School of Energy Resources
Center for Energy Regulation
& Policy Analysis

NUCLEAR SERIES PART 1

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

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ACKNOWLEDGMENTS

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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.

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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 opportunities and the economic outcomes of fostering a uranium enrichment industry in Wyoming. The unique challenges and advantages of attracting the industry to Wyoming are identified. Additionally, an event study is performed that estimates economic outcomes of building a uranium enrichment facility.

The research team found only limited opportunities for construction of new uranium enrichment production facilities in Wyoming. The considerable financial commitment required for enrichment infrastructure and competition with established producers were major obstacles. However, future enrichment sector development in Wyoming would result in numerous economic benefits by increasing state tax revenues, creating employment opportunities, and promoting a regional nuclear industry.

As shown in Table 1, the team developed a scoring system to evaluate the economic opportunities and barriers for new uranium enrichment infrastructure in Wyoming. Each category is color coded to define a continuum between *Major Advantages and Severe Obstacles.*

Table 1
Opportunities and Barriers Scoring Method

Level	Description
Severe Obstacle	Development impossible
Major Obstacle	Significant support required for development
Moderate Obstacle	Some support required for development
Minor Obstacle	Development is hindered
Neutral	No effect
Minor Advantage	Incentive to continue development
Moderate Advantage	Moderate incentive for new development
Major Advantage	Strong incentive for development in Wyoming

Table 2 shows the ranking of the seven most significant economic factors affecting future Wyoming investment opportunities in uranium enrichment. The team concluded that a single adverse factor could result in a major obstacle to new development independent of other economic factors. For example, this was the case for existing industries.

Table 2
Significant Economic Factors Related to Wyoming Enrichment

Factor	Level	Summary
Economic	Moderate Obstacle	Natural monopoly limits entry
Existing Industries	Major Obstacle	Operating firms have a cost advantage
Tax Structure	Moderate Advantage	Net taxes lower than other states
Location	Minor Advantage	Existing uranium supply in state
State Legal	Minor Obstacle	Local zoning and construction permitting
Federal legal	Minor Obstacle	NRC license and environmental review
Technology	Neutral	Sufficiently developed
Overall Rating	**Major Obstacle**	**Development requires financial support**

Table 3 shows the projected economic benefits that new enrichment infrastructure investments would bring to the State. These results are formed from an economic impact model of the short- and long-term outcomes of a Wyoming enrichment facility. Upfront investment spurs short-term growth in the construction sector and generates spillover effects to other industries. Once the facility is operational the induced employment decreases, but the State continues to benefit from property taxes, and the development of the nuclear industry.

Table 3
Total Costs and Benefits of Uranium Enrichment

Benefits

Long-Term Jobs	Short-Term Jobs	Direct Tax Revenue	Indirect Tax Revenue	Development
230 - 290 employment	51,000 - 79,000 person-years	$66 - $82 million	$72 - $111 million	Promotes other related industries

Costs

Program Costs	Storage Costs	Social Costs
$6.6 - $10 million	Uranium hexafluoride requires long term storage or conversion	Social equity concerns have stopped previous projects

1.0 INTRODUCTION

Wyoming is a keystone state in the energy supply chain of the United States. Through the mixture of coal, oil and gas, and renewable energy, the State produces 6.1% of the country's energy, leading the nation in energy production per capita (Energy Information Administration 2021). Nuclear produced electricity can become a core component of this resource mix as the energy economy evolves. Advances in small modular reactor technology, anticipated coal-fired electricity unit retirements, and the state's commitment to energy development all add interest to the development of the nuclear supply chain in Wyoming (Brown 2022; World Nuclear Association 2023b; Wyoming Energy Authority 2023). Starting at the uranium mine and ending with material storage, the nuclear supply chain encompasses multiple economic sectors. Each of these sectors has unique opportunities and challenges for adoption in the State. This report focuses on uranium enrichment infrastructure which links the existing Wyoming uranium mining industry with markets for nuclear generated electricity being explored in the state.

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 new Wyoming investments in the nuclear sector expansion. 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.

The report begins with a summary of the history, technology, and existing enrichment sector infrastructure. The report follows with analyses of the economic factors creating opportunities and challenges to potential investments in the Wyoming enrichment sector. Finally, the economic benefits and costs of developing an enrichment industry were estimated. Changes in Wyoming employment and tax revenue were estimated using micro economic models.

2.0 BACKGROUND: URANIUM ENRICHMENT

2.1 WHY URANIUM ENRICHMENT IS IMPORTANT

The uranium enrichment process increases the usefulness of natural uranium for use in nuclear power plants. In nature, uranium consists of two dominate isotopes, U-238 and U-235[1] (World Nuclear Association 2022). U-235 is conducive to nuclear fission but is only 0.7% of uranium ore. A typical operating light-water reactor requires a U-235 enrichment level of between 3% and 5% U-235 to operate (World Nuclear Association 2022). Enrichment of the uranium increases the proportional amount of U-235, improving the fuel source's consistency.

Uranium enrichment is a crucial step in connecting the uranium produced in Wyoming to the final stage product needed for electricity generation. The first step in this process is for the mine to send solid uranium oxide to a conversion facility where it is chemically changed into uranium hexafluoride, which is a gas[2]. The UF_6 is then shipped to the uranium enrichment facility[3], where the difference in mass between the U-235 gas and U-238 gas is leveraged to separate the two. For more details on the technical aspects of this process refer to Section 3.6. The enriched uranium gas is then processed at a fuel fabrication facility, where it is converted back to a solid and prepared for use at a power plant. Appendix A provides additional information about the nuclear fuel cycle.

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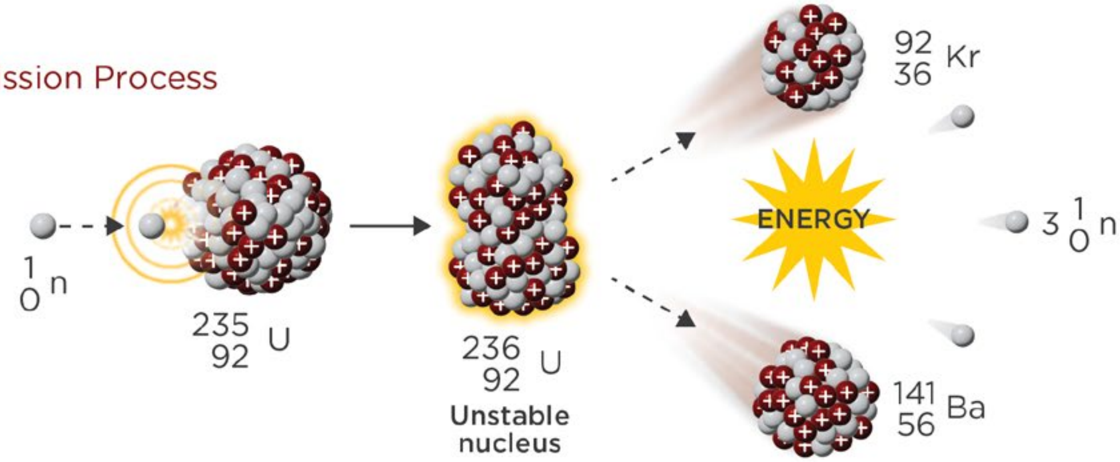
[1] The number indicates the atomic mass of the isotope with U-238 having three more neutrons than U-235.
[2] At atmospheric conditions.
[3] The gas is converted to a solid at the plant but heated back into a gas once at the facility.

Figure 1
Nuclear Fission Process



Science Ready, Nuclear Fission, Uncontrolled and Controlled Chain Reactions (https://scienceready.com.au/pages/nuclear-fission-and-reactors)

The uranium enrichment industry acts not only as a source of demand for Wyoming mined uranium, but also as a supply of inputs to future power plants in the State, such as the TerraPower Natrium™ facility (TerraPower 2023). The need for enrichment comes from the physical process of fission. Fission results when a neutron interacts with a fissile[4] isotope, resulting in the release of highly energetic fission products, neutrons, and gamma radiation (Figure 1). At commercial power stations, the heat generated by the fission products[5] is transferred from the fuel matrix to a generator conversion system[6]. In addition to commercial power generation, U-235 is also used for naval propulsion, research reactors, medical isotope production, and weapons. The nuclear industry measures the enrichment of uranium by percent of U-235. The amount of effort needed to increase the proportion of U-235 is measured in separative work units[7] (SWU).

The existing domestic nuclear electricity generation industry uses "light water" (moderated)[8] reactor technology. This technology requires enriched uranium fuel[9] between 3% and 5% U-235 (World Nuclear Association 2020). Advanced nuclear reactors, which may develop in the State, commonly use High-Assay Low-Enriched uranium (HALEU), which is in the range of 5% and 20% (NEA and OECD 2021). In contrast, naval propulsion reactors typically use between 93% and 97% U-235 enrichment (Moore, Banuelos, and Gray 2016) and weapons use 90% to 93% U-235 (World Nuclear Association 2017). Other reactor technologies, such as the Canadian CANDU and British Magnox reactors use natural (unenriched) uranium fuel (World Nuclear Association 2020). These designs provide sufficient reactivity without U-235 enrichment.

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[4] Fissile isotopes (low energy neutrons) include U233, U-235, and plutonium Pu239.

[5] Each U-235 fission produces 200 MeV. 83% of this is kinetic energy from the fission products (Rumble 1977).

[6] Conventional steam or electric.

[7] SWU is the amount of separation done by an enrichment process. SWU is a function of the concentrations of the feedstock, the enriched output, and the depleted tailings; and is expressed in units proportional to the total input (energy/machine operation time) and to the mass.

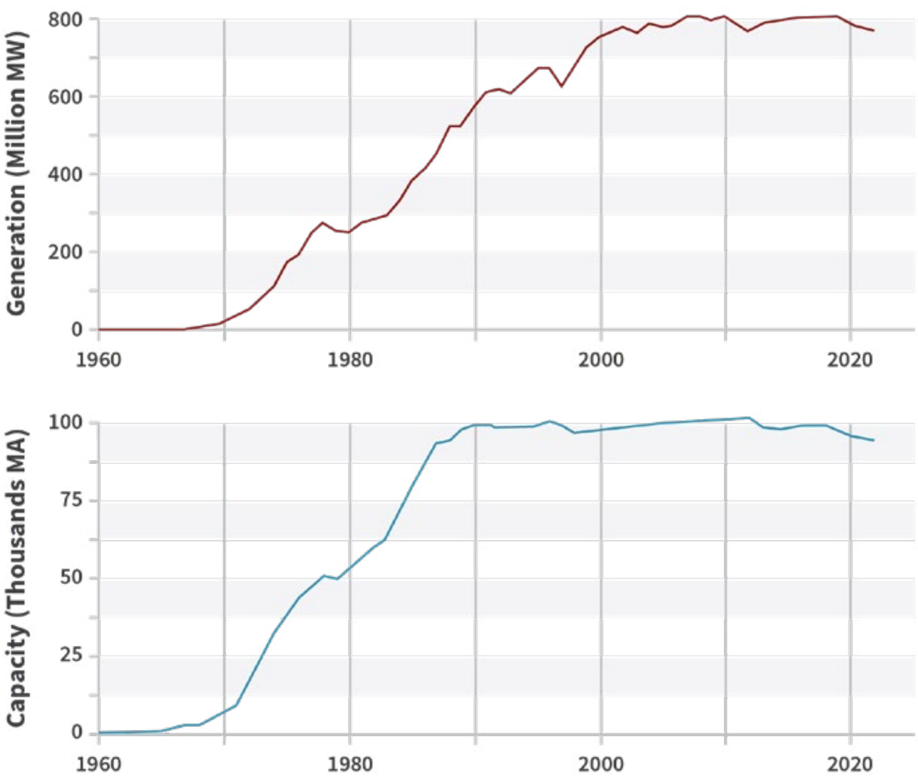
[8] U-235 fission is optimized by thermal (slow) neutrons (in thermal equilibrium with the environment). Moderation is the process of slowing down fast fission neutrons. Common moderators include water, heavy water, and graphite.

[9] Current NRC Rules limit power reactor enrichment to 5% U-235, 10 CFR 50.68, "Criticality Accident Requirements," 10 CRF § 50.68.

Domestic nuclear utilities typically enter long-term contracts for the purchase of uranium ore, conversion, and enrichment services[10] (Poneman 2020). These contract prices reflect the long-term expectations of supply and demand by investors and can deviate from spot market prices that capture short-term constraints on the supply chain. There is a link between uranium prices and enrichment SWU prices. Uranium enrichment companies can create a secondary supply of uranium by underfeeding the centrifuges. In this process, more energy is used to produce the desired product, but less feed uranium is required. This and other price drivers are explained in Appendix E.

The demand for enrichment services is driven by fuel needs of nuclear power plants. About a quarter of the fuel cost of operating a nuclear power plant comes from the cost of enrichment (Owen 1985; Pouris 1986; World Nuclear Association 2020). However, the day-to-day cost to operate a nuclear power plant is much lower than the capital costs involved. This leads to a situation where the production of nuclear produced electricity is only weakly correlated with uranium and enrichment prices. Figure 2 shows the United States output of nuclear power aligned with the nuclear capacity. The trend in nuclear electricity can be explained by the capacity installation of nuclear power plants indicating that the quantity supplied of electricity is not responsive to enrichment prices.

Figure 2
Nuclear Power Generation and Capacity

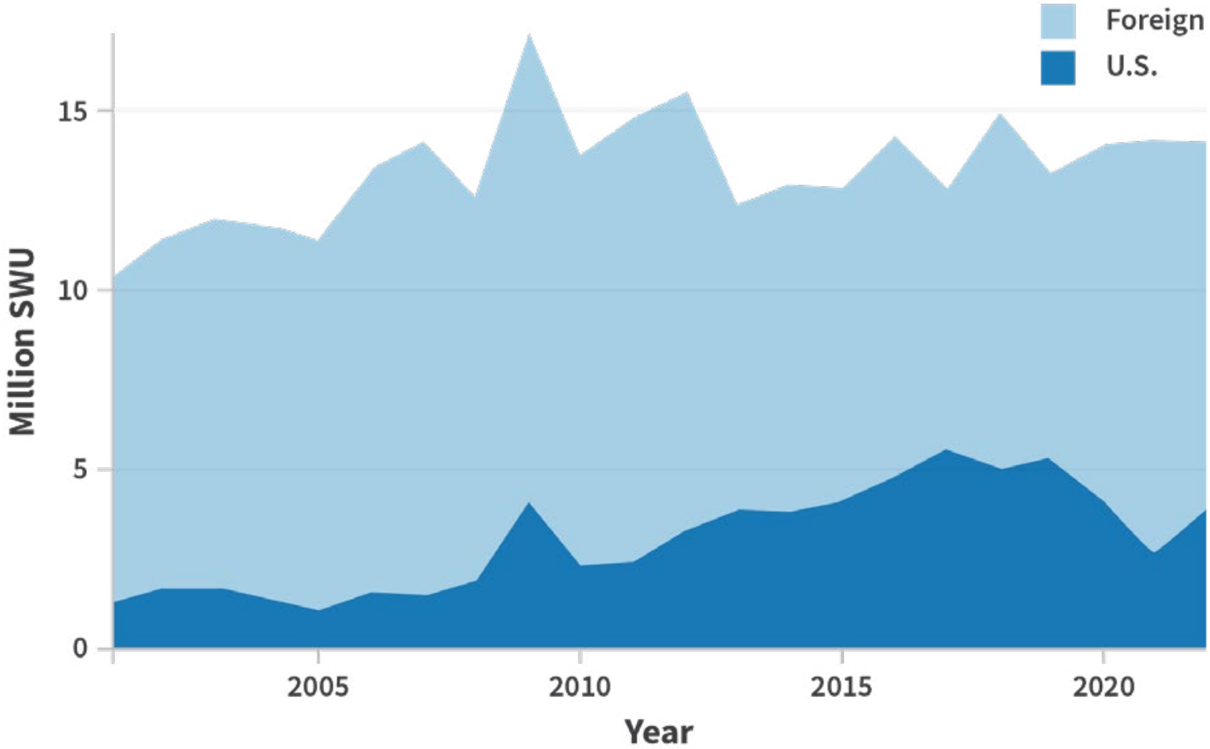


Data Sources: United States Energy Information Administration Open Data (Oct 2023)

[10] Or from an arbiter that contracts uranium supply and SWU from multiple countries.

The quantity demanded of enrichment services by United States nuclear power plants and the source of the purchased enrichment is provided in Figure 3. The annual average volume of SWU purchased remains relatively flat reflecting a stable nuclear electricity generating fleet. However, SWU purchases do deviate from this trend on a year-to-year basis. This is because there are substitutes for uranium enrichment services. One alternative to producing new enrichment is storing surplus supplies. Utilities may hold inventories of enriched uranium to reduce the risk of supply shocks (Owen 1985)[11]. In any given year, nuclear power plants may withdraw from this reserve, decoupling present purchases with contemporary electricity production. Nuclear weapons have also acted as alternative sources of enriched uranium. Under disarmament agreements, nuclear weapons were down blended to the 3%-5% enrichment range needed for power plants. An agreement between the United States and Russia provided 5.5 million SWU from down blending nuclear weapons from 2002 until 2013 (International Atomic Energy Agency 2005). Also, in 2021, Norway also provided the United States an unspecified amount of 20% enriched U-235 down blended from HEU (World Information Service on Energy 2023).

Figure 3
Source of Enrichment Used in United States Power Plants



Data source (Energy Information Administration, 2022)

[11] These inventories are not always held on site, and are held physically at the enrichment or fabrication facility.

2.2 ENRICHMENT: HISTORICAL PERSPECTIVE

The history of enrichment in the United States provides insights into the unique challenges faced by the industry. A summary of all operating or planned enrichment facilities is provided in Table 4. The landscape of the industry has changed, with early projects focusing on government use of uranium but eventually switching to the private sector. Costs of every project are in the billions of dollars, and the technology has shifted from primarily gas diffusion to centrifuge enrichment, with laser enrichment being attempted. HALEU licensing has also become more common, as advanced reactor technology emerges on the horizon.

The first operating enrichment facilities were the Y-12 and K-25 plants located in Oak Ridge, Tennessee, which aided in the fabrication of nuclear weapons. These plants produced highly enriched uranium.

Table 4
U.S. Enrichment Facilities

		ENRICHMENT PLANT NAME							
		Y-12	K-25	Paducah	Portsmouth		NEF	Eagle Rock	GLEF
					Initial	Refit			
FACILITY STATUS	Status	Closed	Closed	Closed	Closed	Planned	Operating	Canceled	Canceled
	Operating Year	1943	1945	1952	1954	2023	2010		
	Closed Year	1946	1964	2013	2001			2013	2021
	State	TN	TN	KY	OH	OH	NM	ID	NC
PRODUCTION AND COSTS	Technology	Mag.	Diff.	Diff.	Diff.	Cent.	Cent.	Cent.	Laser
	Initial Cost (Billion USD 2023)	4.32	8.59	9.23	8.55	4.49	5.72	5.55	W
	Capacity (Million SWU/Year)			8.0	8.3	3.8	4.9	6.6	6.0
FACILITY USES	Status	Closed	Closed	Closed	Closed	Planned	Operating	Canceled	Canceled
	Operating Year	1943	1945	1952	1954	2023	2010		
	Closed Year	1946	1964	2013	2001			2013	2021
	State	TN	TN	KY	OH	OH	NM	ID	NC

Technology Abbreviations Mag.: Electro Magnetic, Diff.: Gaseous Diffusion, Cent.: Gas Centrifuge.
Operator Abbreviations Tennessee Eastman Company (TNE), Global Laser Enrichment, LLC (GLE)
Other Abbreviations National Enrichment Facility (NEF), high-assay low-enriched uranium (HALEU).
Centrus was formerly the United States Enrichment Corporation.
The Portsmouth site is being refit with centrifuges with plans to begin operation in late 2023.
Y-12 and K-25 capacities are not comparable to peacetime operations and are omitted.
Global Laser Enrichment Facility (GLEF) construction costs were withheld (W) in NRC in filings.

All data sources provided in Appendix B.

Preceding these, the Paducah plant was a government-owned gaseous diffusion facility commissioned in 1952. The facility initially produced enriched uranium feedstock for the national weapons and naval propulsion programs. However, Paducah was later used for enriching commercial power plant fuel.

In the 1990s, the Department of Energy (DOE) leased the Paducah facility to Centrus Energy Corp[12]. The controlling regulatory authority transferred from DOE to the NRC[13] prior to privatization. In 2013, the facility was permanently shut down and is undergoing decommissioning. DOE has estimated decommissioning costs to exceed $17 billion (United States Energy Department 2023). Regulatory authority transferred back to DOE after commercial operations ceased.

The Portsmouth facility (Pike County, Ohio) produced enriched uranium from 1954 to 2001. DOE leased major portions of the facility to Centrus in 1997. Centrus operated the low-enrichment trains to supply domestic commercial fuel manufacturers. In 1980, an industrial scale centrifuge enrichment plant addition was planned by the DOE. More than $3 billion was invested before abandoning the project in 1985 (United States Government Accountability Office 1985). The regulatory authority transferred to the NRC for the leased sections of the facility. In 2011, the NRC approved the decommissioning of the Portsmouth facility under the purview of the DOE (NRC 2011a). Decommissioning costs are estimated to exceed $5.9 billion (World Nuclear News 2023a).

In 2019, Centrus began refitting the Portsmouth site to deploy a cascade of centrifuges to demonstrate production of HALEU, called the American Centrifuge Plant (ACP). The NRC issued the revised license approving Centrus to demonstrate production of HALEU through the end of 2024. Centrus subsequently requested that the NRC approve expanding HALEU production to 1,400 kg by the end of 2024. The NRC is currently reviewing Centrus' License Amendment Request (Fitch 2023).

The National Enrichment Facility (NEF) located in Eunice, New Mexico, began production of enriched UF_6 in 2010. NEF was one of the largest single industrial projects built in the United States during the past decade and can produce about half the enriched uranium needed for the domestic nuclear power industry once it expands to full capacity (See Figure 3). The facility is currently licensed for 10 million SWU/year (Laughlin 2012; NRC 2014, 9; World Nuclear News 2015). The initial limit was 3 million SWU/year (NRC n.d.). This was increased to 5.7 million SWU/year in 2005, the current limit was approved in 2015 (NRC n.d.; Plimpton 2015). After this expansion costs rose from a projected $2.5 billion to a realized cost of $5.7 billion (Mann 2016; NRC 2005)[14]. Urenco has also given notice that they plan to file for an increase from 5.5% enrichment levels to 10% (Cowne 2021).

[12] Formerly United States Enrichment Corporation, USEC.
[13] The NRC issued a certificate for commercial enrichment.
[14] Values CPI adjusted to July 2023 from 1.5 billion in 2004, and 4.5 billion in 2016, respectively. It is unknown if the 2016 estimate was adjusted, so the actual costs may be higher than this estimate.

Recently, investors have abandoned two new major NRC licensed enrichment projects before beginning construction. The Eagle Rock Enrichment Facility (EREF) was the first project to be canceled. EREF was owned by Areva Enrichment Services (AES) and located on private land adjacent to the Idaho National Laboratory (NRC 2023a). The original 2008 NRC License Application allowed production of 3.3 million SWU/year (NRC 2023a). The NRC subsequently amended the license to increase production to 6.6 million SWU/year (NRC 2010). EREF was originally scheduled to begin production in 2014 increasing output through 2018 (NRC 2010). However, AES subsequently canceled the start of production based on post-Fukushima economic forecasts (World Nuclear News 2009). Upon AES's request, the NRC terminated the facility license in 2018 (Smith 2018).

The GLE Uranium Enrichment Facility was the second recently canceled commercial-scale enrichment facility. The facility was constructed by Global Laser Enrichment, LLC (GLE), in Wilmington, North Carolina. The NRC approved the license in 2008 for building a test loop and amended the license for a full-scale commercial facility 2012. After multiple project delays, GLE requested a license termination of the commercial facility by the NRC in 2021[15] (Bartlett 2020; Damaris 2021). GLE has shifted efforts to focus on a facility in Paducah (PLEF) where testing of laser enrichment continues. A contract with the Department of Energy provides the site with depleted uranium, which can be re-enriched up to natural uranium levels. This acts as a direct substitute for mined uranium (Department of Energy 2016; World Nuclear News 2023b)[16].

15 The test loop is still operational.

16 Re-enriching tails is treated as being a source of natural uranium, rather than a supply of enrichment for the purposes of this analysis. While enrichment is used, the final product is natural uranium that other enrichers will process.

3.0 BARRIERS TO DEVELOPMENT

The team identified significant barriers to attracting new enrichment infrastructure investment in Wyoming. Economies of scale and the existing industry structure are the leading obstacles. On net, the challenges posed are significant and make it unlikely that a facility can be constructed in the State without significant direct government support. While federal funding will mitigate the barriers created by economies of scale, to overcome the advantages of existing industries, local funding is necessary.

First, the fixed capital investment required for a new uranium enrichment project is extensive, averaging a construction cost of $6.7 billion. Both the NEF enrichment facility and the centrifuge refit at Portsmouth are capable of expanding capacity without this high upfront cost. This limits the number of opportunities to construct a new facility and removes the option of gradual adoption within the State. Even under ideal economic conditions, the United States will likely have no more than three operating enrichment facilities.

Two existing mothballed locations have a cost advantage to a Wyoming site. The Eagle Rock and GLE projects have undergone safety and environmental approval from the NRC prior to their cancellation. This regulatory advantage reduces the time to market and cost of developing the existing sites when compared to starting from scratch in Wyoming. Based on history, a six-to-ten-year license and environmental review period can be expected before new construction could begin. Reactivating one of these projects would reduce this timeline, providing a significant market advantage over a new location. Also, some of the sunk cost accrued in the research, development and licensing can be recaptured if the Eagle Rock or GLE locations are reconsidered.

Our findings are supported by two empirical analyses: First, the Herfindahl–Hirschman Index (HHI)[17] quantified the level of enrichment market power, indicating the economies of scale to production have led to a non-competitive market structure. Second, a profit model of enrichment was developed, using benchmark prices predicting that licensing delays decrease profit more than early retirement. Reactivation of the previously NRC licensed EREF or GLE projects would present a distinct cost-saving advantage over a new project in Wyoming.

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[17] Herfindahl–Hirschman Index measures the size of companies relative to the size of the industry they are in and the amount of competitiveness. The HHI is calculated by squaring the market share of each firm competing in a market and then summing the resulting numbers. The HHI ranges from close to 0 to 10,000, with lower values indicating a less concentrated market.

Despite these challenges, Wyoming offers several attributes that would attract investment in enrichment infrastructure. The State's tax structure, land prices, and location are all factors that improve profitability for enrichment firms. On an even playing field, Wyoming could be a top choice for a firm selecting a new location for an enrichment facility. However, the existing market obstacles are large enough that direct investment in the enrichment industry is necessary to attract a new enrichment facility, even after accounting for Wyoming's advantages.

The preceding sections apply the developed obstacle scoring system to each category of economic barrier. In Section 3.1-3.6 a score is assigned ranging from *Major Obstacle* (red) to *Major Advantage* (Green). For each obstacle the score and rationale are provided in a *Scoring Criteria* section. For those seeking a more thorough explanation, a detailed discussion of the steps used to identify the score is provided under the *Analysis* section.

3.1 ECONOMIC BARRIERS

Score: Moderate Obstacle

Economic Barriers: Scoring Criteria

The economics of uranium enrichment are identified as a *Moderate Obstacle* to Wyoming enrichment development. Large economies of scale have led to a highly concentrated market, with most production occurring outside of the United States (see Table 5). Within the country these economic considerations led to most production being sourced from a single location. As the only operating enrichment facility in the United States, NEF can expand production at a lower average cost than constructing a new facility. Similarly, reusing the existing infrastructure at the Ohio ACP provides a cost advantage over new builds. These factors limit the number of opportunities available to develop a multibillion dollar enrichment facility within the country, and consequently in Wyoming. This places the economic barrier in the *Moderate Obstacle* range.

Economic Barriers: Analysis

Increasing returns to scale of production capacity are identified as a major barrier to building an enrichment facility in Wyoming. These returns to scales resulted in an oligopolistic market, where a few firms centered in Europe provide the lowest cost enrichment. To be cost competitive, a Wyoming-based enrichment facility would require many billions of dollars in upfront capital costs.

Table 5
Uranium Enrichment Facilities

Country	Company	Location	Capacity *(Mill. SWU/y)*
Russia	Tenex	Angarsk, Novouralsk, Zelenogorsk	27.7
Other Europe	Urenco	Germany, Netherlands, UK.	13.7
France	Areva	Tricastin	7.5
China	CNNC	Hanzhun, Lanzhou	6.3
United States	Urenco	New Mexico	4.9

(World Nuclear Association, 2022)

As shown in Table 5, the global enrichment market is centralized in Europe. Only six countries have a significant market share, dominated by four companies. Currently, NEF is the only domestic commercial facility supplying enriched UF_6 to reactor fuel manufacturers. In 2023, Urenco announced plans to expand NEF annual production from 4.6 million SWU/year to 5.3 million SWU SWU/year (NRC n.d.; Urenco 2023a, 2023b).

Uranium enrichment may be classified as a natural monopoly market structure.[18] This is relevant for Wyoming because natural monopoly industries have limited entry for new firms. A natural monopoly is an economic term for any industry where increasing the scale of production reduces the average production costs. Consequently, the existing firm can charge lower prices than any potential competitor.[19] This leads to the large firm having some market power over the price of the goods being produced that would be absent if the market consisted of many competing firms.

In the case of uranium enrichment, large upfront costs in the multibillion dollar range (see Table 4) are required. A few factors can explain this, including the number of trains of centrifuges needed to minimally operate, fixed safety investments, and decreasing production costs of centrifuges at scale. Other factors contribute to the non-competitive structure, such as government subsidies for existing firms, and anti-proliferation concerns. These upfront capital costs and government barriers provide economies of scale for existing enrichment firms and set the low optimal number of firms.

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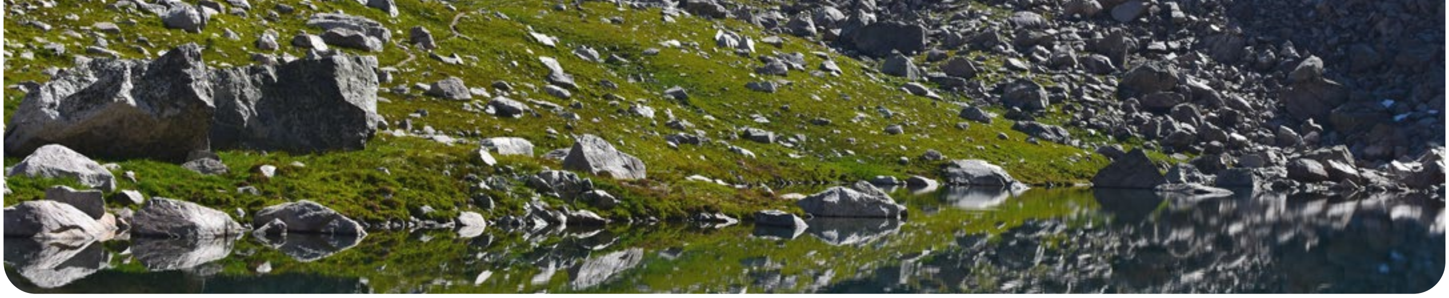
[18] Since multiple companies exist this is not strictly a natural monopoly, but the same market considerations exist.

[19] An example of a natural monopoly is the midstream gas pipeline market. The more pipelines that are laid the easier it is to connect markets. For a new firm to compete with the existing pipeline company, it will need to duplicate the pipeline network already in place for the existing firm.



To support the claim that the enrichment industry is not a competitive market, the Herfindahl–Hirschman Index (HHI) is used as an empirical test.[20] The HHI is a measure of industry concentration commonly used in anti-trust legal disputes (Hirschman 1980). The maximum HHI[21] score (10,000), corresponds to a perfect monopoly. Any HHI above 2,500 is an indication of a highly concentrated industry, while index values below 1,500 are indicative of a competitive market. The HHI of the enrichment industry was 3,340 in 2020 and forecasted to be 2,989 in 2025 and 2,804 in 2030.[22] This indicates that the market structure is consistent with returns to scale and the number of entrants is limited by this economic factor.

This helps explain why a single firm currently supplies the entire domestic market. Having already invested in the upfront capital for operating a commercial plant, capacity can be expanded by increasing additional centrifuges. A new facility would require a large upfront capital cost that NEF does not need to pay. As a result, when demand increases, the NEF facility fills that gap by increasing output rather than a competitor entering the market. The returns to scale of capital investment incentivizes expansion of existing infrastructure before investment is financially attractive in new greenfield sites.

This is also relevant to the retired Portsmouth site being refabricated with centrifuges. This site can be retooled at a lower cost than other locations because much of the upfront cost in warehouses, licensing, and uranium specific costs is available at the site. This reduces the upfront costs and thus the barrier to entry at this location.

This creates multiple challenges for investments in constructing an enrichment facility in Wyoming. The economies of scale reduce the optimal number of firms in the United States. Changes in demand schedules for enriched uranium are likely to be filled by existing facilities in Europe.[23] If the demand for United States enriched uranium increases, which is probable, the existing facilities are likely to expand before investment in a new facility is considered. Taken together there may be only one or two opportunities to construct a new facility anywhere in the country, even under ideal economic conditions. Wyoming is not at an economic disadvantage in a potential competition for acquiring one of these enrichment facilities, but the opportunities will be limited.[24]

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20 This is an update of the work in (Rothwell 2009). The HHI has reduced since this initial work. where MSi is the market share of a (Hirschman 1980).

21 $HHI = \sum (MS_i)^2$ where MSi is the market share of a (Hirschman 1980).

22 HHI to this index is calculated with the data in Table 5, with both current and forecasted enrichment production.

23 Figure 3 demonstrates that currently United States demand for uranium is primarily supplied by foreign firms.

24 Recent actualized and proposed federal funding for enrichment can move up the time horizon of these projects (Day 2023; Department of Energy 2022; World Nuclear News 2022). This funding offsets some of the expenditures the state would need to provide to incentivize new enrichment facilities. However, such funding cannot address the identified competitive advantage of existing firms over greenfield sites.

3.2 EXISTING INDUSTRIES

Score: Major Obstacle

Existing Industries: Scoring Criteria

The team identified the existing domestic industry structure as a *Major Obstacle* to Wyoming enrichment investment. An empirical analysis using a Monte Carlo simulation indicates that the two canceled projects in other states have significant financial advantages to a new facility in Wyoming. These sites can go from planning to operation in less time, and at a lower cost than a new site can. This timing element is found through the Monte Carlo model to be a more significant factor than in other industries due to the large irreversible costs in enrichment. It was found in Section 3.1 that opportunities to attract investment in enrichment are rare. Since the two canceled sites have a cost advantage over any new site, they could price out all opportunities to build in the state if there are not additional financial incentives for locating in Wyoming.

Existing Industries: Analysis

As found in Section 3.1, existing operating facilities create competition for potential greenfield enrichment. Due to the economies of scale, it is usually more cost effective to expand these existing locations to meet demand than to start a new facility from scratch.

Canceled sites also compete with Wyoming for future enrichment expansion opportunities. As discussed in Section 2.2, the EREF and GLE facilities were canceled after receiving NRC Licenses. Both of the major licenses needed to begin construction on an enrichment facility were approved by the NRC (see Section 3.5 for more details about licensing). Reactivation of a canceled facility has cost advantages over developing a new site.[25] By redeveloping these sites, some of the sunk costs[26] in research, safety analysis, and planning can be recovered. As a result, upfront costs are reduced and the time to go from planning to construction is minimized.

25 It also exceeds the pure time value of money savings created by moving all profits earlier.
26 Sunk costs are any costs that are irreversible when building a project.

This effect has influenced the selection process of enrichment firms in the past. In the GLEF planning phase, GLE identified a cost advantage for established or canceled locations over greenfield locations. Therefore, GLE focused on pinpointing sites with either existing or canceled nuclear projects. The benefits of these sites were identified as:

> *"These advantages include previous selection as environmentally suitable sites (and possibly superior, as compared to others in the surrounding region), vetting as reasonable candidates through previous site studies and regulatory licensing proceedings, community support, and existing nuclear operations infrastructure (GLE, 2008). The availability of existing infrastructure likely reduces the amount of land disturbance and the resulting environmental impacts" (NRC 2012).*[27]

In industries where there are large irreversible capital investments, the construction time is an important factor in profitability (McDonald and Siegel 1986). In the case of uranium enrichment, the multibillion dollar investment is committed once construction begins. Enrichment infrastructure cannot be easily reconfigured for other uses. Because of this, there is added value in waiting for market prices to rise above the profitability threshold. Delaying operations until prices rise is a buffer to reduce the risk of negative outcomes. Firms that have more flexibility to reduce costs as a response to price decreases (or vice versa) place less value on the option of waiting to build.

In practice, most enrichment facilities share risk with the nuclear power utilities offering long-term contracts (Poneman 2020). Even though these contracts reduce the risk of loss, the underlying economic principle still applies, and higher contracted prices for SWUs can be obtained by waiting for prices to increase.

Monte Carlo Model

The team created a Monte Carlo model of enrichment profits to provide additional economic insights about the enrichment market.[28] The Monte Carlo model simulates enrichment plant profits using 200,000 predictions[29] of SWU prices over the next 100 years. Construction and operating cost assumptions are made based on existing enrichment facilities. A profit model is detailed in Appendix D that was used to calculate expected profits relative to a benchmark cost.

[27] Page 2-42.
[28] Detailed description of the model and assumptions was provided in Appendix D.
[29] The SWU prices are predictions because SWU values are not available at the monthly level. The SWU prices used in the model are a predicted price created using the long-run relationship between uranium and SWU prices. This procedure is detailed in Appendix E.

Next, the profit is calculated under different assumptions about the time it takes to go from planning to operating an enrichment plant and the operating life of the plant. Combined with changes in strategy, this creates multiple relative profit curves to compare outcomes. See Appendix C for a complete explanation of this process.

The tabulated results are presented in Tables 6 and plotted in Figures 4. Table 6a and Figure 4a hold all factors constant except the time to go from planning to market. Table 6b and Figure 4b show the relationship between profit and facility lifetime. Comparing these outcomes identifies which factors are the most important when selecting a location for new infrastructure.

The analysis predicts that there are no scenarios where a greenfield site in Wyoming will be profitable before one of the two canceled projects begins to be redeveloped. Increasing the time to market by three years moves the profitability curve down three years from the baseline, as shown in Figure 4a all points on this curve are negative, meaning that with a three-year decrease in time to market afforded to a redeveloped site, a greenfield site will never be profitable before one of these projects begins construction. The team did not identify any scenario where a Wyoming greenfield site would be profitable without a three-year reduction in construction time or a significant subsidy.[30]

Table 6

Factor Adjustment in Monte Carlo

(a) Changes in Time to Market

Construction Time (Years)	Profit Increase (%)
0	44.9
1	37.9
2	31.7
3	26.0
4	20.7
5	15.9
6	11.2
7	7.2
8	3.5
9	0.3
≥10	Prof< 0.0

(b) Changes in Operating Life

Operating Life (Years)	Profit Increase (%)
≤20	Prof< 0.0
25	2.1
30	7.2
35	12.0
40	16.4
45	20.3
50	23.4

30 The three-year reduction in construction time corresponds to being three curves higher in Figure 4a. At three curves lower than the benchmark curve (shaded in blue) there are no prices at which profits are above zero. However, providing a subsidy of 13.5% of the expected plant revenue would even this playing field. This value should not be taken as exact due to the model assumptions.

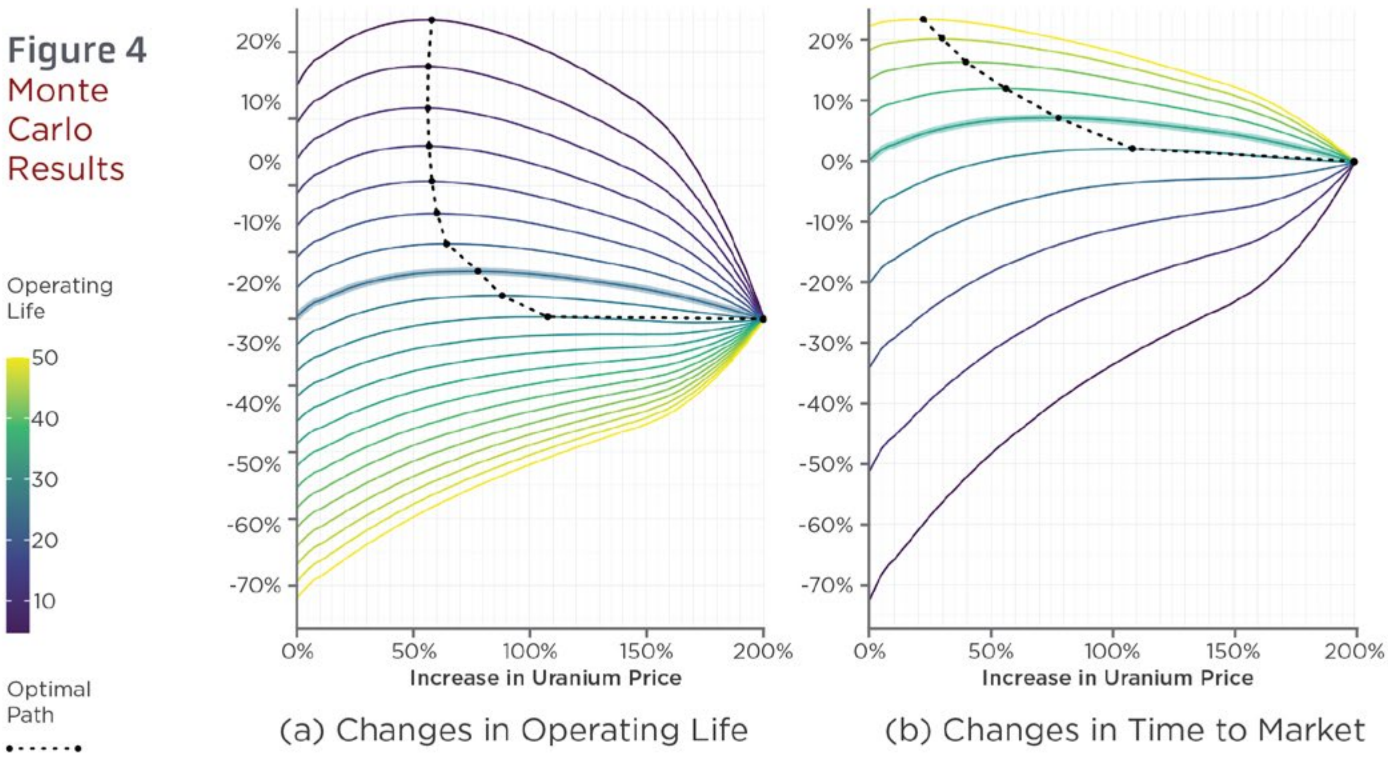

Figure 4 Monte Carlo Results

(a) Changes in Operating Life (b) Changes in Time to Market

When reviewing Table 6a at the benchmark construction time of 7 years, the profit can be increased by 7.2% of the startup costs by strategically waiting for prices to increase before beginning construction. This factor illustrates how the value of waiting to construct is relevant to enrichment companies. The less time spent constructing the enrichment plant, the more valuable the project becomes. Reducing construction time from 7 to 6 years increases the benchmark profits by 3%, but reducing construction time from 2 years to 1 year increases profits by 6.2%.[31]

Tables 6 show larger returns resulting from decreasing the “time to market” rather than increasing the facility “lifespan”. This result is driven by the fact that the lifespan of a typical project is 30 years, so any new revenue will be worth 74% less than an equivalent present income stream.[32] On the other hand, reducing the time to go from planning to market shifts the entire revenue stream forward.

The most significant finding is that the value to firms of reducing the time to go from planning to market is a larger determinate of profits than in other industries. While the numerical results will change if the model assumptions are modified, the relative ranking of factor importance is robust. The analysis shows that an unsubsidized investment would be ranked behind more profitable previously-licensed sites in Idaho and North Carolina, all else equal. This is before accounting for the discount in development costs of the existing sites, which further favors the redevelopment of historically planned locations.

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[31] 37.9 − 31.7 = 6.2.

[32] Due to the time value of money any revenue in 31 years at a discount rate of 4.5% discounted by 74%.

3.3 TAX STRUCTURE

Score: Moderate Obstacle

Tax Structure: Scoring Criteria

The team concluded that the Wyoming tax structure provides a *Moderate Advantage* for the enrichment industry. Data from enrichment plant licensing was used to estimate how the expected tax burden might change if these facilities were relocated to Wyoming. The results show that locating in Wyoming will reduce the overall tax rate in both case studies. The two states compared to Wyoming, Idaho and New Mexico, have lower corporate property tax rates, ranking as the number one lowest tax rate and number three lowest, respectively (Fritts 2022). This is a key factor for industries that are capital intensive and labor light as is the case with the enrichment industry. Wyoming compensates for higher property tax rates by having no corporate income tax. While the estimates are dependent on the final assessed value and mill rate, the expected tax savings are large enough to justify a *Moderate Advantage* for the State.

Tax Structure: Analysis

Wyoming's tax code is generally favorable to the business interests of enrichment firms. The State levies no corporate income tax and uranium enrichment does not fall under a mineral severance tax structure. The only direct tax on the enrichment industry would come from property taxes on the plant, which is higher in Wyoming than the two references states selected (Idaho and New Mexico) (Fritts 2022).

In Wyoming, an enrichment facility would fall under the classification of "industrial private property", which has a tax base of 11% (Wyoming Taxpayers Association 2022). Under the Wyoming tax code, property tax rates are adjusted based on the annual cost of operating government programs. This adjustment is referred to as the mill levy and the most recent state average was 0.068 (Wyoming Taxpayers Association 2022).

Two facility plans were used to benchmark the Wyoming tax rate, the NEF facility in New Mexico and the EREF facility in Idaho. NEF was selected because it is the only operating uranium enrichment facility. The EREF facility was selected because it is the closest licensed enrichment facility to Wyoming. The EREF facility was used to create a tax burden benchmark to calculate the final assessed property values. There is limited data on the estimated tax expense of enrichment firms, but the plans for EREF include enough data to formulate an assessed value estimate. This facility was estimated to bring in $3.5 million annually in property taxes to the county, which had set property taxes to between 1.01-1.06% (Areva and NRC 2011). This implies the assessed value of the plant was $487.15 million.[33] The team assumed no variance in regional land values based on the highly specialized facility. The low population region selected by Areva has comparable land prices to Wyoming, but ignoring these differences introduces some bias to the estimate.

[33] This number is inflation adjusted to 2023.

The plans for the New Mexico NEF site provide expected gross tax payments, but does not distinguish between property tax and income tax. Therefore, the assessed property value cannot be calculated for the project. However, the EREF project and the NEF site have identical planned SWU capacities, making the total tax burden comparable between the two.

Using these estimates, a six million SWU facility would contribute $4.52 million per year to Wyoming. The total tax burden for the Idaho Eagle Rock project was projected to be $6.92 million per year (Areva and NRC 2011). A tax burden at $9.65 million per year can be calculated using the Urenco New Mexico plans (NRC 2005).

Using these estimates, the Wyoming tax structure would save an enrichment company $34.8 million compared to Idaho and $74.75 million compared to New Mexico[34], suggesting that the tax system is a net advantage for attracting greenfield facilities to Wyoming. However, the actual rate of return is complex, and this projection is likely to be an overestimation of tax benefits. The expected value of saving $34.8 million at the state level is offset by tax write-offs at the federal level. These write-offs depend on the portfolio of the firm and the timing that the costs of construction are deducted[35]. It should also be noted that paying larger rates in terms of property values imposes additional financial risk. If market conditions crash, the firm will still need to pay taxes based on the property value whereas an income tax will shrink as the price of SWU declines. Even accounting for this uncertainty, the tax code in the State is a net positive for uranium enrichment facilities and promotes development.

3.4 LOCATION

Score: Minor Advantage

Location: Scoring Criteria

The team concluded that locating in Wyoming is a *Minor Advantage* for the enrichment industry. Location-specific attributes in Wyoming are found to allow development to proceed. Wyoming has regions that are amenable to enrichment site development due to reduced risk of seismic events and extreme weather. This lowers costs for the firm through risk mitigation and reduces the dependence on safety equipment. However, sources of uranium hexafluoride are farther from Wyoming than other sites, increasing transportation costs. Wyoming's burgeoning nuclear industry and well-established energy industry provide an economic draw for enrichment investment.

Location: Analysis

Location-specific factors affect the profitability of the enrichment industry and change the ranking of sites being evaluated. In consideration of revenue, firms are better off if they can reliably operate the centrifuges, transportation to markets is consistent and there is a steady source of inputs. Weather events that require shutting off production or unreliable roadway infrastructure reduces expected income. Costs are also affected by site location. The risk of damage to the facility is influenced by weather, construction costs are affected by ground conditions, and environmental monitoring costs are dependent on the local ecology.

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[34] Assuming a 30-year operating life, a 5% discount rate, and a 5-year linear project deprecation.

[35] Much of the data necessary to make a complete tax estimate is not available publicly.

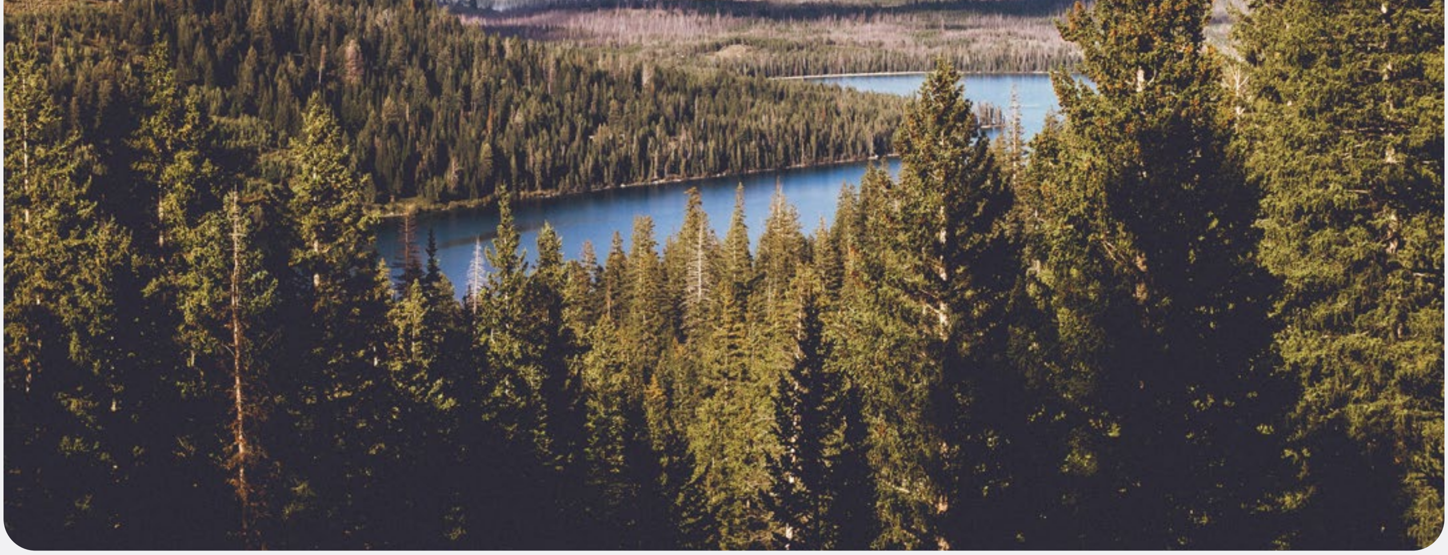
The team applied a qualitative approach, comparing the location considerations used by the industry to the conditions in Wyoming. We relied on the environmental reports filed with the NRC to pinpoint the categories of location factors most pertinent to the firm's cost considerations. These final reports reveal the factors that are important to potential investors even though the underlying costs remain confidential information.

Key cost considerations can be found in the process used by Areva to select the EREF enrichment site in Idaho. In the Environmental Impact Statement, Areva followed a four-step process in selecting a final location for construction. These included: 1) identifying potential regions; 2) screening sites; 3) evaluating in more detail the sites screened; and 4) selecting the preferred site (NRC 2011b).

For the initial screening phase of the EREF project, three cost considerations were used that can be applied to Wyoming. Areva noted that many "*environmental impacts can be avoided or significantly reduced through proper site selection*". Enrichment firms consider not only a site's suitability to meet NRC regulatory standards from a legal and engineering perspective, but they also rank the costs of compliance at each site with economic considerations. There is a balance between mitigating risk and avoiding risk. The enrichment firm can mitigate the risk of hurricanes by improving construction, purchasing insurance, and creating contingency plans. However, insurance costs can be lowered by selecting a location in the center of the country without hurricanes. This trade-off between risk avoidance and mitigation affects the bottom line and explains the selection process of Areva.

The criteria used by Areva to avoid such costs were as follows.

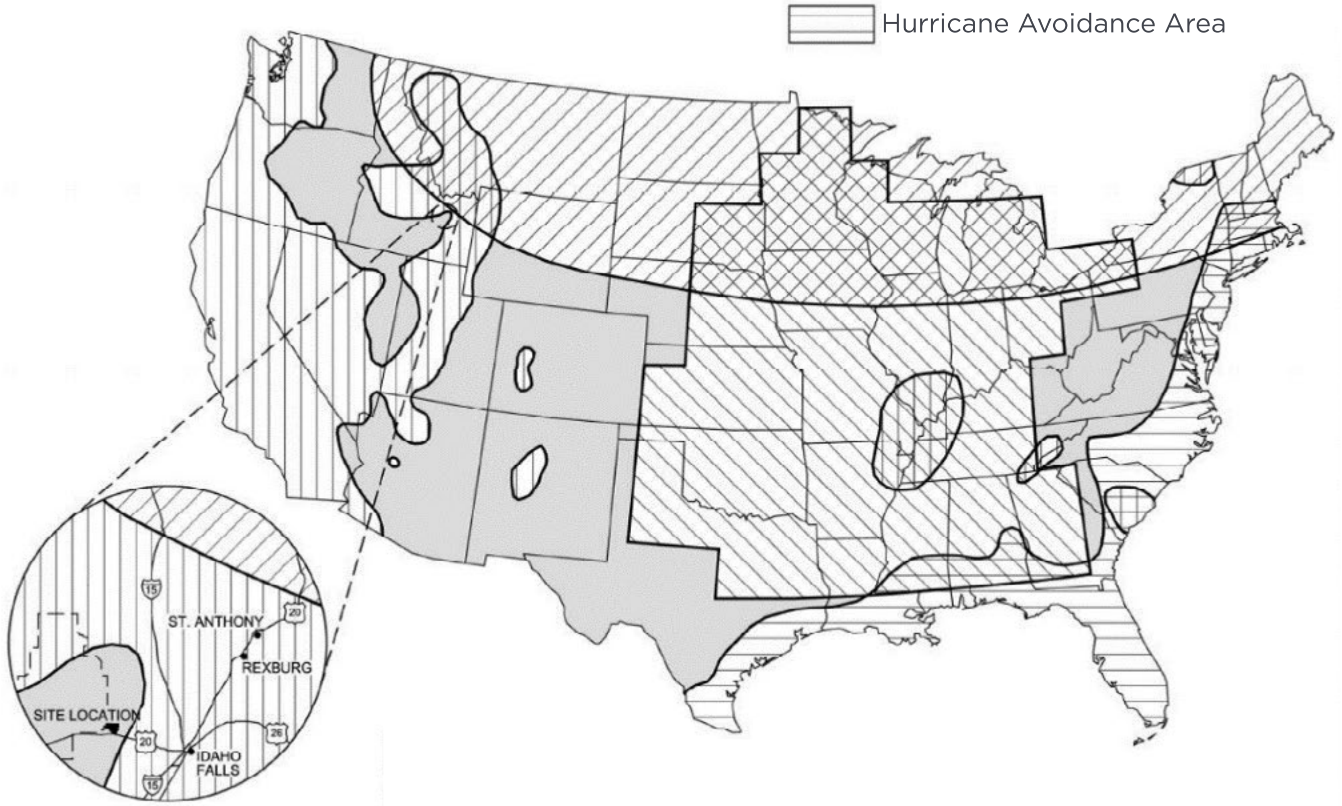
- **Peak ground acceleration:** A revenue factor, the centrifuges are sensitive to vibration and geologic activity can disrupt or damage output.
- **Tornado frequency & Hurricane frequency:** Cost factors, facilities built to withstand high winds were too expensive to be economical.
- **Severe winter weather:** A revenue factor, the frequency of road closures in the surrounding area, was considered. Such closures limit input and output shipments, restricting production.



From these initial screening criteria, Areva created a map of all potential sites reproduced in Figure 5. Most of the United States was ruled out as candidate sites. Notably, Wyoming has areas in the South of the State that Areva identified as providing a low operational risk.

Figure 5
Screening Process for EREF

Regions that Meet Initial Criteria
Seismic Avoidance Area (g > 0.09)
Tornado/High Wind Avoidance Area
Winter Weather Avoidance Area
Hurricane Avoidance Area



(NRC, 2011).

In the second selection phase, Areva considered eleven additional factors, that can be used as a litmus test for potential Wyoming sites. All compared sites were given a pass or fail grade by experts in each of the categories:

1. Seismic history
2. Geology
3. Site size relative to facility footprint
4. Redundant electrical power supply
5. Flooding potential
6. Prior land contamination
7. Availability of existing site data
8. Threatened and endangered species
9. Sensitive properties
10. Climate and meteorology
11. Wetlands within the facility footprint

Using these factors, Wyoming could be a competitive location. Locations in the state possess redundant electricity sources and large plots of land. While the State does have endangered species, such as the black footed ferret, the sensitive territories can be avoided. The initial list of sites being screened by Areva did not include a location in Wyoming, so there is not a direct scoring metric provided for a Wyoming location. However, it is notable that the site selected was the closest to Wyoming of any of the candidate sites. Overall, this scoring system indicates that some parts of the State boast features that are beneficial to a greenfield site development.

The GLE plant plans also provide insight into location economic factors that affect site selection (NRC 2012). The initial screening of locations for GLE begins with transportation cost considerations as compared to Areva's evaluation of risk mitigation. GLE only considers sites that are within 600 miles of key inputs and outputs. In deciding between the final two sites, GLE found the transportation cost savings of the Wilmington site, which has a collocated de-conversion facility, to be the deciding factor (NRC 2012)[36].

While mines supply the raw source of uranium, enrichment plants require an input of converted uranium hexafluoride. At the time the report was written, there were no operating uranium conversion plants in the US, so inputs had to be imported from overseas, or trucked from Canada. The distance from these sources determines the final operating costs of the plants. Since then, the Metropolis Works plant located in Illinois restarted operation in 2023 after six years of being idled (World Nuclear News 2021).

The next step in the supply chain after the enrichment is the fuel fabrication facility. The distance from these markets also affects operating costs. Rather than selecting the cost minimizing location, GLE considers all locations within a 600-mile radius of the centroid of these markets to be a cost-effective option. Other factors can outweigh the importance of transportation costs, so any site in this region was considered worth evaluating. The map of this initial screening process is reprinted in Figure 6.

The high concentration of markets for the final good (fuel fabrication sites) and markets for input goods (ports and conversion plants) lead GLE to narrow in on sites on the east coast.

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[36] Pg 2-49.

Figure 6
Screening Process for GLEF

(Nuclear Regulatory Commission, 2012).

While Wyoming was eliminated from consideration based on this initial screening, the outcomes of this cost factor are mixed for the State. Shipping requirements for uranium hexafluoride in specialized cylinders does add to operating costs and comes with some contamination risk (Department of Energy 1987; L. Begue et al. 2013). The State is far from both input and end demand sources making a Wyoming location less appealing than east coast enrichment facilities, all else equal.

However, as the nuclear supply chain evolves, this disparity will shrink. The planned TerraPower facility provides one source of demand within the State and any other advanced nuclear reactors developed near the west coast will encourage fabrication facilities to be built nearer to the State. In turn, this would pull the centroid nearer to Wyoming. Additionally, the report identifies an existing nuclear industry and stakeholder support as important considerations. Regional economic theory predicts that related firms often cluster together. The development of specialized infrastructure, availability of trained labor, and localized knowledge drive down operating costs for companies that move to a centralized area (McCann 2013)[37]. Wyoming has existing uranium mining, a robust energy sector, and a populace that is favorable towards the nuclear industry (Western and Gerace 2020). These can lead to regional clustering, further encouraging long-term nuclear sector development in the region.

The second screening process for GLE provides more insight into location factors relevant to Wyoming. In this phase, GLE scored potential sites under consideration for weighted metrics:

Impacts to the Environment (weighting factor = 0.27)

Impacts to the Facility (weighting factor = 0.25)

Impacts to Time and Cost (weighting factor = 0.24)

Employment and Stakeholders (weighting factor = 0.24)

These factors are comparable to the cost categories used by Areva. Under "Impacts to the Facility", geologic, climate and wildfires are identified as important considerations. In the "Impacts to Time and Cost" category, contamination, existing infrastructure, colocation, and physical characteristics are notable factors. The "Employment and Stakeholders" metric includes stakeholder support, as well as labor force availability.

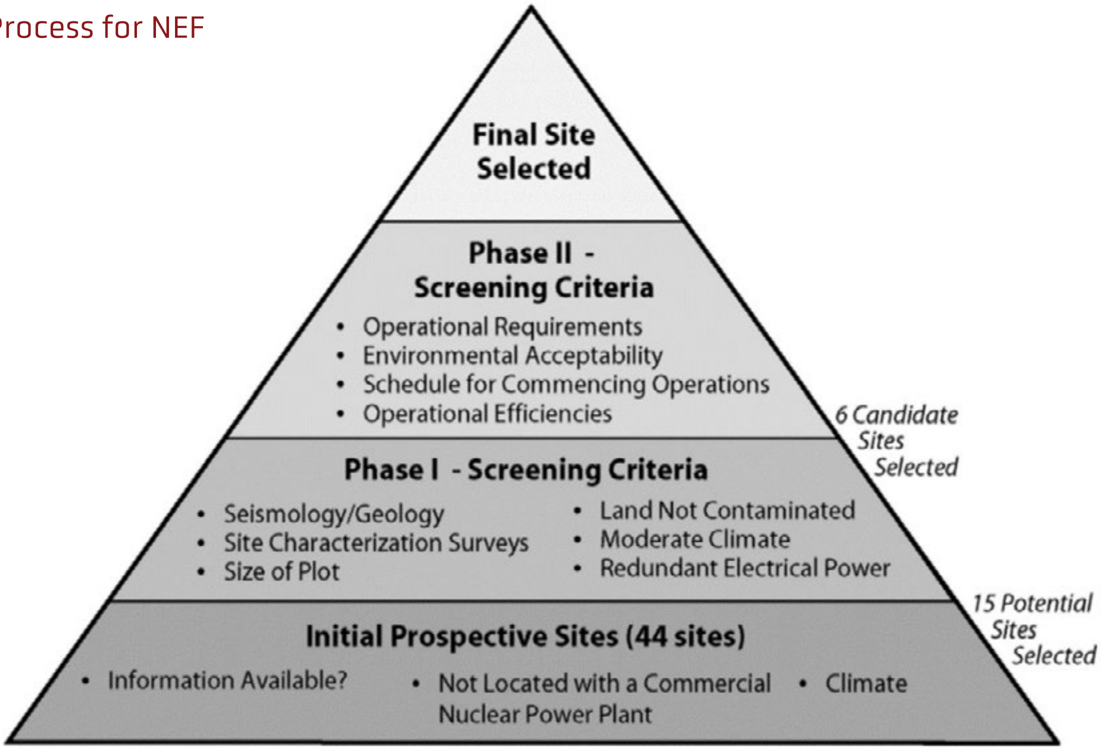
While Wyoming was ruled out due to transportation cost issues, a future site could score well in this second set of criteria. There is collocation with other segments of the supply chain, including mining and electricity production. In addition, there are lower risks of fire and hurricanes than in most parts of the country and stakeholders are already deeply involved in the energy sector.

The final Environmental Report evaluated was from the operating NEF facility (NRC 2005). Unlike the other two sites, there are no prescreening criteria listed for the initial sites. However, 44 sites were identified by LES (Louisiana Energy Services) as potentially viable. The process of selecting a site from this list is detailed, with the procedure diagrammed in Figure 7.

LES eliminated 66% of the initial sites, based on factors affecting safety and costs. Sites located near operating nuclear power plants require additional security and were eliminated from consideration. The other sites were eliminated because they lacked environmental information. This demonstrates that a Wyoming-based site could receive consideration in future projects if environmental studies are available. Environmental uncertainty adds a cost because the range of outcomes is large. The cost of surveying a site cannot be recovered if the site is found unsuitable. There is less risk of project delays when detailed environmental information is available.

[37] An example of this is Silicon Valley. In theory, software companies could locate anywhere on the globe, but they tend to cluster in areas where existing competitive and complementary firms operate.

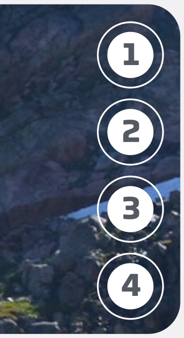
Figure 7
Screening Process for NEF



(NRC, 2005)

The phase one screening eliminated nine of the remaining 15 sites. Six sites had too large of an earthquake risk, four sites were too small, and one site had too large of a flood risk.[38]

The final NEF selection process accounts for factors of economic, safety, and environmental concern. These are weighted to provide a score to each remaining site, as follows:



1. Operational Requirements (weighting factor = 100)
2. Environmental Acceptability (weighting factor = 80)
3. Schedule for Commencing Operations (weighting factor =70)
4. Operational Efficiencies (weighting factor = 60)

[38] These numbers do not add up to nine, because some sites had multiple eliminating factors.

These are some of the most important factors to consider, but legal factors can still supersede them when considering a site for development. The highest scoring site in Eddy County, New Mexico was not selected for development due to property rights concerns. The site was owned by the BLM and leased for cattle grazing. Federal regulations require that the permit holder be given two years' notice before the land can be sold. As analyzed in Section 3.2, the time to go from planning to market is a major factor to profits. This potential delay to the start of the project was deemed a significant enough obstacle that LES did not move forward with development at this top scoring location.[39] Wyoming has over 17.5 million acres of land under BLM management (Bureau of Land Management n.d.). However, there is more private land located in the Southeast of the state (Fahrer and Bureau of Land Management 2020).[40] Addressing this potential delay will minimize the location-based barrier for Wyoming.

The scores of other sites were lowered for multiple reasons. In Tennessee, zoning requirements could not accommodate the proposed site (see section 3.5 for zoning discussion). In Alabama, the site was located near an Indian reservation, creating an added cost of historic preservation assessment. Other sites had the potential for contamination from potash mining, oil-field welding, and firing ranges.

A few trends emerge in these site selection processes. Locations with lower operating costs due to transportation, or risk mitigation are preferred. Sites are also selected in regions amenable to nuclear development, that avoids hold-ups in land purchasing or permitting. Finally, the availability of information can make or break a potential site. All else equal, available seismic, weather, and environmental data increases the value of a candidate site. Viable sites are passed over when there is an elevated level of uncertainty about cost overruns. Providing this information reduces uncertainty in outcomes to the firms, which adds to expected profits. One avenue to encourage development in Wyoming is to make such evaluations available to enrichment companies.

3.5 LEGAL

Score: Minor Obstacle

Legal: Scoring Criteria

The legal barriers to uranium enrichment development are scored as *Minor Obstacles* at the state and federal level. Of the two, federal legal requirements are found to be the most difficult to overcome. Federal regulations require companies to provide evidence of environmental, social, and economic efficiency. While this process takes a few years and can be expensive, most applications succeed in receiving an operating license from the NRC. States that can assist in this phase of development have a leg up over other regions.

39 This two-year delay period can be waived by the lease holder. But even accounting for this LES considered the risk of project delays significant.

40 The southeast of the state meets many of the other criteria used, so is a prime area for future consideration.

In Wyoming, there are no uranium enrichment regulations that would create development obstacles. Zoning regulations and waste disposal laws are relevant, but unlikely to create an undue burden on firms. Therefore, State legal barriers are also scored as a *Minor Obstacle*, albeit these are closer to a *Neutral* score than the federal legal barriers.

Legal: Analysis

The NRC has responsibility for licensing and enforcing Rules and Regulations at United States commercial enrichment facilities. Licensing requirements are specified in Title 10 of the Code of Federal Regulations (10 CFR) Part 70, "Domestic Licensing of Special Nuclear Materials". The content of license applications is complex and must conform to NUREG-1520, "Standard Review Plan (SRP) for the Review of a License Application for a Fuel Cycle Facility" (NRC 2015). In practice, two reports must be prepared, an operation report (covering safety and technical plans) and an environmental report (NRC, 2003).

The license application must include detailed facility safety analyses, design bases, physical security plans, emergency preparedness plans, financial reviews, and National Environmental Policy Act environmental reviews, which are extensive. A license application takes several years to complete. Additionally, the NRC may take several years to conclude their review after the application has been submitted.

NRC reviewers compare the contents of the application to the specific governing regulations, detailed requirements and format specified in the SRP (Standard Review Plan). For example, Louisiana Energy Services submitted the National Enrichment Facility License Application to the NRC in 2003 (NRC n.d.). The NRC did not issue the "Construct and Operate" License until 2006. The NRC charges variable rates to recover expected operating costs. In 2023, the professional hourly rate of NRC license and review is $300/hour (Castellon 2023). As a starting point for a license cost, if it takes three years, with 10 FTE, the initial license review would cost at least $22 million. An annual operating fee is also required, with the most recent fee for enrichment being $2.247 million (NRC 2023c). Both costs are significant and contribute to the economies of scale identified in Section 3.1.

Another federal legal obstacle emerges when the facility is to be built on BLM land. The lease holder must be given two years' notice that the land will be sold.[41] As explained in Section 3.2, project delays affect profitability of enrichment firms more than most industries. That makes this delay a major barrier for enrichment facility development. A case in point is the NEF facility, where the number one preferred site was passed over because it was located on BLM land (NRC 2005) (see Section 3.4).

The authority of regulating nuclear material can be passed over to the state under an agreement with the NRC. Wyoming has opted into such an agreement, but it only extends to the mining and milling process explicitly excluding:

> "The regulation of the construction and operation of any production or utilization facility or any uranium enrichment facility" (NRC, 2018)

[41] CFR § 2711.1.3

The state legal responsibility, therefore, only includes existing non-nuclear specific regulations; zoning and waste management regulations being the most likely to hinder development. This can be a determining factor for site selection, and a potential site for the NEF was eliminated due to zoning restrictions preventing development (see Section 3.5). However, no Wyoming laws were found to significantly burden the construction of a greenfield facility. While the state of Wyoming is not directly involved in approving the environmental report, there are ways that the State can ease the process. The availability of seismic, infrastructure, and environmental data from State studies reduces the cost of compliance.

3.6 TECHNOLOGY

Score: Neutral

Technology: Scoring Criteria

The uranium enrichment industry is mature relative to other segments of the nuclear industry. Technological innovations in the laser enrichment process have the potential to improve economic efficiency, but will not change the underlying market structure. No technological barriers were found to disproportionately affect Wyoming industry. Since the trajectory of the enrichment industry will continue without a need for innovative technology, technological barriers are scored as being *Neutral* to Wyoming development.

Technology: Analysis

Technological limitations can affect industry growth if increased research and development will make new production cost effective. In some cases, technology can disrupt existing processes promoting growth in some locations, but causing a contraction in other regions. Here, the available and developing enrichment technology is reviewed. This is done to identify any limits to Wyoming growth in the enrichment sector due to technology constraints. Enrichment technology has changed over time, but none of the future developments are expected to dramatically change market conditions.

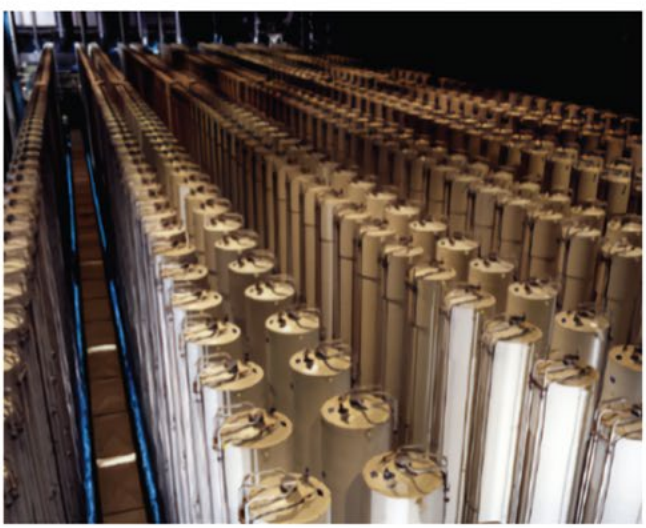
There are four categories of enrichment technologies. These include: (1) electromagnetic isotope separation; (2) gaseous diffusion; (3) gas centrifuge separation; and (4) molecular laser isotope separation (Hogan 2021).

The first technology used to enrich uranium is electromagnetic isotope separation (EIS). The United States Corps of Engineers constructed and operated the first industrial scale uranium enrichment facility using this methodology during World War II in the Y-12 plant (Department of Energy 2023; Hogan 2021). Using the same principle as the modern mass spectrometer, the lighter U-235 travels less distance than U-238 when exposed to the large magnetic field (Department of Energy n.d.). While some innovations to EIS technology have been explored, it is unlikely to return as a major source of enrichment (Arias and Parks 2016).

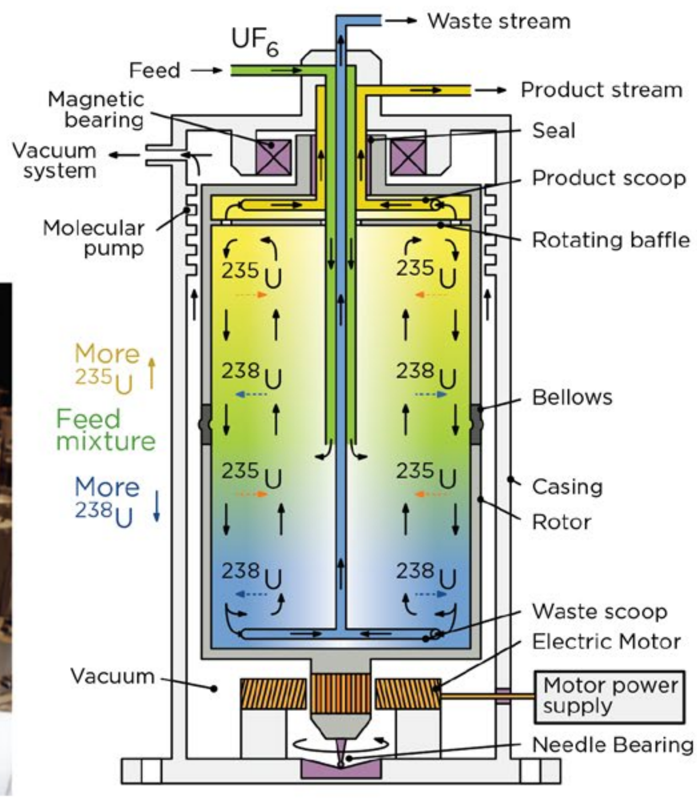
The second technology applied to enrichment is gaseous diffusion. The first step in this process is converting uranium into a gaseous form. Uranium oxide is shipped to a conversion plant in drums (Charette 2015). The ore is then processed in the conversion plant which binds the uranium to fluorine, creating uranium hexafluoride. The uranium hexafluoride gas (UF_6) is the feedstock of the enrichment facility. The separation operates on the principle that lighter isotopic molecules pass through a porous barrier more readily than heavier isotopes.

The UF_6 gas is pumped through a series of diffusion trains. Each train uses a semiporous membrane to separate U-235 (UF_6 gas) based on the slight differences in the velocity of the lighter U-235 isotope (World Nuclear Association 2020). This form of enrichment has the largest economies of scale, requiring major infrastructure to achieve cost effective outcomes. Additionally, the process is energy intensive, which makes the operating costs of gas diffusion plants highly dependent on electricity prices.

Figure 8
Gas Centrifuge Enrichment



(b) Centrifuge Cascade



(a) Centrifuge

Figure 8a: The Conversation (https://theconversation.com/enriching-uranium-is-the-key-factor-in-how-quickly-iran-could-produce-a-nuclear-weapon-heres-where-it-stands-today-186985) from (https://en.wikipedia.org/wiki/Gas_centrifuge#/media/File:Countercurrent_Gas_Centrifuge.svg)

Figure 8b: Energy Education. https://energyeducation.ca/encyclopedia/Gas_centrifuge_for_uranium_enrichment) From https://en.wikipedia.org/wiki/Gas_centrifuge#/media/File:Countercurrent_Gas_Centrifuge.svg

The third enrichment technology applied at commercial scales is gas centrifuge separation. Like gaseous diffusion, this process starts by converting solid uranium into a gaseous form. Centrifuge technology separates the lighter UF_6 molecules through centripetal force. The UF_6 stream is rotated and the slightly U-238 gas is brought to the rim of the centrifuge and expelled and repossessed or stored in cylinders (Saylor et al. 2021). The remaining U-235 rich gas is withdrawn and fed into the next centrifuge. Figure 8a represents a single stage in this process and Figure 8b shows an enrichment chain. This technology is now the dominant commercial method of uranium enrichment, having lower operating costs than gaseous diffusion (Rothwell 2018). The first centrifuge enrichment facility in the United States is the National Enrichment Facility (NEF) which began production of enriched UF_6 in 2010 (Urenco 2023b). While still requiring large economies of scale, average plant sizes have been reducing since the adoption of this technology. It also allows for enrichment facilities to be built modularly, completing one enrichment chain at a time. This is how the NEF facility has gradually added capacity since beginning operation in 2010 without requiring shut ins of the operation.

The final category is laser separation, investigated since the 1970s, but only recently attempted to be operated at commercial scales (International Atomic Energy Agency and IAEA 2023; Midkiff 1978). This method uses lasers to excite flowing uranium isotopes, allowing the lighter isotopes to be separated at the nozzle (Makarov 2020).[42] This technology was tested for commercial development by Urenco in the 1990s. The conclusions of these tests were that the process can be moderately more cost effective than centrifuge technology, but that gas centrifuge technology comes with less uncertainty (Schneider 1995). The Global Laser Enrichment Facility (GLE) was planned to begin laser enrichment in 2014, but was delayed and finally canceled in 2021 (Damaris 2021; NRC 2012; Olivier 2012).

When evaluating the barriers posed by technological development, the obvious future path of research is in laser enrichment technology. The biggest advantage for Wyoming is that the technology can be operated at a smaller scale, requiring only one enrichment stage, potentially mitigating the economic barrier of large economies of scale identified in Section 3.1. However, since the only planned laser facility was intended to be larger than any existing United States enrichment plant, there still are economies of scale. Advances in enrichment technology will not reduce the cost of site permitting and these permitting costs continue to provide an incentive to develop large sites.

42 Much of the methodology is proprietary, but the outcomes of the process make this the most likely process being applied.

4.0 BENEFITS AND COSTS

4.1 GENERAL BENEFITS

New Wyoming uranium enrichment sector investment would generate direct and indirect economic benefits in the form of employment and tax revenue, while also attracting related industries. Much of the immediate effect on jobs and tax revenue would come through capital investment into constructing the facility. This would provide jobs in the construction sector and create wage pressure, raising construction salaries in the State for approximately a decade. Once operational, the enrichment facility would provide direct jobs in engineering, transportation, and storage experts. Other economic gains will come from spillover effects in industries such as restaurants, road work, and housing. There will be increases in revenue from the money spent by workers hired to construct the new facility.

The indirect effects may also be the longest lasting, primarily driving agglomeration of related nuclear industries in the State. Having local mining and enrichment facilities would provide an additional incentive for nuclear reactors to be built within the State along with the associated activities.[43] The effect of the enrichment includes the potential to draw in sectors that themselves will have direct economic impacts to the State.

4.2 GENERAL COSTS

To have a complete picture of the outcomes created by the enrichment industry, financial, environmental, and sociological costs also need to be considered. The main material cost to Wyoming residents from permitting a uranium enrichment facility is associated damages with stored uranium hexafluoride. The stored gas creates risk of fire and toxicity to local inhabitants (Department of Energy 2020; Fisher et al. 1994; Mohsendokht 2017). While the technology exists to convert hexafluoride back into uranium oxide with low background radiation levels, the costs are significant. Often, it is most cost efficient to store uranium hexafluoride in reused cylinders until plant retirement. This storage risk will persist for the life of the enrichment plant, which can exceed fifty years. Enough uranium hexafluoride is stored at the Paducah and Portsmouth that environmental legal liability is $7.2 billion (United States Government Accountability Office 2022).

[43] See Section 3.4 for details.

Policy can be used to manage this risk, but not without tradeoffs. New Mexico reached an agreement for NEF to limit the total volume of depleted uranium hexafluoride to 60,000 tons (Johnson 2006). While some considered this a major safety improvement, others estimated the money set aside for damages would not cover disposal costs (Johnson 2006; World Information Service on Energy 2005). In either case, there are inherent policy tradeoffs. On the one hand, increasing the required retainer limits the risk of unfunded cleanup efforts; however, adding these upfront costs reduces the project's value. Shifting the cost of disposal from the future to the present reduces the project's total expected value due to the time value of money.

There are also justice concerns in managing the enrichment facility application process. An example of this risk is the case study of an enrichment facility planned to be built in Homer, Louisiana, in 1993. The NRC permitted Louisiana Energy Service to begin construction, but received additional legal scrutiny when it was noted that the location was rural and had a large minority population (Payne 1997; Wigley and Shrader-Frechette 1996). Despite having permits, the planned facility was canceled. Most comments sent to the NRC from the local community were positive, with 100 letters supporting the project compared to 50 opposing it (NRC 1994). While Wyoming residents have a higher-than-average positive view of nuclear energy, (Western and Gerace 2020) there is still a risk that after development, societal concerns could halt development. This is particularly true in low population density regions of Wyoming, where a facility will be incentivized to locate, due to lower land costs.

4.3 LONG-TERM ECONOMIC IMPACTS

Potential enrichment industry employment in Wyoming was empirically estimated using a micro economic strategy. NEF was used as a benchmark since it is the only United States enrichment facility in operation. It employs 230 full-time staff (Urenco 2023b). In comparison to another Wyoming industry, the entire United States uranium mining sector[44] has an employment rate of 207 person-years (Energy Information Administration 2023).[45] A new Wyoming enrichment facility would create a similar number of jobs.

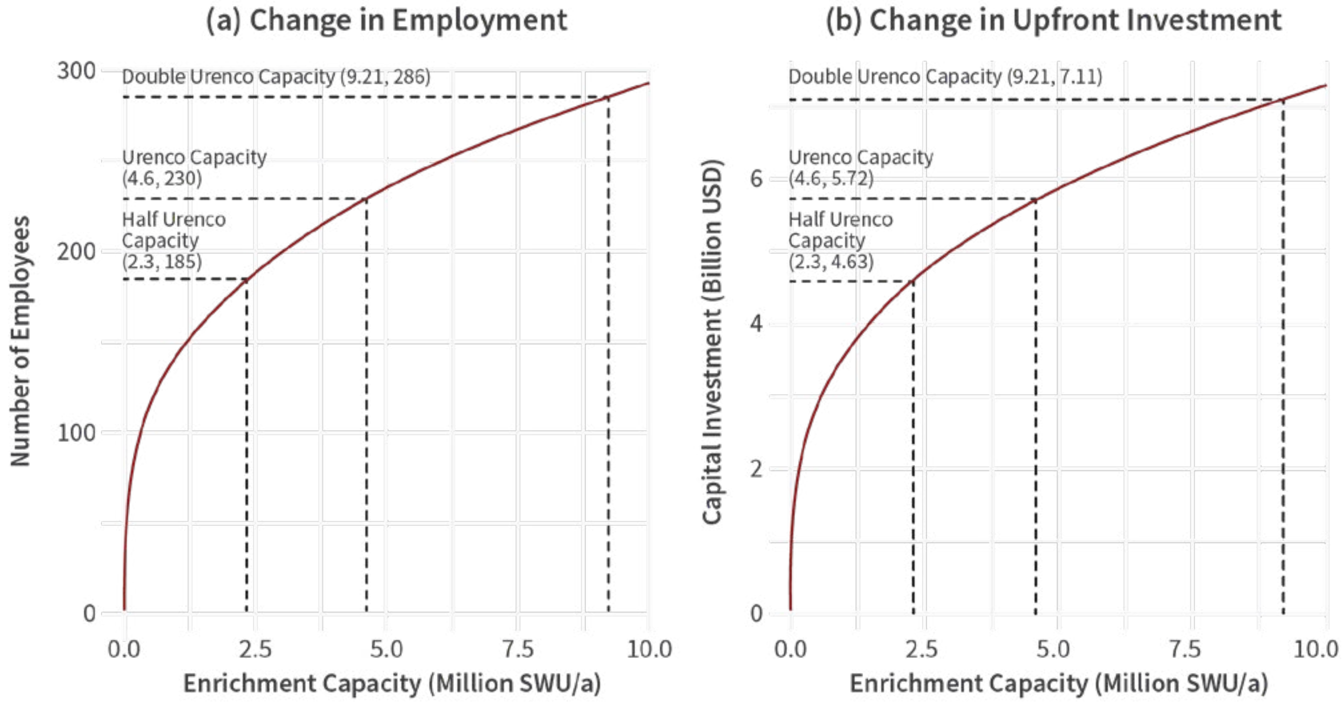
By combining this reference point with estimates of the returns to scale of uranium enrichment, the impacts to the Wyoming economy can be approximated over a range of facility sizes. Given the market's natural monopoly structure, it is unlikely that two or more enrichment facilities will be built within the State. This allows for plant level data to be used to estimate the overall economic effects on the State. The most recent estimates of return to scale in enrichment facilities imply that for every 1% increase in SWU capacity the construction costs are increased by 0.75% and long-term employment by 0.46% (Rothwell 2009).

44 This broad sector includes the industries of exploration, mining, milling, and reclamation of uranium.

45 It should be noted that Urenco states that there are 230 people employed, which may include part-time workers. Whereas this estimate of employment would consider a part-time worker as a fraction of a person-year.

By assuming the production rate's functional form, these estimates predict economic impacts in Wyoming. A Cobb-Douglas model (Cobb and Douglas 1928), which treats output as a function of capital investment and labor, is calibrated using these economies of scale (see Appendix F for model details). Figure 9a shows the number of jobs added to the State as the plant's capacity increases. The same sum for initial investment in the facility is provided in Figure 9b.

Figure 9
Economic Outcomes with Plant Capacity



This analysis indicates that the relationship between the number of added jobs and the amount of initial investment are not linearly related to the output capacity of enriched uranium. Under a high price scenario where demand leads to a facility double the size of that in New Mexico, the increase in long-term jobs only increases by 56 people, from 230 to 286. Similarly, a plant of that size would increase initial investment from $5.72 billion to $7.11 billion. Doubling the SWU output increases either value by approximately 24%. The direct gains to Wyoming from employment and economic stimulus from facility construction are likely to remain bounded by these economies of scale. However, continued returns to scale benefit the state in indirect ways. They provide a demand source for uranium mined in the State and a low-cost supply of enriched uranium to new nuclear power plants.

4.4 SHORT–TERM ECONOMIC IMPACTS

Complementing this analysis, economic gains from the initial construction were estimated using an input-output model of production (Leontief 1986). These forms of models balance the economic system of equations by linking the output of one sector to the input to another.

The model used comes from IMPLAN[46] and allows for observed sector level data in Wyoming to balance the model. The model provides estimates of the total tax revenue and employment changes added up over the life of the project.[47] If a $5.72 billion facility were built, tax revenue for the State is predicted to increase by $90 million through indirect spillover effects that stimulate economic growth. However, the direct effects are estimated to cost the State resources, with a net increase in state program costs of $8 million. The facility would induce an increase in employment of 63,000 person-years primarily in the construction industry.

The upper bound estimate of a $7.11 billion facility would induce a total increase of tax revenues of $111 million, but with a cost of $10 million in increased spending. Total employment during construction would reach 79,000.[48] A lower bound estimate is generated by assuming a facility with half the capacity as NEF is built. Total tax revenue for the State would be $72 million, and program costs would rise by $6.6 million. Employment totals induced would be 51,000 person-years.

These tax estimates only account for the economic effects during the facility construction period. Following the same procedure as in Section 3.3[49] the direct taxes during operation can be estimated. The expected annual property taxes from the project are expected to range from $4.54 to $5.63 million per year. This has a net present value of between $66 to $82 million for the State.[50]

4.5 TIME HORIZON OF ECONOMIC IMPACTS

These economic effects will persist over many decades and are not sensitive to future uranium prices. The choice to construct a new enrichment plant is dependent on the long-term expected price of enriched uranium, but the economic impacts of the plant are robust to price declines after construction. The day-to-day cost of uranium enrichment output is low and equipment can be damaged if it is not continually operated. Despite the high upfront (sunk) cost of construction, the output rate will only have slight fluctuations. This extends the operating horizon of facilities. A recent example is the closure of the Paducah, Kentucky, facility which operated from 1952 until 2013. These sunk costs decouple the expected benefits to Wyoming from the fluctuation of the uranium enrichment market.

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46 More information on the IMPLAN modeling process is available at IMPLAN.com.
47 This includes residual effects after the project is completed.
48 Results are rounded to the nearest $100,000 and 100 people.
49 An assumption of a $487 million assessed value, with a 687 mill levy adjustment is applied.
50 Under the assumption of a 30-year project, with a 5-year deprecation period, at 5% interest.

5.0 CONCLUSIONS

The study evaluated the opportunities and barriers for new uranium enrichment industry in Wyoming. The most important barriers that limit development were identified and then the costs and benefits to the State were calculated. By evaluating the market conditions globally and in the State, two major obstacles to development were identified along with two factors that promote development in the state.

Barriers to Development

1. **Economic:** Large economies of scales required to build an enrichment plant.
2. **Existing Industry:** Operating and historically permitted sites have an advantage over a new facility in Wyoming.

Factors Supporting Development

1. **Location:** Locating in Wyoming reduces operational risks when compared to other states because Wyoming has a robust energy sector and a developing nuclear supply chain.
2. **Tax Structure:** The Wyoming tax structure would add to revenues compared to other locations.

The economic conditions of the market drive the industry to be concentrated. This limits future opportunities to develop additional United States enrichment facilities. Even if a greenfield site is developed, the two sites that were previously permitted in Idaho and North Carolina have advantages over potential Wyoming sites. By commencing operations at one of these two mothballed projects, sunk costs in research can be recovered reducing both the planning cost and the time to market of these projects.

On net, the challenges are deemed to be a *Major Obstacle* under the qualitative scoring criteria, meaning that inducing a greenfield site would require continued demand for enrichment services[51], as well as direct incentives provided by the State.

[51] Which has been occurring due to global conflict in regions with high levels of uranium production and enrichment.

The costs and benefits to the State of securing a local enrichment facility were estimated. The benefits were found to be:

Benefits of Wyoming Uranium Enrichment

1. **Jobs:** 230-290 permanent jobs, 52-58 thousand person-years during construction.
2. **Tax Revenue Increase:** $171-$200 million.
3. **Long-Term Development:** Regional development of related supply chains in the nuclear industry.

The main costs identified include:

Costs of Wyoming Uranium Enrichment

1. **Direct Costs:** $10 - $12 million in direct state support paid for construction.
2. **Environmental Risk:** Management of uranium hexafluoride waste.
3. **Social Cost:** Previous projects have created environmental justice concerns.

Under a status quo development path, the most likely outcomes are: (1) Uranium enrichment expands at existing facilities; and/or (2) A new enrichment facility is opened in either Idaho or North Carolina. Either of these outcomes would provide economic benefits to the State because the expansion of NEF or the construction of the EREF Idaho site will promote the development of the nuclear industry in Wyoming. The change would secure a demand source for the existing uranium mining industry in Wyoming and provide a nearby stream of enriched uranium for promoting the expansion of nuclear power plants in Wyoming. Such an outcome would also eliminate the identified costs associated with direct development. However, the financial benefits of increased employment and tax revenue would not come with this development path. Alternatively, an enrichment industry in Wyoming could form with significant State assistance.

In a broader policy analysis, these identified costs and benefits should be compared to alternative uses of State funds as any money spent to attract an enrichment facility could not be used for other programs. Future research will evaluate other opportunities for Wyoming along the nuclear supply chain, applying a similar scoring system. This roadmap will allow stakeholders to compare these opportunities to one another.

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APPENDIX A: THE NUCLEAR FUEL CYCLE

Basic understanding of the domestic fuel cycle provides an important foundation to the enrichment economic analyses. About 95% of the uranium currently used in domestic power production was imported (Energy Information Administration 2023). The fuel cycle begins with mining, and milling. After milling, the "yellow cake" is transported to a conversion facility to be hydro-fluorinated and distilled to UF_6. Globally, only five conversion facilities are licensed. The two closest facilities, for United-States-Sourced uranium are the UF_6 conversion facilities in Port Hope, Canada and Metropolis, Illinois.

The UF_6 is transported to a uranium enrichment facility. Domestically, almost all the UF_6 currently went to the NEF (located at Eunice, New Mexico). The NEF used Zippe-type centrifuges to increase the ratio of U-235 to U-238 to between 2% and 5% U-235. The enriched UF_6 is transported to one of three NRC Licensed Category III fuel fabrication facilities. These facilities include Global Nuclear Fuel-Americas, located at Wilmington, North Carolina; Westinghouse Columbia Fuel Fabrication Facility, Columbia, South Carolina; and Framatome, Inc., in Richland, Washington. These fuel manufacturers convert the UF_6 to uranium dioxide ceramic cylindrical pellets.[52] The pellets are sealed in 12 or 14-foot zirconium rods and assembled into fuel bundles. A typical light water reactor fuel load includes about 113 tons of uranium dioxide, including about 100 tons of enriched uranium, and between 9 and 18 million fuel pellets.

The fuel fabricator will work closely with the utility core designer. The U-235 enrichment of each fuel pellet is designed to maximize power output while minimizing core power peaking factors. For example, natural uranium is typically used for the top and bottom six inches of each fuel rod. Light water reactors operate on a 18-to-24-month fuel cycle. About 1/3 of the fuel is replaced at the end of the cycle. The amount of fissile material in the fuel bundle is monitored by the facility reactor engineer, the engineer in charge of reactor operations.

Depleted[53] UF_6 is transferred to "deconversion facility" where UF_6 is chemically reduced to uranium dioxide (UO2) and tri-uranium oct-oxide (U3O8) and fluoride. In the United States, deconversion is performed by Mid-America Conversion Services (located at Portsmouth, Ohio).

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[52] Cylindrical fuel pellet, about a 3/8-inch diameter and 5/8-inch length.
[53] About 0.3% U-235.

APPENDIX B: UNITED STATES ENRICHMENT FACILITY DATA

All facts used in Table 4 are provided in this Appendix. The costs reported in Table 4 are inflation adjusted using the United States CPI to July 2023, which are calculated from the unadjusted values provided here.

National Enrichment Facility in New Mexico. Owned by Urenco

1. There are plans to move from a 5.5% licensed enrichment level up to 10% (Cowne 2021). This is high enough to be considered HALEU. Therefore, HALEU is checked.
2. Producing 4.9 million SWU in 2022 (World Nuclear Association 2022).
3. Construction costs are approximately 4.5 billion in 2016 (Mann 2016).
4. Started operation in 2010 (Urenco 2023b).

Eagle Rock Enrichment Facility planned to be in Idaho. Owned by Areva

1. 6.6 million SWU (Areva and NRC 2011).
2. Construction costs are estimated to be 4.1 billion dollars in February 2011 (Areva and NRC 2011).
3. Canceled in May 2018 (Smith 2018).

Global Laser Enrichment Facility planned to be in North Carolina.

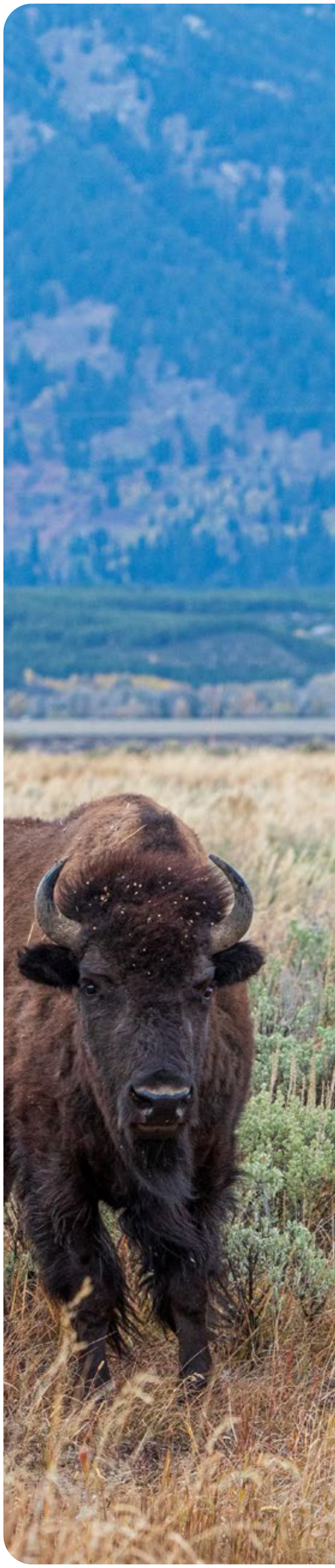
1. 6 million SWU (NRC 2012; Orr 2009).
2. Proposal to enrich uranium up to 8%. This is high enough to be considered HALEU (NRC 2012; Orr 2009).
3. Cost estimates were submitted to the NRC but are withheld from the public (NRC 2012; Orr 2009).
4. Planned operation in 2014 ramping up until 2020 (NRC 2012).[54]
5. License canceled in 2021 (Damaris 2021).

Original Portsmouth Gaseous Diffusion Plant in Ohio.

1. Cost of 750 million dollars in 1956 (Centrus 2011b).
2. 8.75 million SWU capacity after expansion planned in 1977 (Liverman and Energy Research Development Administration 1977).
3. Started operation in 1954 (Centrus 2011b).
4. Closed commercial operation in 2001 (Centrus 2011b).

American Centrifuge Plant refit of Portsmouth with centrifuges in Ohio.

1. 10% enrichment level target (Centrus 2020).
2. 3.8 million SWU capacity (Centrus 2020).
3. Construction cost of 3.1 billion in 2008 dollars (Centrus 2020).[55]
4. First license for HALEU (Department of Energy Office of Nuclear Energy 2021)
5. Planned first operation in 2023 (NRC 2023b)



[54] On page iii of the report.
[55] On pages 1-64.

Y-12 facility, for nuclear weapons enrichment in Tennessee.

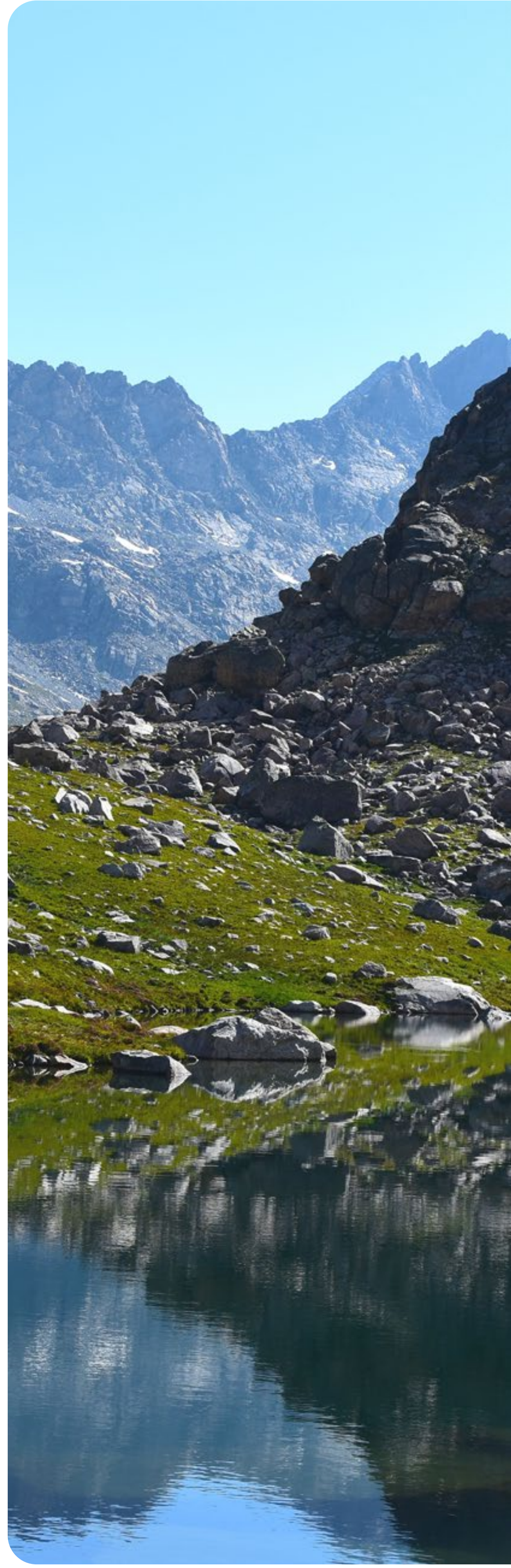
1. Initial cost of $303,787,176 in 1942 dollars (United States Army Corps of Engineers Manhattan District and United States Department of Energy Office of History and Heritage Resources 2013).
2. Building completed in 1943 (Department of Energy 2023).
3. Shut in of enrichment and conversion to nuclear parts manufacturing began in 1946 (Department of Energy 2023).
4. Operated by Tennessee Eastman Company (Department of Energy n.d.).

K-25 gaseous diffusion plant to feed Y-12 in Tennessee.

1. Cost of $500 million in 1945 (Department of Energy n.d.).
2. Began operating in 1945 (Department of Energy n.d.).
3. Ended operation in 1987 (Department of Energy n.d.).
4. Operated by Kellex, a secret branch of Kellog (Jones 1985).

Paducah Gaseous Diffusion Plant in Kentucky.

1. Construction contract cost of 800 million dollars in 1950 (Centrus 2011a).
2. Began operating in 1952 (Centrus 2011a).
3. Closed operation in 2013 (United States Energy Department 2023).
4. 8 million SWU capacity (World Nuclear Association 2023a).[56]



[56] Some source list capacity at 11.3 million SWU but this could not be verified.

APPENDIX C: MONTE CARLO MODEL

The profit equation 6 is used to gain insight into policies that can improve the economics of constructing a new facility. A Monte Carlo simulation is completed that uses historic price variations in uranium (see Appendix A) to predicted firm profits.

The enrichment has a set of economic conditions that makes predicting optimal strategies more complex than a simple net present value calculation. A project is evaluated by discounting revenues and costs with an internal discount rate. If the sum of these discounted costs and benefits are greater than zero, then the project is economically viable. This is generally the case when new production can be easily added in the future.

The enrichment firm cannot easily construct new facilities. This fact adds an opportunity cost. If a firm constructs an enrichment facility this year, then it cannot build one in the following year. If the price drops in the following year, the project's net present value also decreases. By waiting to see how prices change, the firms decrease the chances of having the project lose money and increase the average expected profits of the firm. However, this waiting reduces net present value by delaying the future profit streams. A firm with this situation should wait to build a project until the value of waiting is equal to the cost of losing future income (McDonald and Siegel 1986). As a result, an enrichment firm will tend to wait for prices to rise above the point where the net present value is zero.

The baseline model of use assumes that a project will take 7 years to go from planning to operation and the plant will operate for 30 years. These assumptions are based off the Urenco facility plans. The internal rate of return is assumed to be 4.5%, which is a common value used in government evaluations. The plant has a fixed but unknown capital cost.

With these assumptions the revenue of the firm is estimated under different strategies. In the first strategy the firm starts construction immediately with a price of $40 per pound. The other strategies are to wait for a certain price point to be reached before starting construction. The higher the price the firm wants to achieve then the lower the odds are that the facility will be built. This sometimes avoids scenarios where the price drops and the NPV is negative but sometimes leads to profits being left on the table.

The firm is assumed to be profitable at the $40 price point, which provides a relative benchmark by which to compare. To form this benchmark, the capital costs are estimated to be the same as the average expected revenues when the facility is built immediately. These costs are then used to estimate the returns of various strategies and under different scenarios. The values are reported as relative to the revenue received at the baseline conditions. Relative values are used to avoid confusion in interpreting the results. Since the values are not calibrated with actual cost data, they provide insight into the relative importance of factors but little in terms of actual profits.

APPENDIX D: PROFIT MODEL

A model of uranium enrichment firm-level profit is derived, under some simplifying assumptions. First, a plant is assumed to operate at full capacity once constructed. This is based off the fact that the machinery can be damaged if not in use, and the low operating costs of plants. From this assumption, it follows that the daily cost of operating the facility is fixed, and that the quantity of enriched uranium produced each day is fixed. This is used to construct equation 1.

$$\pi = \int_{t=b}^{T+b} \left[e^{-rt} \left(P_{SWU} \cdot q - V_c \right) \right] dt - P_k \cdot K \cdot e^{-rb} \tag{1}$$

Where ϖ is the profit produced by the enrichment plant, r is the discount rate (or interest rate) of the company converted to instantaneous values, t is time, b is the time at which the enrichment plant begins construction, T is length of time that the plant operates, PSWU is the price paid for a separative work unit, q is the amount of separative work units the plant produces at any moment, Vc is the variable cost of operating the plant, K is the capital invested in the facility, and Pk is the price of capital.

Because the variable cost is assumed to remain constant, the equation can be reduced to the form in equation 2. If the price received also remains constant, as in the case of fully scheduled long-term contracts, the final profits can be calculated in advance as presented in equation 3.

$$\pi = q \cdot \int_{t=b}^{T} \left(e^{-rt} P_{SWU} \right) dt - \frac{e^{-rb} - e^{-rT}}{r} V_c - P_k \cdot K \cdot e^{-rb} \tag{2}$$

$$\pi = \frac{e^{-rb} - e^{-r(T+b)}}{r} \left[P_{SWU} \cdot q - V_c \right] - P_k \cdot K \cdot e^{-rb} \tag{3}$$

APPENDIX E: URANIUM PRICE FORECAST

As an input to the Monte Carlo simulation of enrichment profit, 200,000 forecasts of SWU prices up to 100 years are made. This provides context for the economic factors that influence enrichment profitability. The preceding simulation provides a series of plausible price forecasts that capture historic variation in prices. By generating thousands of possible price shifts that match historic variation, the expected profit of firms applying various strategies can be calculated under the law of large numbers. An Auto Regressive Moving Average model (ARMA) is used to forecast future prices with lags of prices as explanatory variables. Reasonable economic constraints are added to this model to bound the long-term forecast to a range that matches theoretical limits.

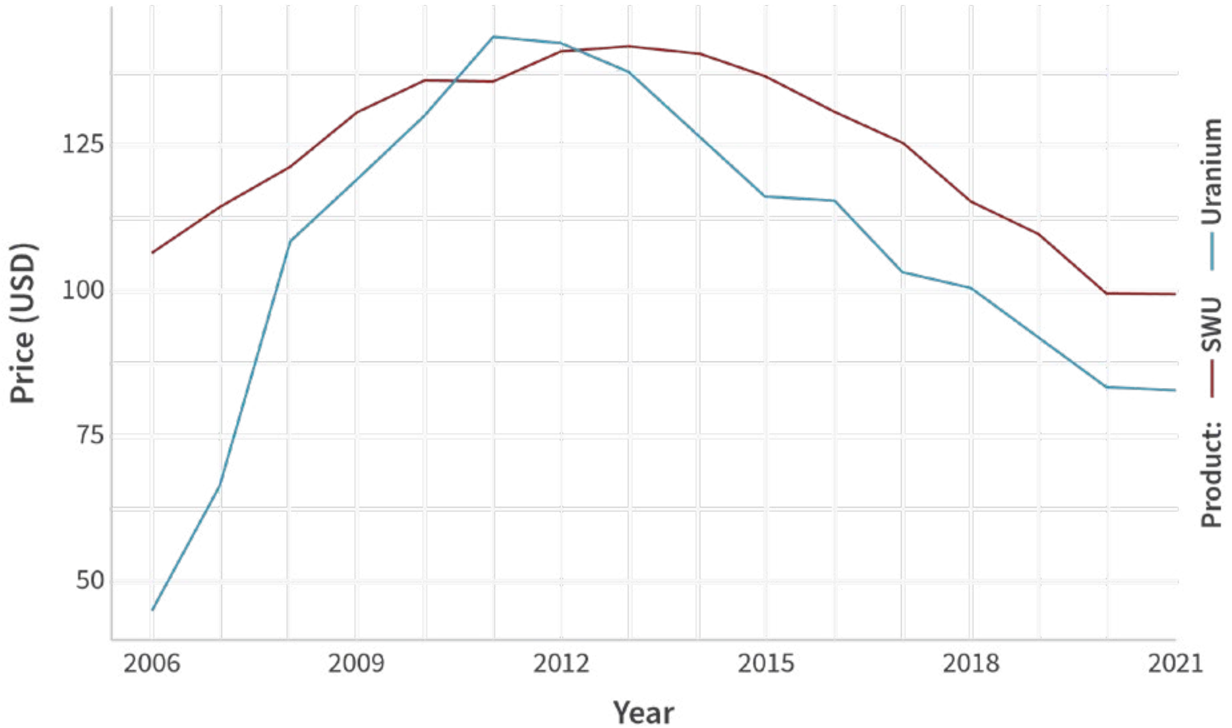
There are challenges that need to be overcome to make these predictions tenable. First, monthly SWU prices are not freely accessible. Using yearly rates is insufficient because there are too few data points and monthly information is lost by aggregation. The second challenge is that the nuclear industry is volatile, and prices are not stationary at level, so a transformation must be performed to avoid a spurious regression.

The issue of limited SWU price data is addressed by leveraging the relationship between uranium prices and SWU prices. There are theoretical reasons to suggest that the SWU prices and uranium prices are correlated. The ability of enrichment plants to underfeed uranium is a key driver of this relationship. This process allows enrichment firms to produce a secondary source of uranium in response to prices. Enrichment companies are contracted to deliver a set volume of enriched product with a predefined U-238 to U-235 ratio for power plants. To perform this task a quantity of unenriched uranium hexafluoride is delivered. The contract may specify the expected SWU value that needs to be provided, but the enrichment firm can increase the actual amount of SWU used, as the product is delivered within specifications. An option for the enrichment company is to input less feed uranium than the initial plan (underfeeding) and apply more cycles. This requires the company to use more energy to produce the same amount of product, but they are left with spare uranium. This is analogous to an enrichment firm having an options contract to purchase uranium at a certain price. The enrichment company has the option to pay an added cost in the form of increasing SWU output, to secure the right to unrefined uranium. This is analogous to an options contract because when prices are low the enrichment company does not have to execute the option to purchase the uranium. This leads to market arbitrage between the two products. If the price of uranium rises, then SWU inputs become more valuable, as SWU generates a secondary supply of uranium. Conversely, if the price of uranium decreases, there is less demand for SWU to produce secondary uranium, thus SWU prices decrease. This process was estimated to provide 6,000 tons of uranium in secondary supply in 2021. (World Nuclear Association 2022)

There are also other price links. Since uranium is a complement good to SWU, demand shocks to either product will cause shifts in price that move together. However, supply shocks will lead to divergent price shifts. The primary use of both products is production of nuclear energy, so shocks to nuclear supply or demand will move prices of both goods in the same direction. This cointegration can be more formally tested; the P-value of the Augmented Dickey Fuller test for the difference in the prices is 0.76, suggesting the gap between the two prices is stationary.

Figure 10 plots the yearly price of uranium in dollars per kilogram, and the price of uranium ore in dollars per pound. The connection between the markets is evident through the common trends followed by each.

Figure 10
Relationship Between Uranium and SWU Prices



Notes: Long-term uranium prices were extracted from figures in (International Atomic Energy Agency & Nuclear Energy Agency, 2023) using the WebPlotDigitizer software (Rohatgi, 2022). SWU prices from (EIA, 2023b).

This connection between the price of SWU and price of uranium allows changes in uranium prices to stand-in for SWU prices. Using monthly SWU prices would be ideal, but given the data limitation, this proxy can sufficiently substitute for SWU.

The applied Autoregressive Moving Average model is based on a market model of shocks. Uranium prices are driven by shocks in supply or demand such as new power plants coming online, or the response after the Fukushima accident of 2011. These changes affect the underlying price only after a delay as purchasers respond to the new information. Assuming these types of shocks are random, but follow an underlying probability distribution, the possible range of future price can be bounded.

The data for the analysis is in the form of the percent change in the price of uranium from month-to-month rather than the absolute price.[57] This has many advantages, but one key point is that prices tend to move relative to the current price. A price change from $1 to $2 over one month is less likely to occur than a price change from $100 to $101. By using the percentage change this effect is captured. In technical terms, the uranium price time-series is transformed using the natural log and then first differenced. The raw data is the global uranium price from the International Monetary Fund as reported by the Federal Reserve (International Monetary Fund 2023).

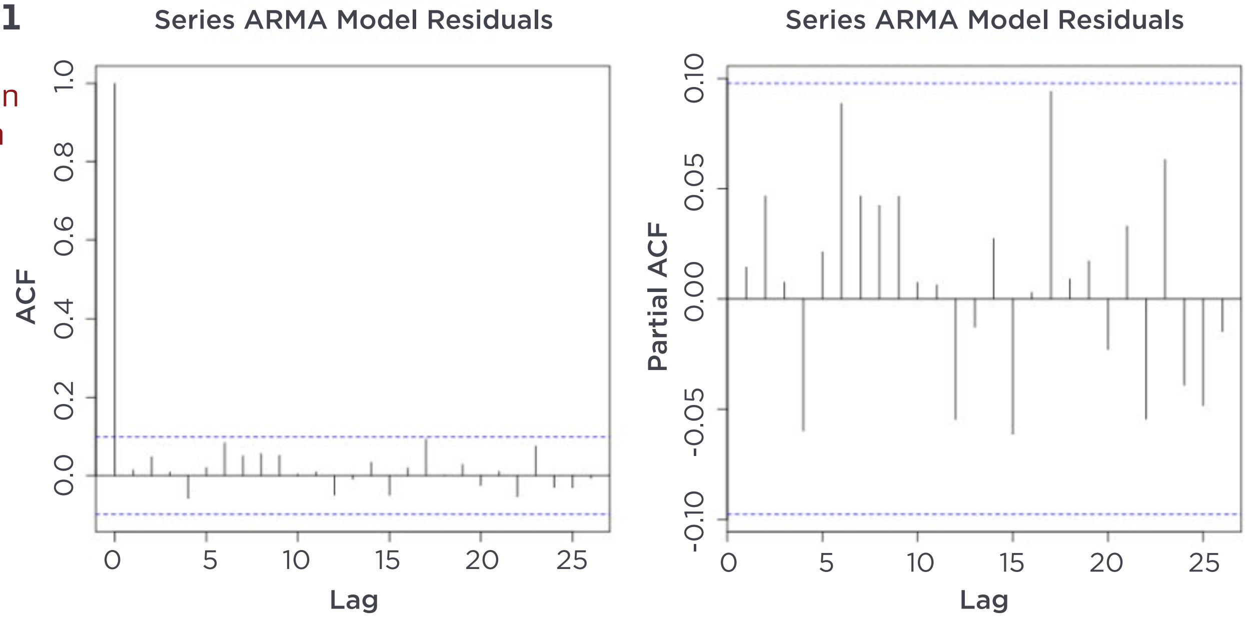
Table 7
ARMA Model Regression

	Dependent variable:
	Log differenced uranium price
ar1	−0.370***
	(0.107)
ma1	0.709***
	(0.082)
intercept	0.004
	(0.004)
Observations	402
Log Likelihood	551.380
σ^2	0.004
Akaike Inf. Crit.	−1,094.761
Note:	*p<0.1; **p<0.05; ***p<0.01

The final model predicts the uranium price based on a one-month lag of the percentage change in price, as well as a one-month moving average term. The number of these lags was selected based on the Akaike information criterion, which is a procedure that balances gaining more precise estimates by adding lags, with the risk of overestimating the price. The model estimates are presented in Table 7.

[57] Prices are inflation adjusted to 2023 levels with United States CPI, however first differencing the data will mitigate any inflation effects.

Figure 11
Auto Correlation Validation

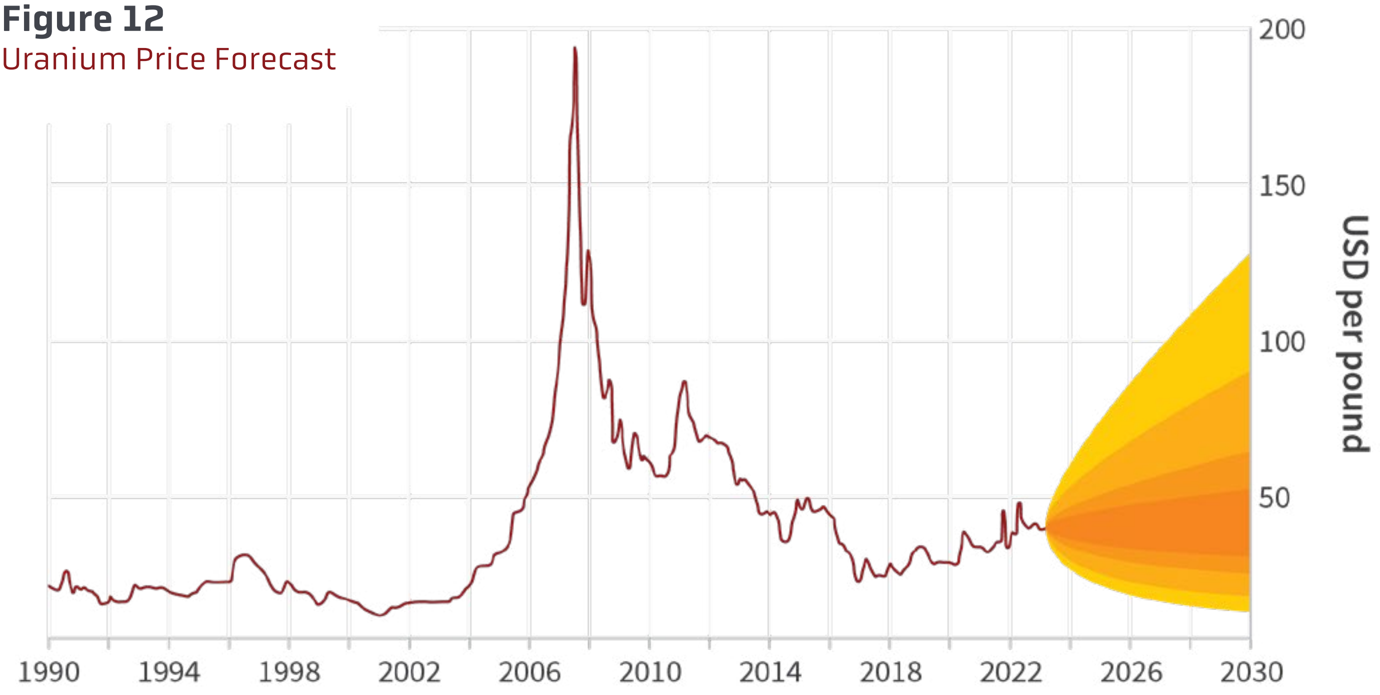


(a) ACF Lags (b) PACF Lags

International Monetary Fund, Global price of Uranium [PURANUSDM], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/PURANUSDM, November 27, 2023.

There is no evidence of serial autocorrelation of residuals in this model. The Autocorrelation Function and Partial Autocorrelation Functions of the model residuals are provided in Figure 11a and 11b, respectively.

Figure 12
Uranium Price Forecast



International Monetary Fund, Global price of Uranium [PURANUSDM], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/PURANUSDM, November 27, 2023.

The results of these estimates are shown graphically in Figure 12. The confidence intervals of 30%, 50%, 75% and 90% are recorded as a fan chart that goes from darker to lighter as the band is widened.

Another serious challenge is dealing with stationarity over the long run forecast of 100 years. While the data is stationary in log-differenced prices, converting back to actual price levels leads to explosive predictions. This model cannot account for unobserved price factors that bound the price to reasonable ranges. The spread of the price predictions increases over time, as can be seen by the increasing fan size in Figure 12. This is theoretically sound because there is far less certainty about the price of uranium in 100 years from now than there is in the next six months. However, there are more fundamental constraints an economist can place on the price not captured by the pure historic price variation. For example, in the long run the price of uranium should not exceed the retail value of the amount of electricity created by the unit of uranium. If the uranium price was this high, then there is no feasible way to produce nuclear energy at a profit. Therefore, the upper ceiling of the price is bounded by reasonable expectations of electricity prices. This intuition is used to add constraints to the model outcomes.

If the predicted uranium price in a hundred years is above $300 per pound (double the maximum historic price) or below $7.5 (half the historic low) the forecast is removed from the dataset. With the understanding that prices have a ceiling bound by prices of electricity and other commodities, removing these outlier predictions prevents an untenable long run forecast. Additionally, Huber weights are applied which pull outliers toward the mean. This process biases the random nature of the simulation, skewing prices lower in early periods. To adjust for this, the mean monthly price growth rate is estimated from the unconstrained models. This was found to be a 2% increase per year. The mean of each time period was then shifted, so the model's average matches the random process. This matches the expectation that uranium price variation is lower and skewed down as prices increase above observed levels, while maintaining the predicted long run trend of the ARMA model within the range of historic prices.

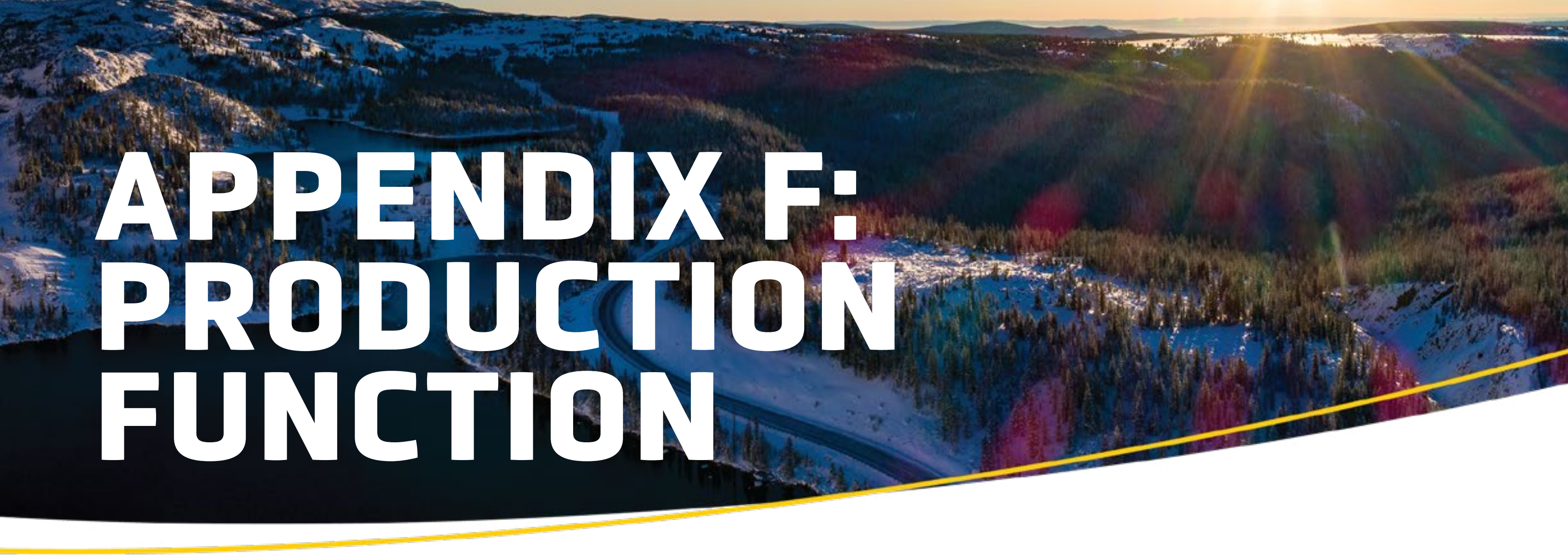
This process is selected as the optimal way to incorporate the known economic constraints in future prices, while including the historical price relationships as a driver in price. These predictions provide a range of price outcomes that are plausible in the long and short run. As applied in the Monte Carlo simulation, these forecasts are used to estimate the relative importance of factors such as construction costs, and the time to go from planning to market for the profit of firms. When used in this way, the forecast works as a foundation for ranking importance, but the outcomes should not be taken as predicting a precise actual profit level of the firm.

An alternative specification was developed that avoids the need to add economic constraints on long-term prices. In this second model, the market for uranium is being treated as trend stationary. The price of uranium has month-to-month price variation that reverts to a long-term trend line. However, if a structural break is caused by an unforeseen factor, such as a nuclear disaster or new emission standards, then the price has a sudden change and a new trend forms. To estimate this model, structural breaks were identified by using a Chow test on the relationship between the price of uranium and time, where three breaks were identified under this test. These breaks in price trend are shown in Figure 13.

Figure 13
Uranium Price Break Points

International Monetary Fund, Global price of Uranium [PURANUSDM], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/PURANUSDM, November 27, 2023.

Creating ARMA models within each break is stationary using price levels instead of present change, avoiding explosive predictions. However, it is not preferred over the adjusted ARMA model for the Monte Carlo, because the trend and intercept must be assumed before predictions are made. In both cases assumptions must be made. In this trend stationary model, the long run trend must be assumed along with the breakpoints. In the adjusted ARMA model the assumptions about long-term bounds are necessary.



APPENDIX F: PRODUCTION FUNCTION

To better estimate the possible economic impacts of an enrichment facility being built in Wyoming, a microeconomic model is constructed.

The production function of enriched uranium is assumed to follow a Cobb-Douglas model (Cobb and Douglas 1928). This model is seminal in economic literature and treats production output as being the input of generic capital and labor. While more granular categories can be devised when firms are rational in investment choice, the subcategories can be aggregated to these higher levels and provide explanatory power with only a few variables. This model is applied to uranium enrichment facilities in equation 2, with coefficients estimated in equation 6.

$$SWU = A \cdot K^{\alpha} \cdot L^{\beta} \tag{4}$$

Where SWU is the separative work unit capacity of a firm, K is capital input which in this case is the cost to construct an enrichment facility, L is the labor used to operate the plant, and A is a constant that adjusts for units. The coefficients α and β are the returns to scale of capital and labor.

The only operating enrichment facility in the United States is in New Mexico and is used as a reference point. The predicted cost to construct the plant was 5.75 billion dollars, it employs 230 workers, and produces 4.6 million SWU. The scale factors of labor and capital have been econometrically estimated as 0.43 and 0.76, respectively (Rothwell, 2009). “A” is solved in equation 5:

$$A = \frac{SWU}{K^{\alpha} \cdot L^{\beta}} = \frac{4.6}{5.75^{1.76} \cdot 230^{1.43}} = 8.25 \cdot 10^{-5} \tag{5}$$

$$SWU = 8.25 \cdot 10^{-5} K^{1.76} \cdot L^{1.4353} \tag{6}$$

Without a detailed cost function for capital and labor, the precise expansion path cannot be estimated. However, if the optimal ratio of capital and labor is assumed to remain constant, the equation can be solved. This assumption will not bias the results over a narrow range. The most profitable ratio of capital to labor inputs is not likely to deviate from the observed data point until the output capacity of the plant expands well beyond the reference point. Additionally, a constant ratio is implicitly assumed by the model used to estimate the return to scales, and so this functional form should fit the data as best as is possible.

Under these assumptions equation 4 is applied to create the outcomes in Figure 9.

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