impractical;
   C. It is so contaminated that it would be economically or technologically impractical to render the water fit for use as fresh and potable water;
   D. It is located over a mining area subject to subsidence or catastrophic collapse; or,
   E. It has a total dissolved solids (TDS) of more than five thousand (5,000) and less than ten thousand milligrams per liter (10,000 mg/l) and is not reasonably expected to be used as fresh or potable water." 055-4 Wyo. Code R. § 4-12

After meeting these guidelines, uranium operations must install monitoring wells around the produced aquifer's perimeter. These monitoring wells are used to sample water around the mine, ensuring that no movement of contaminates into non-exempt aquifers takes place as required by SDWA (International Atomic Energy Agency, 2016; US EPA, 2015a).

The law also requires that groundwater restoration take place after the retirement of a well. The mining cycle begins by drilling wells in high yield regions and moving down the roll front over time. This means the retirement costs are not limited to the final site closure but are a rolling cost over the project. As part of this process, a bond or collateral is required to ensure that the groundwater restoration will take place (Kuhn, 2006). This is frequently done through a bond agency, which issues a surety bond covering the total estimated cost of restoration in cases of default. The mining company must put up collateral which is returned after restoration is completed and pays a market rate for the value of the bond.

Restoration requirements mandate that the water quality of the produced aquifer be restored to pre-mining pollution levels. This is accomplished by either showing all 20 constituents are at or below initial tested levels, or that the category of aquifer is the same[60]. Wyoming oversees these restoration requirements as an agreement state. The Department of Environmental Quality allows an aquifer to be restored to levels based on the water use classification (Wyoming Department of Environmental Quality, 2018). For example, water with an initial quality only suitable for industrial use needs to be restored to the maximum constituent levels of industrial use. However, a clean aquifer suitable as a source of drinking water must be restored to the standards set for drinking water. Where the Wyoming water quality standards are different from federal rules, the strictest standard is applied. As an example, if Wyoming includes radon as constituent in the water classification standard a uranium bearing aquifer may be labeled as an industrial use water source. Since radon is generated from uranium many uranium producing aquifers will have naturally elevated levels of radon. However, if federal guidelines do not include radon in water classification standards, the same aquifer will be classified as a suitable drinking water source. In that instance drinking water restoration standards will be applied.

In a typical restoration, multiple steps are taken to reduce post-mining increases in aquifer chemical constituents. The first stage of aquifer restoration is typically what is termed groundwater sweep. This is the entire pore volume of groundwater within a wellfield area is brought to the surface and disposed of, either through disposal well injection or other techniques. The groundwater sweep process draws in native groundwater from outside the mining zone with lower dissolved solids refills this pore space (Saunders et al., 2016; Yang et al., 2023). Other projects manage the produced water using evaporation ponds, or water treatment followed by surface discharge (Wyoming Department of Environmental Quality, 2018). If surface discharge is applied, the constituent concentration of the water must be tested before being applied to the ground (Wyoming Department of Environmental Quality, 2018).

Next, the water is run through reverse osmosis filtration and water treatment processes to reduce pollutants to allowable levels. Once these thresholds are reached, the monitoring wells are used to track mineral content and PH. If the decline rate of these factors is shown to be stable, the restoration is complete, bond collateral is returned, and the operation can be plugged and abandoned. (International Atomic Energy Agency, 2016; Saunders et al., 2016)

When evaluating the importance of these costs, it is useful to compare regulations across the globe. The top four uranium producing countries are Kazakhstan, Namibia, Canada, and Australia (International Atomic Energy Agency, 2023).

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[60] See 40 CFR 192 (Environmental Protection Agency, 1983)

Kazakhstan does not require any groundwater cleanup after a mining site is approved, contributing to significantly lower operating costs for Kazakhstan operations (Clark et al., 2018; Fyodorov, n.d.). The evaluated Wyoming in operations had an average total cost of $46 per pound[61] of uranium produced compared to the Inkai Kazakhstan operation which has total costs of $23.43 per pound (Clark et al., 2018). These costs differences are not entirely caused by the elimination of groundwater restoration. Another contributing factor is the use of acid based lixiviant.

Most Wyoming operations use an alkaline lixiviant, such as baking soda to dissociate uranium (Gregory & Drean, 2015; Kehoe, 2023). Acid has been found to be a more cost-effective means of extracting uranium, including in Wyoming, and total uranium recovery increase from about 80% to 90% (McDowell et al., 2017; World Nuclear Association, 2020; Yang et al., 2023). In 2019, the Ross Project became the only licensed uranium operation in Wyoming using acidic leaching, partly due to the lower carbonate content of the produced deposit (World Nuclear News, 2019). Acid lixiviants dissolve carbonate rock, which releases additional dissolved solids into the aquifer (Mudd, 2001; World Nuclear Association, 2020).

Unlike Kazakhstan, Canada and Australia have comparable water restoration requirements as the SDWA. However, the circumstances of the mining in these locations make such requirements inapplicable. The operation with the highest production in Canada also has the highest ore grade in the world (Bishop et al., 2015). This makes traditional mine and mill techniques more cost effective than in situ mining and in turn mitigates the groundwater restoration costs. In Australia, the in situ produced uranium deposits have very high dissolved solid levels, making the aquifers unsuitable for either drinking water or industrial uses (Commonwealth of Australia & Lambert, 2010). Due to these geologic characteristics, Australian operations are not required to perform the same filtration cleaning as completed by Wyoming operations. Since the standards require that the water quality be returned to the pre mining use, no level of pollution in the Australian operations effects the final possible water uses.

[61] The technical reports for uranium mines in Wyoming include (Malensek et al., 2022; Moores & Western Water Consultants, Inc, 2021b; Schiffer & Moores, 2023, 2023; Western Water Consultants, Inc, 2024a)

The in situ best practice guide for Australia states:

> "The best documented ISR mines have been in the US, mainly in Wyoming, Nebraska and south Texas....In the US, operators are required to remediate affected groundwater within the mine site to the pre-mining average constituent concentrations (restoration standard) or drinking water maximum contaminant levels (whichever is higher), regardless of sequential land uses.... In contrast, the uranium at Beverley (South Australia), occurs in isolated sand lenses that are surrounded by impermeable clay-rich strata and contain naturally poor-quality saline, radioactive and stagnant groundwater. As the Beverley aquifer had no use before and has no foreseeable use after recovery of uranium, natural attenuation was considered appropriate rehabilitation for the situation at Beverley; there is an extensive monitoring program to measure the progress of natural attention." (Commonwealth of Australia & Lambert, 2010)

Wyoming, on the other hand, has high starting quality of water. The reviewed environmental reports placed the starting groundwater quality as either usable for domestic or livestock. This means an identical mining operation in Wyoming, producing the same amount of dissolved solids in an aquifer, will require more restoration costs than one operating in Australia.

To identify the range of costs added to producers by these regulations, five technical reports for Wyoming were evaluated. These include the Gas Hills Uranium Project, the Nichols Ranch Project, the Lost Creek Uranium Project, the Ross Project, and the Shirley Basin Project (Malensek et al., 2022; Moores & Western Water Consultants, Inc, 2021b; Schiffer & Moores, 2023; Strata Energy Inc., 2010a, 2010b; Western Water Consultants, Inc, 2024a). The project plans were used to identify the change in net present value of the projects due to restoration costs. Estimated costs include restoration bonds, groundwater restoration, and deep disposal. Costs are calculated in terms of dollars per pound of uranium produced to approximate the effective change to the uranium supply function.

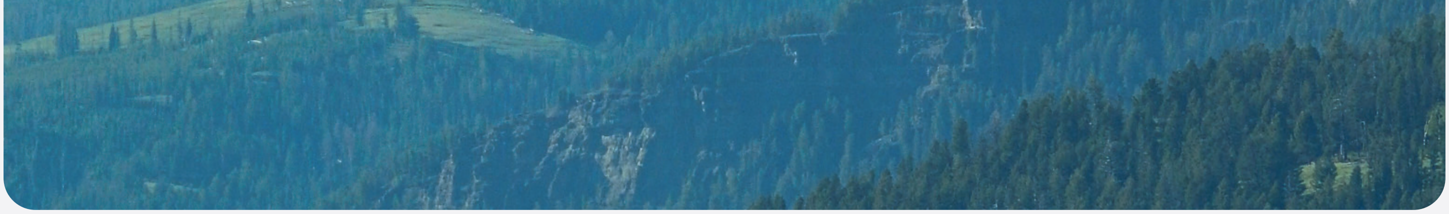
Cost and revenues were discounted at 10%, to calculate the net present value of the operations. When groundwater restoration costs are not explicitly separated from overall restoration costs and 66% of the total is assumed to be attributable to aquifer remediation based on surety bond data (Uranerz Energy Corporation, 2010). The average cost estimate was $4.30 per pound, with a low of $1.67 per pound in the Lost Creek Project, and a high of $10.84 per pound for the Shirley Basin Project This has the same production outcome as Wyoming operators receiving $4.30 less per pound of uranium on the market. The resulting effect of this cost increase is dependent on the market price. For example, the average operating cost of these recovery facilities were estimated to be $18.40 per pound of uranium, but with an average total cost of $47.29 per pound. At a price of price of $50 per pound, this restoration cost precludes the operations from being developed with any profit. However, at a price of $100 per pound, the restoration costs can be overcome and each of these operations would develop. The added cost also cuts into profits and, consequently, Wyoming tax revenue. The State can expect to receive 8 cents less in tax revenue per pound of uranium, or $2.3 million over each of the four operations, due to these added restoration costs.

The total effect of this regulation on production can be estimated with the results from Table 3. If prices are above $42 per pound but below $47 per pound the regulation is a *sever obstacle* completely halting all uranium production in Wyoming[62]. At higher prices, the result is a reduction in output proportional to the ratio of the production cost to the price of uranium. For example, at $50 per pound of uranium the restoration requirements reduce production by 5.6% and at $100 per pound production is reduced by 2.3%. This makes the regulatory obstacle score dependent on the market conditions presented in Section 3.4. Below $50 per pound the score is a *sever obstacle*, at prices above $60 per pound the score is *moderate obstacle*.

The outcomes from the SDWA can be considered under an economic lens. Economic policy analysis considers the costs and benefits of rules with the goal of finding the best societal outcomes. In the case at hand, the restoration costs of aquifers need to be weighed against the value of cleaner groundwater to judge how much restoration is optimal.

The usability of aquifers for drinking, ranching, and recreation are all relevant policy considerations for Wyoming. At the same time, the income from the uranium recovery, tax revenue, and economic development provides benefits to the State. The economically efficient policy provides enough groundwater restoration that the marginal benefit of cleaner water equals the marginal cost of restoration. This balance does not exist under the current regulatory structure.

[62] This range is based on the average startup cost of mines reviewed but is not an exact estimate. Rounding the results may represent the actual decisions of miners more accurately. So, in the range of $40-$50 these rules halt all production in Wyoming.



Providing a detailed estimate of the optimal restoration thresholds is beyond this report's scope. However, there is evidence that the current policy is too restrictive, and operations are required to spend more on restoration than is socially optimal for Wyoming.

Economic factors are evaluated to determine if the current restoration requirements are efficient. Six points were identified to support the conclusion. Each of these facts speak to the relative value of aquifer restoration, the social costs of lowering restoration from current requirements, or present alternatives to restoration that provide similar benefits but at lower cost. These include:

1. Exempt aquifers cannot be used for public drinking water.
2 Under current restoration requirements water quality must be restored to original levels[63]
3. Aquifer contaminates are naturally contained to a limited area around the operation.
4. Alternative sources of groundwater are available.
5. Alternative methods of groundwater restoration are available.
6. Economic studies of groundwater value indicate restoration costs exceed social benefits.

Points 1-3 speak to economic inefficiencies in the current regulatory structure. These indicate that the added value from restoration is limited, but restoration costs are elevated by current standards.

Points 3-6, provide a framework for a hypothetical economically efficient restoration policy. Alternative methods of achieving the same social benefits as aquifer restoration are available. Further, relaxing post operation constituent limits will increase total economic welfare.

An obvious economic inefficiency of the SDWA application is that aquifers must be exempted as drinking water sources before uranium can be extracted from the aquifer. At the same time, the operators must restore the aquifer to the starting water quality standard. If an aquifer has already been exempted, the restoration costs are unnecessary from an economic welfare perspective. A clean reservoir that is never used for any other purpose than uranium extraction provides the same economic benefit as a dirty reservoir. In both cases, the opportunity cost of alternative uses is nearly zero and the value of low-cost mining outweighs the benefits of restoring the aquifer.

[63] The law requires that the aquifer is restored to a pre operating state, but alternative standards are allowed when complete balance is impossible. Alternative standards typically require any increased particulate pose no additional health risk compared to background levels.

Another economic issue for consideration is the elimination of certain aquifers as a uranium source. An aquifer that cannot receive an exemption may still provide economic net benefits if in situ projects are allowed to operate. Consider a possible in situ operation that is near a city limit and meets the standards of potable water. This aquifer could not receive an exemption because the water may reasonably be used as a public water source. However, when the operation is completed, under federal requirements, the groundwater quality will be restored to original levels. Since the groundwater is the same quality as the water that existed before the uranium recovery, the projects created no cost to future water users. Even though there are no social costs to the extraction such a facility cannot operate under current rules. This limits uranium production which would generate private income, jobs and State tax revenue.

A typical uranium recovery facility does not affect the water quality of adjacent properties. Without spillover costs to neighbors, market prices lead to efficient economic outcomes (Chavas, 2022). If uranium extraction did create costs to neighbors, then some restoration requirements that lower operation profit would create net benefits, otherwise such requirements reduce total economic gains.

Some facts make spillover costs to neighbors from uranium extraction plausible. Exempt aquifers cannot be used for public water sources, but they can be used for private groundwater wells. In fact, some Wyoming residential wells are within two miles of active in situ operations, creating a potential risk of contamination in adjacent aquifers (The Natural Resources Defense Council, 2016).

In practice, Wyoming in situ projects are well contained by geologic barriers. Over time, the dissociated minerals from mining equalize with the surrounding water and become immobile in a process called attenuation (Borch et al., 2012; Hu et al., 2011; World Nuclear Association, 2020). The properties of the aquifer and mineral content also affect this risk of contaminating nearby aquifers. Most of the dissolved solids created from the uranium extraction process are large and relatively immobile. Permeability[64] and groundwater flow rates determine the rate of drift of these elements. A case study of these two factors is provided in Figure 21, showing how total dissolved solids from a mining operation without remediation are forecast to migrate over a hundred years.

[64] A measure of the size of the sandstone grains. Larger grains reduce fluid flow friction (McCain William D Jr, 2017).

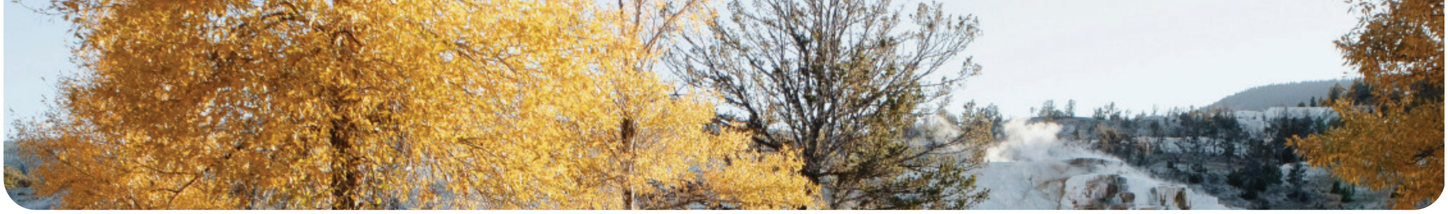
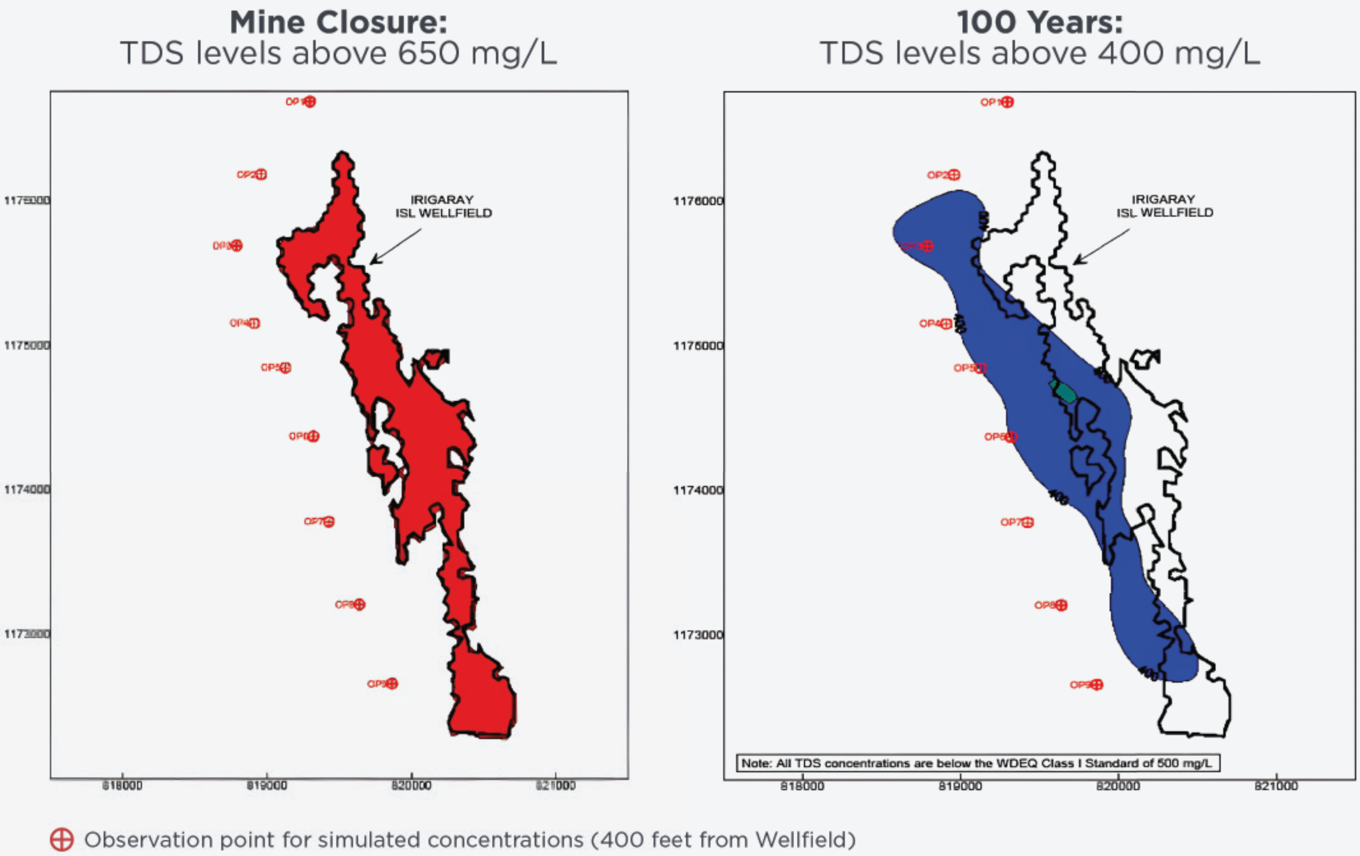


Figure 21:
Drift of Total Dissolved Solids from Uranium Over 100 Years at Irigaray ISL Field (Thomas, 2024)



The forecast predicts that the primary pollutants from the Wyoming Irigarray operation would have some natural attenuation over 100 years, dropping from a peak of over 650 mg/l to 400 mg/L. This is a lower attenuation rate than in regions such as Kazakhstan which can see full equalization over this time frame (Yazikov et al., 1985). However, the drift of the dissolved solids is very slow, with the total movement only traveling about 500 feet in any one direction. This is comparable to other simulated in situ operations, which found the maximum movement of lixiviants over four hundred years to be half a mile (Roshal & Kuznetsov, 2006).

While the drift of a plume must be evaluated on a case-by-case basis, Wyoming operations with similarly slow drift pose little risk of contaminating nearby aquifers. A groundwater well drilled only 1000 feet away would not have an increase in constituent levels caused by an unremediated in situ operation.

There are examples where increased constituent levels were measured outside of the in situ recovery area, but no cases were identified where this affected neighboring properties. A pertinent instance of this occurred in 2011, at the Wyoming based Highland Uranium Project[65]. This constituent increase occurred due to a well casing failure during operation (Leftwich, 2011). Future casing failures were remedied by adjusting the drilling and completion process (Wright, 2013). However, an NRC review of water samples at multiple U.S. in situ projects found no cases of elevated constituents beyond the monitoring boundary, which is typically one quarter of a mile (Nuclear Regulatory Commission, 2014). This limits the economic cost analysis to the direct mining expanses and suggests that current restoration requirements add to project costs, without providing the potential benefit of improving the water quality to nearby residents.

One method to identify polices that will maximize the economic benefits of uranium extraction in Wyoming is a cost benefit analysis of in situ projects. However, there is not enough data to complete this analysis for Wyoming in situ sites. Instead, a literature review is performed which identifies the value of increased groundwater quality, which is then compared to the cost of restoring a in situ site.

The market price of land reflects an array of attributes associated with the property including groundwater water quality (Rosen, 1974). The land price of uranium producing areas is compared to the cost of aquifer restoration which provides evidence that current restoration requirements are more stringent than is economically efficient. If a in situ operation results in higher groundwater constituents, this in turn decreases the selling price of that land by some fraction of the original price. The difference between the selling price of the land at the initial aquifer constituent levels, and the price after the constituents are increased is the social value of restoring the aquifer back to original levels. If this difference is small than the restoration provides only moderate value to Wyoming citizens, if this difference is large there is justification to invest resources in restoration.

The social value of a restoration varies, depending on the starting price of land, the alternative sources of water, and the current use of the aquifer. However, the current aquifer restoration requirements make it impossible to measure the difference in land value directly. In all cases of uranium extraction, the aquifer is returned to a near pre uranium extraction constituent levels, so no data points exist to compare the value of land after the constituent levels are increased. Nevertheless, this information can be used to ascertain if the current regulations are economically efficient, and to provide a range of possible efficient policies.

[65] Now the Smith Ranch-Highland project

First the cost of aquifer restoration of Wyoming in situ operations is estimated from the available technical reports and found to average $15 million dollars[66,67]. This is compared to the value of land of Wyoming properties, that overlay uranium bearing resources as reported by various Wyoming county assessors. The average market price of the land in lease area of an in situ operation is estimated to be 3.2 million dollars[68] (EIA, 2020c; Wyoming Department of Revenue, 2024)[69]. Meaning that the average restoration cost is 4.7 times larger than the average total value of the land. This makes it implausible that current restoration requirements maximize welfare to Wyoming.

Only a fraction of the market price of the land is attributable to the aquifer, yet the costs applied to restoring the aquifer are multiple times larger than the entire land value. Despite the lack of detailed land sale price data, it can be concluded that economic welfare in Wyoming will increase if constituent remediation rules are relaxed, or even removed. The cost to restore the aquifer to initial consistent concentrations exceed the benefits to landowners from a restored aquifer.

To provide insight into a potentially efficient aquifer remediation policy a literature review is performed. Two relevant papers were identified that provide the estimated cost of increasing constituents in groundwater. The details of these studies are provided in Appendix (A). The predicted outcomes depend on the starting quality of groundwater, the use of the water, and the level of contamination. These models identify the total cost in terms of a ratio of the starting land value. The total cost of increasing dissolved solids in the ground water ranged from 0.3% to 15% of land values. These values are used to estimate a range of final restoration cost under an ideal policy. The maximum aquifer restoration efforts under a hypothetically efficient policy will cost between $9,600 and $480,000 dollars, for an average Wyoming in situ operation. When balancing these benefits of restoration with the total cost of restoration, economic welfare has been reduced by between $15 million and $14.5 million per in situ operation because of the aquifer remediation rules. This prediction is based on an average uranium recovery project, and individual project estimates depend on the actual conditions at the facility, and surrounding area.

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[66] The acreage weighted average land value of properties overlying uranium reservoirs in the State was identified to be $232 per acre. Of the projects reviewed the average total area was 13,686 acres.

[67] Discounted at 10% per year.

[68] The total lease area overstates the potential benefits of restoration since the area of land underneath a in situ operation is less than the size of the lease. The lease area includes land used for exploration, future production, and other buildings. For example, the Shirley Basin project has an area under pattern of 283 acres, but a lease area of 3,536; only 8% of the lease area is under pattern (Western Water Consultants, Inc, 2024c). Using the total area of the lease in the land value calculation biases the estimate of restoration value upward, giving the best possible chance for the policies to be identified as economic efficient. This gives credence the conclusion that restoration policy is too stringent, since this outcome won't change by modifying the area estimate.

[69] Wyoming legal parcels from assessor's offices were overlayed with a map of uranium resources using the software QGIS. Then the assed actual value of land was divided by the acreage.

Some factors suggest that the optimal aquifer restoration cost is closer to the lower bound estimate, than the upper bound. The value of water is set by quality and a groundwater users access to alternative sources. There are likely to be alternative sources of groundwater adjacent to the uranium recovery facility. Studies evaluating the health consequences of mining are confined to this immediate area, assuming a drinking water well will be drilled overtop of the historic operation (Ruedig & Johnson, 2015). However, an alternative source of groundwater is a well drilled at a location that will not have a future increase in constituents. In many cases, a well drilled only 1000 feet away from the operation will provide water that has no noticeable effect from the uranium processing. The underground water flow's direction is well established by the operation's technical evaluations. This allows alternative groundwater wells to be drilled upstream from constituent drift. On properties with readily available groundwater, the costs created by elevated constituents from mining are minimized. The maximum possible social cost of the uranium extraction is bounded by the value of the next best aquifer quality.

Another alternative to restoring the aquifer is to filter the water before it is used. The optimal pollution management policy extends the right to either pollute or stop pollution to the group with the lowest cost of reducing pollution costs (Coase, 1960). If the operation is required to clean the water, a large upfront cleaning cost must be paid immediately. It is not certain that the aquifer will eventually be used for private use. If the water is not used, then natural attenuation will restore the aquifer without any financial cost. However, assuming a future landowner does drill a water well over the uranium recovery area, home water treatment systems can be used to reduce TDS. This restores the groundwater only in the quantities consumed, and only at the time of use, lowering total restoration costs. This can lead to intermediate solutions not allowed under current SDWA rules, such as the operation performing a single groundwater sweep, and future landowners installing filtration systems to remove the remaining TDS. In some instances, this will restore the ground water to the same quality as the current standards require, but at a much lower cost.

Based on this evidence, the current SDWA structure is a moderate obstacle for Wyoming operations. The cost of restoring aquifers after uranium extraction ends exceeds the benefits of the restoration. This added cost uniquely restricts Wyoming uranium production because other countries producing uranium have higher starting groundwater TDS. The costs of the required restoration are substantial, averaging $15 million, or $4.3 per pound of uranium produced. Yet, this barrier is dependent on the price of uranium. When uranium prices are low, the federal legal structure is either a major obstacle or a severe obstacle. At current high prices, many Wyoming operations are profitable with or without this cost. Even at the high market prices of uranium that exist at the time of this report, the federal legal obligations create a cost disadvantage to Wyoming production compared to other regions. These considerations place the score as a moderate obstacle.

State Legal

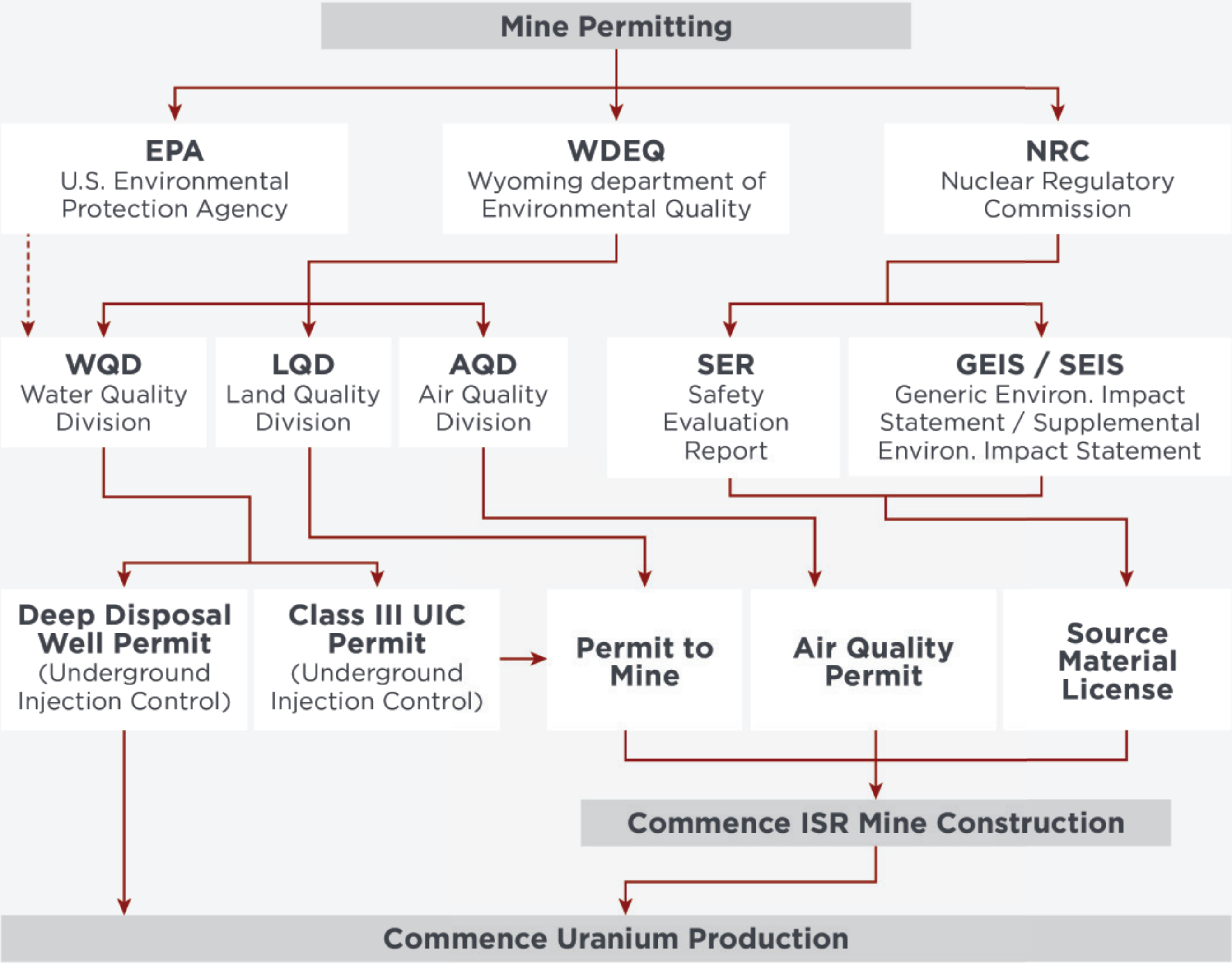
The state legal structure is found to be a *moderate advantage* to establishing uranium recovery operations in Wyoming. Wyoming has a well-established mining sector, providing experience in creating regulations tailored to the unique challenges of uranium recovery. Wyoming became an agreement state in 2018, assuming some of the regulatory responsibility from the NRC (Nuclear Regulatory Commission, 2018). This has reduced the cost of opening a facility and improved economic outcomes for operations in the State.

Economic evaluation of uranium extraction company stock prices in Australia have found significant effects of political expectations and stability. Company stock returns increase when polling numbers predict policy outcomes that will allow continued uranium development. Companies with high exposure to the uranium market are the most affected by political uncertainty. (Ferguson & Lam, 2016).

The long-established mining sector in Wyoming promotes a stable mining regulatory structure. Wyoming receives the third highest percentage of tax revenue from mineral extraction compared to all other States (Nülle & McManmon, 2015). The importance of the sector to State outcomes encourages regulators to carefully consider the impacts of policy on the industry. This reduces policy uncertainty for uranium recovery companies, providing an economic benefit to those locating in Wyoming, as compared to less energy intense economies.

One policy change the State has undertaken is becoming an agreement State with the NRC, to provide regulatory oversight of uranium mining (Nuclear Regulatory Commission, 2018). Prior to this, the regulatory flow for uranium operations followed the diagram in Figure 22.

Figure 22:
Uranium Recovery Operation Permitting Steps (Thomas, 2024)



While Wyoming has acquired some of the regulatory authority of uranium extraction operations the federal government maintains some purview of Wyoming uranium operations. The Environmental Protection Agency (EPA) has maintained authority to regulate uranium mill tailings impoundments, heap leach piles and fluid retention impoundments (lined ponds) at both in-situ recovery and conventional sites[70]. Also, if the operation is on Federal land either the U.S. Forest Service or Bureau of Land Management may require an Environmental Impact Statement (EIS) and subsequent Record of Decision (ROD).

[70] 40 CFR Part 61 Subpart W

By becoming an agreement state, Wyoming takes responsibility for approving the environmental impact statement and safety evaluation report in addition to the injection mine and air quality permits which were already completed by the Wyoming Department of Environmental Quality (WDEQ). The local knowledge of State officials has contributed to significant cost reductions in providing these reports. The NRC charges $300 per hour for work on these reports (Castellon, 2023; Nuclear Regulatory Commission, 2023b). Using this as the hourly rate of NRC staff, the average initial permitting costs for a new uranium operation is $3.2 million, with a ten-year renewal costing $2 million (Nuclear Regulatory Commission, 2023a).

Comparatively, WDEQ can produce the required reports for a lower average cost than the NRC. A technical report from the Shirley Basin project estimates that the fees paid for supporting WDEQ applications average $120,000 per year (Western Water Consultants, Inc, 2024c). Over a ten-year operation, the WDEQ saves the uranium recovery company $2 million in the cost of preparing environmental and technical reports.

The regulatory stability provided by Wyoming instructions, combined with the direct cost savings place the State legal score in the *moderate advantage* range. These advantages are specific to the State and promote development.

BENEFITS AND COSTS

General Benefits

There are non-monetary benefits of uranium recovery in Wyoming worth considering in policy analysis. Uranium projects gather information about uranium bearing ores which provides valuable information to Wyoming residents. For example, geologists evaluating uranium availability also locate radon rich aquifers. Radon exposure increases the risk of lung cancer, and leukemia as well as being linked to emotional dysfunction in children (Al-Zoughool & Krewski, 2009; Gray et al., 2009). Randon is a gaseous decay product of uranium which can accumulate in home basements creating exposure levels comparable to uranium mines (Chen, 2017). By identifying the location of uranium rich aquifers uranium development helps Wyoming residents mitigate radon exposure risk. This applies to other aquifer constituents which are identified in the extraction process. By understanding the water content and geology of a region, ranchers and homeowners can avoid drilling wells in areas with elevated contaminants.

Current restoration standards come with economic costs (see Section 3.9) but create secondary benefits for aquifer quality. Aquifer restoration can reduce some constituents to below initial levels increasing groundwater quality. Each individual constituent is targeted to be restored to original levels. Added effort is made to remove constituents that remain above the highest allowable threshold after pore sweeps, which results in continued reductions of other solids. A study of the Smith Ranch-Highland project in Converse Wyoming, found that radium levels at the in situ site were lower than baseline, even though uranium levels were increased. On net this reduced the health risks associated with drinking the affected water. (Ruedig & Johnson, 2015)

Uranium exploration also promotes future economic development in Wyoming. The geologic knowledge generated by uranium exploration decreases the future price of uranium by identifying uranium resources. Exploration lowers the cost of future uranium operations which are benefited by acquiring a richer understanding of the regional geology. Based off these benefits, economic estimates indicate that active support of uranium exploration will increase economic welfare (Mason, 1985, 2014).

General Costs

Three non-monetary costs to uranium recovery were identified. Each of these costs can be avoided but have the potential to affect Wyoming residents.

First, split land and mineral rights have led to conflicts between uranium operations and homeowners. One instance of this occurred in Colorado, where Global Uranium and Enrichment exercised rights to conduct exploratory drilling in a residential area (Schmelzer, 2024; The Denver Post Editorial Board, 2024). In other States split ownership of surface and mineral rights increased dissatisfaction of landowners from the mineral recovery process[71] (Collins & Nkansah, 2015). While private contracting between surface and mineral rights holders can be challenging, coming to agreements during exploration limits transaction costs and equity concerns (Libecap & Wiggins, 1985). This type of arrangement occurs in the Wyoming extractive industry, as an example Wyoming oil drilling projects rarely resort to posting surface restoration bonds and instead come to terms with surface rights holders prior to drilling (Fitzgerald, 2012). This is attributed to the long-term benefits of amenable relationships with surface rights holders for acquiring future land (Fitzgerald, 2012).

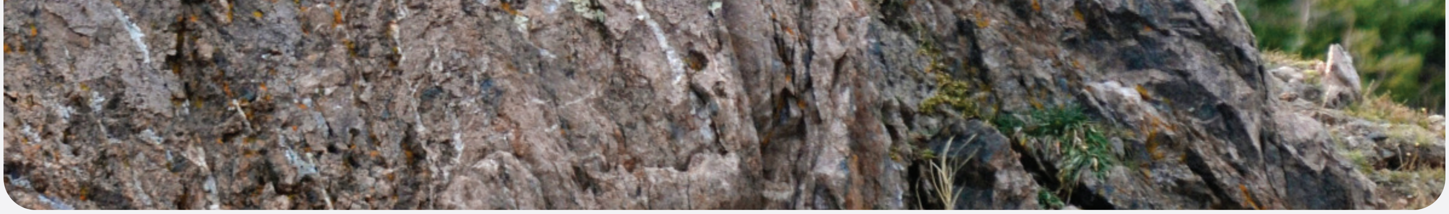
[71] This survey found that the strongest predictor of satisfaction was a property owner reporting that they were informed well in advanced and treated with respect. However, this occurred more frequently for owners of both surface and mineral rights which is attributed to a more even footing between the two parties.

The second social cost consideration of uranium extraction is potential environmental and human health considerations. Only one instance of environmental impacts from a Wyoming uranium recovery operation was identified. The Highland Uranium Project, near Douglas Wyoming completed aquifer restoration through a licensed application of treated water on to the adjacent land. The aquifer water was treated, placed in holding ponds and finally used for irrigation with a center pivot. The elevated levels of selenium in this water were mobilized up the food chain. Selenium levels in soils, grasses, grasshoppers and birds were increased compared to adjacent properties. Consequently, red wind black birds near the operation had toxic levels of selenium in both livers and eggs. (Ramirez & Rogers, 2002).

This environmental outcome from irrigating with reservoir water will be different at each uranium operation. Different types of vegetation bio accumulate constituents at variable rates (Bergmann et al., 2006). In fact, water near the Highland Uranium Project was found to have lower levels of selenium than comparable ponds, which is attributed to the presence of cattails that filter selenium from the water (Ramirez & Rogers, 2002).

There are also cases of negative health outcomes from uranium recovery operations in humans. Exposure to radon by underground mine workers has been associated with higher lung cancer rates, this cancer risk is exasperated when combined with tobacco use (National Academy of Sciences, 1999). However, evaluation of cancer rates in counties with uranium tailings found that the uranium recovery operation did not change the risk of cancer of residents (Boice, Cohen, et al., 2007; Boice et al., 2003, 2010; Boice, Mumma, et al., 2007; Canadian Nuclear Safety Commission, 2009). All Wyoming uranium recovery operations are in situ, which does not put employees in contact with underground radon and does not produce the same form of tailings as traditional methods.

The third non-monetary cost of uranium recovery is a lowered water table in the surrounding aquifer. This occurs when water is removed from the produced zone with disposal wells. During ground sweeps, the water from the pore volume is brought to the surface and can then be injected into lower aquifers. This draws in native groundwater with lower dissolved solid levels. The benefit of this process is a reduction in total dissolved solids in the produced aquifer. On the other hand, this can lower the surrounding water table which in turn increases the cost of pumping from private wells. No studies of this groundwater table reduction were identified, but John Christensen a Wyoming rancher who owns surface rights over the Christensen Ranch Project reported that water levels near uranium recovery operations were reduced by 100 ft (Lustgarten, 2012).



Economic Impacts

Outcomes in employment and tax revenue from the uranium mining sector in Wyoming are estimated. The results conclude that there will be up to 17,700 person-years[72] of employment, with $902 million in State and local tax revenue from this development. The benefits and costs of the uranium recovery sector in Wyoming are evaluated using an input-output model (Leontief, 1986). In these models, the inputs of one sector are treated as the output of another industry, and the system of equations is balanced with available data. The model applied comes from IMPLAN which includes sector level data unique to Wyoming, allowing for the economic impacts to be tailored to the unique economic linkages in the State.

The outcomes of the input-output model are generated under three cases of sustained long run uranium prices in the U.S. Since the output of the uranium recovery sector is directly tied to the price of uranium, these prices are paired with historic production numbers to establish possible output scenarios. The low outcome uses current production numbers as inputs. U.S. uranium production was 146 thousand pounds in 2022, with a total full-time employment of 196 people (Energy Information Administration, 2023b). This production came from four operating U.S. uranium facilities, three of which are in Wyoming. Data is withheld about the total production from each state since the individual operation data could be reverse engineered with this information. A simplifying assumption that each operating mine has an equal amount of employment is applied. This means 75% of all U.S. production and employment is attributed to Wyoming.

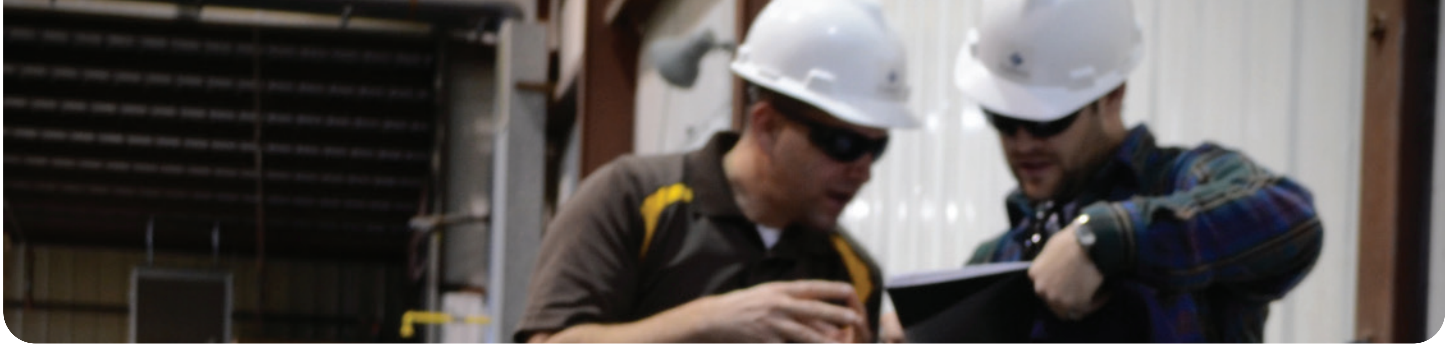
The *middle* and *high* production estimates are based on historic Wyoming mining output. Total Wyoming uranium output peaked at 12 million pounds per year in 1981. Wyoming output is assumed to reach these levels at the $146 per pound reserve cutoffs used by the Energy Information Administration[73] (Energy Information Administration, 2010b; United States Bureau of Labor Statistics, 2023). The middle case scenario assumes at a market price of $90 per pound 4,800 pounds of uranium will be produced per year. This production estimate is based on the uranium supply model in Table 3[74,75].

[72] A person-year is a unit of employment. Two half time workers, or a single full-time worker both add up to one person year. This metric is used to compare short term and long-term projects.

[73] $100 per pound was inflation adjusted from 2008 values to 2024 dollars.

[74] Based on 2014 Wyoming production numbers. This local maximum is selected to provide more accurate estimates. Since the equation estimates growth as percentage increase of production, low production years create a biased estimate. A doubling of a zero is still zero. Production was high enough in 2014 that the relative increase in production based on price, is plausible.

[75] The price of uranium in 2014 was $44.24 (in 2024 terms). A price of $90 per pound is a 103% increase. Wyoming uranium production in 2014 was 3.6 million pounds. Therefore, total production at $90 per pound is predicted to be 0.66*2.03*3,600=4,834 *Thousand pounds of uranium*



Each of these scenarios is used to estimate the total annual industry output of the uranium sector. This is used as an input in IMPLAN to calibrate employment and tax income information. These results are provided in Table 5

Table 5:
Economic Outcomes from Wyoming Uranium Recovery

Production Scenario	Low	Middle	High
Uranium Price	$45	$90	$146
Production (Thousand Pounds)	146	4,800	12,000
Employment (Person-years)	147	4,600	17,700
Tax Income	$362,000	$236,161,000	$902,971,000

Wyoming uranium recovery can become a major contributor to State tax revenue, with moderate changes in State employment. Both the employment and tax income results include the direct changes in the uranium extraction industry as well as induced growth in other sectors such as hospitality and construction. Tax revenue values are the sum of State and county incomes. The estimates assume that all future Wyoming operations will remain in situ. The innovation of in situ recovery has substantially reduced the labor intensity required to extract uranium. This has the advantage of minimizing the barriers to industry development of establishing a large workforce in rural parts of the State. On the other hand, even a large increase in the output of uranium recovery will only induce between 4,600 and 17,700 yearly employment. This assumption may underestimate total employment under high uranium price scenarios where traditional uranium extraction facilities can operate profitably.

Total State and county tax revenues induced by industry growth are substantial. In 2022, the total State tax revenue was $3.45 billion (Wyoming Department of Revenue, 2023). Under the middle and high growth scenarios, direct and induced tax revenue from uranium recovery would account for between 6.8% and 26% of this total revenue respectively.

CONCLUSION

The study evaluated the opportunities and barriers for growing the uranium recovery industry in Wyoming. Under the status quo, uranium operations are expected to increase output. Six of the factors evaluated were found to promote uranium recovery in Wyoming, with only one identified obstacle.

Factors Supporting Development

1. Wyoming has the most uranium reserves of any State.
2. Uranium prices are high enough for Wyoming operations to remain profitable.
3. Graduated severance taxes prevent operations from shutting down if uranium prices are low.
4. Existing operations on standby can be reopened.
5. In situ operations have allowed new resources to be extracted in the State.
6. Wyoming's management of operation regulatory compliance has reduced the cost of opening a facility.

Barriers to Development

1. SDWA requirements place limits on which uranium reserves can be used for in situ operations and add to aquifer restoration costs.

The State is well positioned to expand uranium production, but the net benefits are dependent on output levels. The total benefits to the State include:

Benefits of Wyoming Uranium Recovery

1. 147-17,700 person-years of employment.
2. $0.4-$903 million of tax revenue per year.
3. Reduced environmental impact when compared to historic operations.

Based on this analysis, the Wyoming uranium recovery industry is situated to expand in the coming years. No legal or financial support from the State is required to maintain this growth. However, long run uranium prices are uncertain, and growth could stagnate if demand for uranium decreases. There are potential social costs to this development including concerns of aquifer contamination, and conflicts over property rights. Both concerns can be mitigated through industry standards or Wyoming policy.

Proceeding papers will evaluate other stages in the nuclear supply chain which are fed by uranium operations. These include nuclear produced electricity, direct heat uses of nuclear power plants, and spent fuel storage. This will provide a standard to compare the advantages, challenges, and the economic impacts across the entire nuclear sector.

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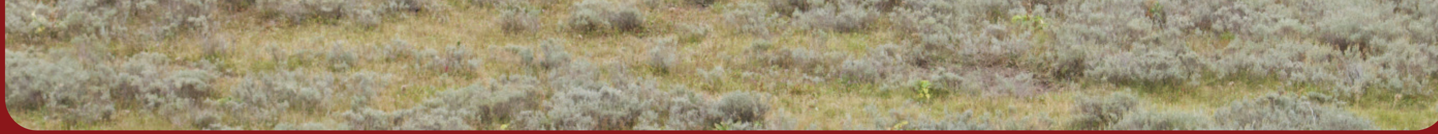

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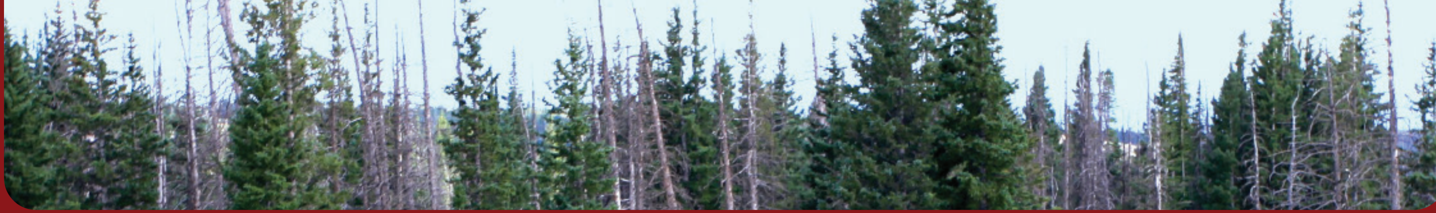

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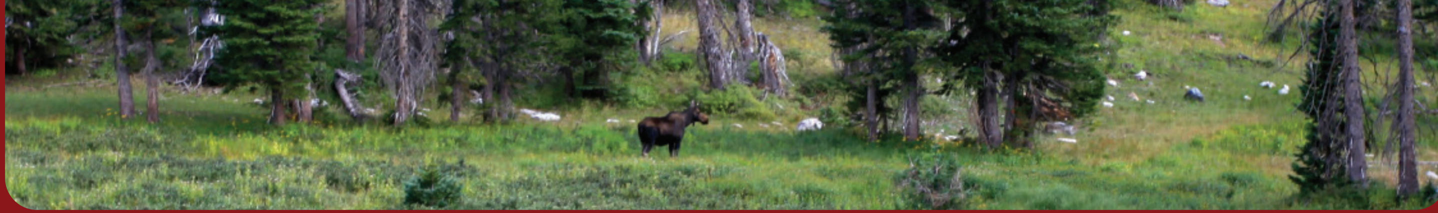

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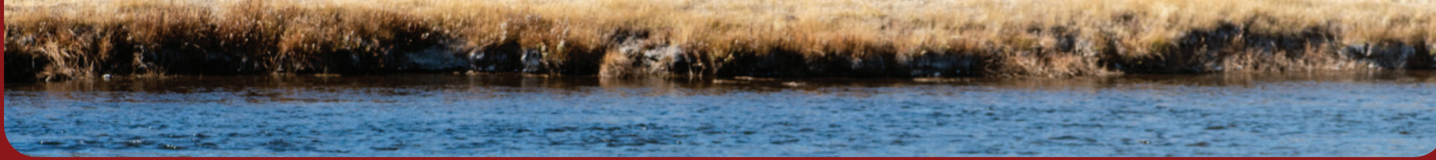

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APPENDIXES

APPENDIX (A) CASE STUDIES OF WATER QUALITY VALUE

Land prices reflect the consequences of pollution, one aspect of the value of the property is the long term expected use of the groundwater (Rosen, 1974). If the groundwater on the property becomes too polluted to drink, future land buyers will be unwilling to pay as high a price for the land. The difference in the sale price before the operation is developed and after the operation closes is the economic cost of the pollution. If the mining company owns the land, then they account for the pollution costs as part of their operating plan. Since the land can be sold for more when the aquifer is remediated, there is a profit motive to keep the reservoir clean. This allows economists to estimate the value of groundwater quality even though there is not a market price for this product. The price of land captures the value of groundwater, as well as a set of other attributes. Once the other factors are controlled, an estimate of the additional value from groundwater can be made. This is referred to as a hedonic model.

The cost of increasing pollutants in groundwater has been identified in other settings. Groundwater salinity has been found to reduce the sale price of farms, but the size of the reduction depends on well depth and starting salinity levels (Mukherjee & Schwabe, 2014). In this study of California's Central Valley, a 30% increase in salinity was found to reduce property values by up to 12%. However non-linear relationships between sale prices and the interaction of well depth with salinity was found, leading to estimates that a 30% salinity increase may only decrease land value by 0.6% to 3% (Mukherjee & Schwabe, 2014). An evaluation of home values using groundwater in Florida, finds raising nitrate levels to twice the EPA drinking water standard reduces home values by 15% (Guignet et al., 2015).

A related evaluation of farms reliant on groundwater found that State curtailment risk temporarily reduced the value of farmland by as much as 55% (Gebben & Smith, 2024). This does not directly estimate groundwater quality value but does provide an upper bound value of groundwater used in agriculture.

The Wyoming setting differs from each study's particulars, but there are important overlaps. In the Florida setting, the homeowners were rural, dependent on groundwater, and were not protected under SDWA standards. However, Wyoming is arid and land is often used in agriculture, such as the Central Valley setting. Groundwater wells in Wyoming are more likely to serve ranches than farmland, but health effects in animals, such as cattle have been identified after consuming high levels of uranium and selenium from groundwater exposure (Ramirez & Rogers, 2002; Ruedig & Johnson, 2015).

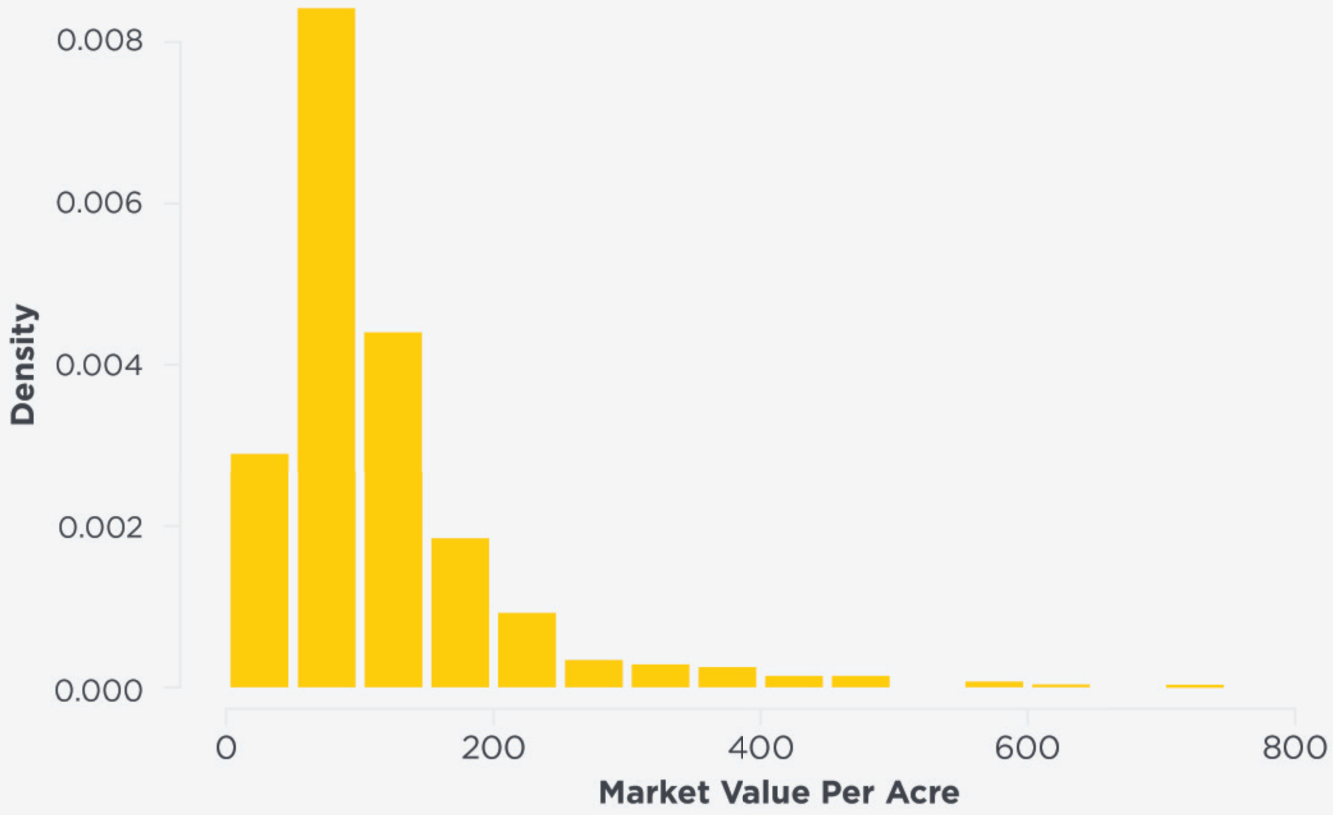
However, it is worth noting that this is a upper bound estimate, as applied to demonstrating that current standards are unlikely to be efficient even under this worst case scenario. In actuality, uranium extraction operations may have a negligible effect on land values. This is particularly true when the land is vacant. Each of these studies applies to land that is currently using groundwater for agriculture or personal use. Where uranium extraction occurs in areas where the water is not actively being used.

APPENDIX (B) LAND VALUE HISTOGRAM

A histogram of the land prices used to estimate the average sale price of land at a in situ operation is provided in Figure 23. To create this data set all Wyoming parcels were overlaid with a map of uranium reserves of the State. All parcels that are not overtop of a uranium resources area were dropped from the data set. Then each parcel was divided into one-acre plots. So, a 100-acre plot contributes 100 data points. The reported "market price" estimate was used rather than the assessed price since the assessed price is for tax purposes. This value may be biased by the assessor process, and true sales records are preferred. However, this value is sufficient for the present analysis which finds a large disparity in land values and restoration costs on a per acre basis.

This is used to create the final histogram. It should be noted that the average outcomes may differ from a specific project. If a uranium recovery facility is located on a plot at the right tail of this distribution the aquifer remediation may be worth more to the landowner.

Figure 23:
Histogram of Assessed Land Values over Uranium Resources in Wyoming[76]



[76] Data sources (Gregory & Drean, 2015; Wyoming Department of Revenue, 2024)

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