School of Energy Resources
Center for Energy Regulation
& Policy Analysis

NUCLEAR SERIES PART 4

WYOMING'S NUCLEAR SUPPLY CHAIN OPPORTUNITIES AND CHALLENGES: HEAT APPLICATIONS

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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.

Contents

Acronyms

AIC	Akaike Information Criteria
ARIMA	Autoregressive integrated moving average
AR	Autoregressive
BWXT	Babcock & Wilcock Technologies
BTU	British thermal unit
CBEA	Center for Business and Economic Analysis
CERPA	Center for Energy Regulation and Policy Analysis
ERCOTT	Electric Reliability Council of Texas
EIA	Energy Information Administration
FR	Fast reactor
GW	Gigawatts
IEA	International Energy Agency
LWR	Light water reactor
LMFR	Liquid metal cooled fast reactor
LMR	Liquid metal reactor
MWe	Megawatts electricity
MWh	Megawatts hour
MWt	Megawatts thermal
MR	Micro reactor
MMBTU	Million British thermal units
MSR	Molten salt reactor
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
Pu239	Plutonium isotope 239
PURPA	Public Utility Regulatory Policies Act
SER	School of Energy Resources
SMR	Small Modular Reactor
SPP	Southwest Power Pool
MBTU	Thousand British thermal units
U235	Uranium isotope 235
U238	Uranium isotope 238
EPA	United Stated Environmental Protection Agency
DOE	United States Department of Energy
USGS	United States Geologic Survey
WEA	Wyoming Energy Authority
HTSE	High temperature steam electrolysis
HTGR	High-temperature gas-cooled reactor

EXECUTIVE SUMMARY

This report quantifies the economic outcomes of potential non-electricity uses of nuclear power in Wyoming. The unique opportunities and challenges of expanding the industry are identified. Additionally, an event study is performed that estimates economic outcomes under a range of technological adoption scenarios.

The analysis concludes that there is potential to apply nuclear technology to non-electricity generation uses in Wyoming. Directly applying nuclear produced heat to industrial processes creates economic cost savings compared to using nuclear energy exclusively for electricity generation. The unique attributes of nuclear power, including reliable heat output and high operational uptime, create technological benefits for nuclear reactors. These benefits provide a pathway for nuclear reactors to be deployed at trona mines and refineries in Wyoming.

Other industrial applications of nuclear technologies are evaluated, including hydrogen production and the extraction of kerogen from oil shale[1]. Neither of these industries are profitable under current economic conditions, which limits nuclear deployment opportunities in the State. However, if these emerging industries take a foothold in Wyoming, it will induce growth in advanced nuclear deployment, providing tax revenue and employment opportunities.

[1] Oil shale is different from shale oil which can create confusion when discussing these processes. Hydraulic fracturing is commonly used to recover oil from shale and is called shale oil. Oil shale is a type of shale with kerogen, an immature oil product that needs to be processed with heat to convert into oil. This report references kerogen rich oils shales, and not shale oil.

This report is one of a series evaluating the feasibility of developing an integrated nuclear sector in Wyoming. From the mine mouth to spent fuel processing, each step in the nuclear supply chain has unique economic considerations. To compare the opportunities for Wyoming across the nuclear supply chain, a qualitative scoring system of advantages and obstacles is applied (Gebben & Peck, 2023). The summary of these scoring criteria for nuclear heat applications of nuclear energy is provided in Table 1.

Table 1:
Significant Economic Factors Related to Wyoming Nuclear Heat Uses

	Industrial Applications		Hydrogen Production		Shale Oil Extraction	
	Level	Summary	Level	Summary	Level	Summary
Economic	Moderate Obstacle	Alternatives are cheaper	Major Obstacle	Developing infrastructure	Severe Obstacle	High cost of production. Not competitive with other oil sources
Existing Industries	Minor Advantage	Trona mines and manufacturing	Minor Advantage	Existing oil refineries	Major Obstacle	No current projects
Tax Structure	Major Advantage	Tax exemptions from State and Federal Government	Major Advantage	Tax exemptions	Major Advantage	Tax exemptions
Location	Minor Obstacle	Existence of trona resources. Low infrastructure	Minor Obstacle	Storage locations for hydrogen. (sandstone)	Major Advantage	Large reserves
Legal	Minor Obstacle	Costs from NRC reports	Minor Obstacle	Cost from NRC reports	Minor Obstacle	Costs from NRC reports
Technology	Minor Obstacle	Cost reductions expected	Minor Obstacle	Cost reductions expected	Moderate Obstacle	Cost reductions expected

Industrial applications of nuclear have the easiest path to deployment in Wyoming. Low-cost natural gas in the U.S. creates the most difficult obstacle to industry growth because current advanced reactor designs are too expensive to be competitive with natural gas[2] in industrial heat applications. Future technological developments, modular reactor designs, and industry learning rates are expected to reduce construction costs, which could close this cost gap in the long term.

Neither oil shale extraction nor hydrogen production from nuclear energy are economically competitive industries in Wyoming. This creates an additional market barrier to entry when compared with industrial heat uses.

[2] When not employing carbon capture technology.

The economic impact of each potential industry is estimated in terms of State and local tax revenue, and employment in the operation of nuclear reactors. Forecasts of industry output are used as an input to the IMPLAN[3] model to calibrate employment and tax income information. These results are provided in Table 2.

Table 2: Wyoming: Yearly Benefits of Direct Heat Applications of Nuclear[4]

	Tax Revenue (Million USD)		Employment
	Gross (Yearly)	Total Revenue[5] (Over 50 Years)	Full Time Equivalent (Yearly)
Industrial Heating	$37.0	$634	2,545
Hydrogen Production	$61.3	$1,052	4,225
Oil Shale Extraction	$886	$15,200	61,019

Although oil shale production has the largest obstacles to development, the abundant resources in Wyoming could induce $886 million of annual tax revenue from small modular reactor energy[6] generation alone.

On the other end of the spectrum, industrial process heating has a clear pathway to development in the next 30 years but has a smaller potential impact on the State economy. Reactor deployment is limited to existing industries in the State that apply large quantities of heat. This encompasses trona mines and four oil refineries. $37 million in tax revenue could be added by developing industrial applications of nuclear heat, but if this replaces existing natural gas heating sources total tax revenues will decline. The net tax revenue estimate is negative because replacing natural gas or petroleum for industrial heating output with nuclear reactors adds additional tax deductions. The tax exemption for advanced reactors encourages the benefits of developing a nuclear economy in the State, but also reduces tax revenue in cases where taxed energy sources are displaced. These results provide policy makers with a tool for comparing the tradeoffs of nuclear tax incentives in Wyoming.

[3] For more information on the IMPLAN modeling process, visit IMPLAN.com

[4] These outcomes only included the operating period of the nuclear reactor. Facility construction may induce additional tax revenue and employment. The construction tax revenues and employment additions are evaluated in (Gebben & Peck, 2024). Those outcomes depend on how many components are supplied by Wyoming firms. The Wyoming component market is growing but currently has only a small market share.

[5] Discounted at 6% APY.

[6] This energy will primarily be produced in the form of heat, but there may be some additional electricity produced. The value of output is calculated assuming both the thermal energy, and the electricity energy is valued at the weighted average price of wholesale industrial electricity produced in Wyoming. This accounts for the value of peaking and other timing effects, although it may overstate the true economic value of the thermal energy generated.

INTRODUCTION

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

This white paper begins by providing an overview of the alternative uses for nuclear power. Market structures that provide opportunities in Wyoming for these applications of nuclear power are assessed. Then, an economic impact analysis is conducted, to determine the outcomes associated with adoption of these technologies. Changes in employment, tax revenue, and non-monetary considerations are provided under different market conditions.

BACKGROUND

The economic opportunities of applying nuclear power to unconventional industries are well recognized in Wyoming. Using the heat generated through reactors as a coproduct can provide cost savings and targeted benefits to Wyoming firms. Recently, the Wyoming Energy Authority (WEA) awarded a contract to BWX Technologies to assess the viability of deploying cogeneration microreactors for industrial applications in the State (BWX Technologies, 2023). In conjunction with this contract, the WEA recommended that the Governor's Office provide matching funds to the School of Energy Resources (SER) to evaluate the use of microreactor process heat to support hydrogen production[7] (Wyoming Energy Authority, 2023). Further, L & H Industrial, a Gillette manufacturing firm, announced the formation of a strategic alliance with BWXT to act as a microreactor vendor (L&H Industrial, 2023). The rapid innovation in the State demonstrates the interest in this emergent sector.

This report identifies four critical alternative uses of nuclear reactors, with three having potential applications in Wyoming. These processes include industrial use, kerogen oil shale production, hydrogen manufacturing, and water desalination.

In each of these opportunities, heat generated from the nuclear reactor is used directly for end use. For example, oil tar sands are extracted by injecting steam into the formation, decreasing the viscosity of the oil and allowing it to flow to the surface. These oil producers require heat, not electricity, to continue production. While electricity can be purchased to create steam, it is simpler and more cost effective to produce this heat onsite. Similarly, some chemical reactions are accelerated when performed at higher temperatures. Reactions used in oil refining, hydrogen production, sugar beet processing, and paper milling are enhanced when performed in specific temperature ranges.

[7] Methane reforming

[8] Thermal energy and electrical energy can be compared in terms of Mw-h.

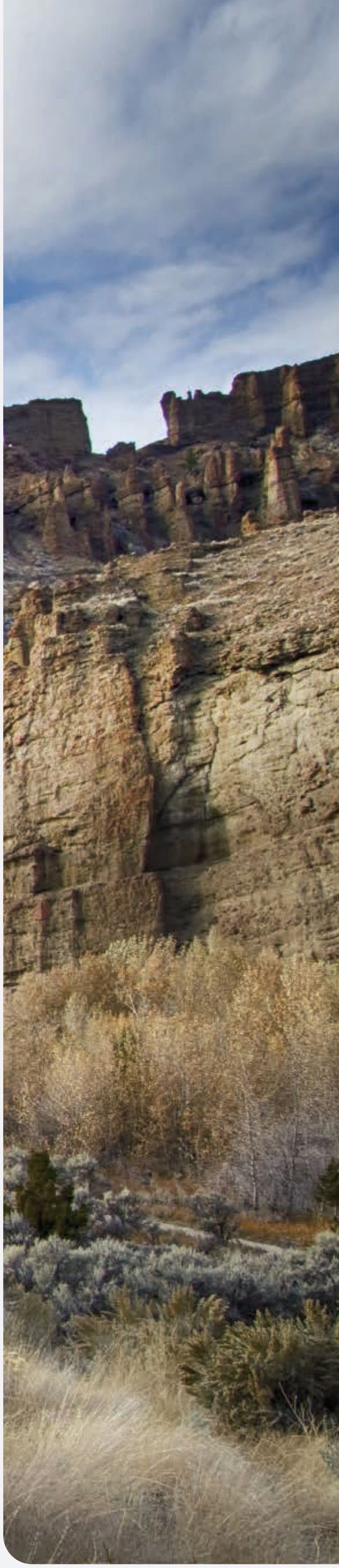
Using a nuclear reactor to supply the heat needed by these industries has a few advantages. For example, intermittent transmission and processing steps are eliminated by directly using the heat, thus reducing the cost to generate energy[8]. Second, some heat which would be wasted can be redirected to these other uses, creating a new source of revenue.

When a nuclear power plant produces electricity, the nuclear fission process generates heat which is then transferred[9] to a system where the heat is typically used to boil water[10]. In turn, this system runs a turbine to produce electricity on the grid. However, this process only converts approximately 30% of the nuclear energy into electricity, with much of the energy being transferred as heat in the ejected steam (Kupitz & Podest, 1984). The laws of thermodynamics guarantee that some energy is lost to heat whenever electricity is generated.

When the waste heat can be used for other purposes, the energy efficiency of the system increases as a previous waste product becomes a coproduct. For example, a nuclear power plant in Sweden was able to go from 33% thermal efficiency to 80% efficiency by using some of the produced heat for use in homes (Lipka & Rajewski, 2020).

Due to these conversion losses, power plants report capacity in both terms of electricity (Mega-Watt of electricity MWe) and total heat (Mega-Watt of thermal MWt). For example, the NuScale VoyGR small modular reactor (SMR) design produces 77 MWe but can provide 250 MWt a 277% increase (NuScale Power LLC., 2022). This means that fewer nuclear reactors are required to supply the same quantity of energy in the form of thermal energy, compared to electrical energy.

There are three scenarios for nuclear power plants providing heat. First, the power plant can maximize electricity output but use some of the waste steam for other uses. In this case, the added revenue from the heat is always an advantage to the nuclear operator, but it may be difficult to create the systems necessary to use this waste steam locally. Second, the nuclear reactor can be used only for heat generation. For example, a microreactor can be shipped to a remote oil field to supply steam for oil production. Under this scenario, the plant operator is dependent on the sale of heat to operate. This also lowers construction costs, since some of the electrical systems can be eliminated.



9 How the heat is transferred to generate steam depends on the design of the power plants.

10 In some advanced reactor designs water is not required for heat transfer of power generation. For example, the Westinghouse eVinci micro reactor applies passive heat pipes circumventing the need for a reactor coolant (Westinghouse, 2024).

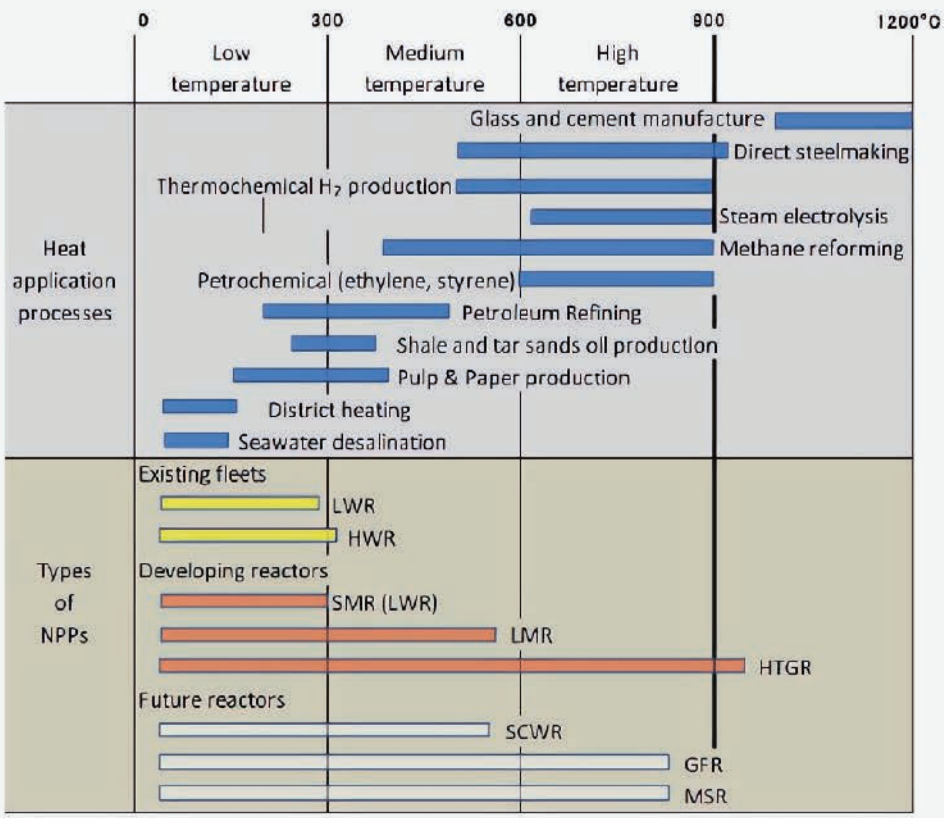
Finally, a reactor can be used to produce some heat and some electricity. An example of this is a hydrogen production facility that requires a set quantity of heat each day. A nuclear reactor at the facility can produce steam at the desired temperature and throughput rate to feed the hydrogen facility and use any remaining capacity to produce electricity for the grid. In a high temperature steam electrolysis (HTSE) hydrogen production process both heat and electricity are required. A nuclear reactor can supply both these products but sell electricity to the grid when hydrogen production is paused. Producing both heat and electricity for end use is referred to as cogeneration.

Recent developments in nuclear designs have opened new doors for cogeneration applications. Traditional light water reactors produce steam under 300 degrees Celsius (McMillan & Ruth, 2018). This limits the type of industries which can use the produced heat without augmentation. However, a range of advanced reactors designs can reach increased temperatures, creating opportunities to serve new markets.

Figure 1 provides a comparison of the temperatures required for different industrial applications and the temperature produced by various nuclear reactor designs.

Figure 1 Industrial Temperature Requirements and Nuclear Produced Heat by Reactor Type (International Atomic Energy Agency, 2017)[11]

Figure 1:
Industrial Temperature Requirements and Nuclear Produced Heat by Reactor Type (International Atomic Energy Agency, 2017)[11]



[11] GFR: Gas cooled fast reactor; HTGR: High temperature gas reactor; HWR: Heavy water reactor. LMR: Liquid metal reactor; LWR: Light water reactor; MSR: molten salt reactor; NPP: Nuclear power plant; SCWR: Supercritical water reactor; SMR: small modular reactor

While some industries can apply heat produced by existing light water and heavy water reactors, liquid metal and high temperature gas reactors can support more industries, without the need to supplement the thermal energy produced. Alternatively investment in heat augmentation of the reactor can be made which increases the temperature supplied for industrial purposes (Singh & Sharma, 2021). Hydrogen production, methane reforming, and petrochemical processing can be served by advanced reactor designs such as High Temperature gas reactors (HTGR), or by utilizing heat augmentation with a light water reactor (LWR).

In addition to general industrial use, the application of nuclear heat in hydrogen production and oil shale extraction are evaluated. Neither of these sectors are currently in operation in Wyoming but could create new opportunities for nuclear produced heat if developed.

Nuclear produced heat or electricity can be utilized in hydrogen production. There are three broad categories of hydrogen production methods: electrolysis, thermochemical conversion, and renewable liquid reforming. The electrolysis process splits water atoms into hydrogen and oxygen components. This requires constant application of electricity to induce the electro-chemical reaction. An on-site nuclear power plant requires electrical components to support this method, but cost savings exist because of reduced transmission costs. In a thermochemical conversion, a feedstock is converted into hydrogen components when exposed to high temperatures in various oxidizing environments. The temperature of this reaction is typically above 750 degrees Celsius. Most hydrogen today is produced with a steam methane reforming process, which uses natural gas as a feedstock to produce four hydrogens per methane molecule. For this thermochemical process, the most important input from the reactor is a consistent supply of heat energy in the appropriate temperature range. (Yukesh Kannah et al., 2021)

New sources of demand for hydrogen are expected to develop in the coming decades, making hydrogen production a potential area of growth for advanced nuclear reactors in Wyoming (Gulli et al., 2023; IEA, 2019).

Oil shales (which differ from shale oil)[12] are a fine-grained deposits which contain about 80% kerogen and 20% bitumen (Yen & Chilingar, 1976). Kerogen is a preliminary form of oil which must be heated to temperatures above 300 degrees Celsius to be transformed into a final oil product (Speight, 2012c). The extraction of oil shale involves either mining the rock and processing at the surface, or injecting heated liquids into the reservoir in a in situ extraction process (Kang et al., 2020; Speight, 2012a). Similar to tar oil production, generators are required at the oil shale extraction site, in order to supply the temperatures needed for recovery and processing (Biello, 2013; Speight, 2012b). This creates a demand for a baseload energy sources, such as nuclear. The oil produced on-site can be used to fuel this process, but the application of SMR or micro reactor technology can fill this need and increase overall recovery rates. If oil prices are high enough, applying nuclear energy to production will become feasible. Alternatively, this market can be developed by reducing reactor and oil shale processing costs.

Wyoming, Colorado, and Utah are homes to the largest reserves of oil shale in the world, with over one trillion barrels identified (Dyni, 2006; USGS, 2011). Oil prices are not high enough to incentivize the production of oil shales in Wyoming, but this use case is considered because of the unique position of Wyoming if oil shale resources are utilized.

[12] Shale oil is mature oil contained in any shale layer. Oil shale is kerogen rich requiring additional processing to be converted into oil.

ADVANTAGES AND BARRIERS IN WYOMING

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

ECONOMICS

Industrial Heat	Hydrogen	Oil Shale
Moderate Obstacle	Major Obstacle	Severe Obstacle

Economic Barriers: Scoring Criteria

Economic conditions are identified as a *moderate obstacle* to using nuclear energy for industrial heat. The U.S. produces an abundance of natural gas, lowering natural gas prices relative to Europe or Asian markets. As a result, natural gas is a cheaper alternative to produce industrial heat than current reactor designs allow. Presently, U.S. Henry Hub natural gas prices are $2.50 per million BTU. Providing the same amount of heat energy with SMR designs would cost $6.78[13] (Vanatta et al., 2023). Profit maximizing firms, therefore, select natural gas when adding industrial heat equipment.

[13] See the analysis section for more details on this study. Full system costs were considered while balancing an electricity market based on real price and quantity data. Inflation adjusted from 2023 dollars to 2023 dollars.

The economics may change in the future as significant federal and State support for SMRs reduces the relative cost gap between these two technologies. Further, SMR costs are expected to decline as the technology matures, and the supply chain is developed eventually achieving economies of scale in the manufacturing sector. It is reasonable to expect this obstacle to be reduced to a *minor obstacle*, or even a *minor advantage*, in the next ten to twenty years.

Other applications of nuclear heat currently face additional hurdles. Oil prices are too low to support kerogen oil shale production in Wyoming, whether or not nuclear energy is applied, placing the score as a *severe obstacle*. Hydrogen manufacturing has a similar obstacle as industrial heat applications, being constrained by low price natural gas alternatives. However, hydrogen is not yet produced at a commercial scale in Wyoming. This moves the economic obstacle score from a *moderate obstacle* to a *major obstacle*, since larger reactor cost reductions are required to establish hydrogen production using nuclear energy in Wyoming.

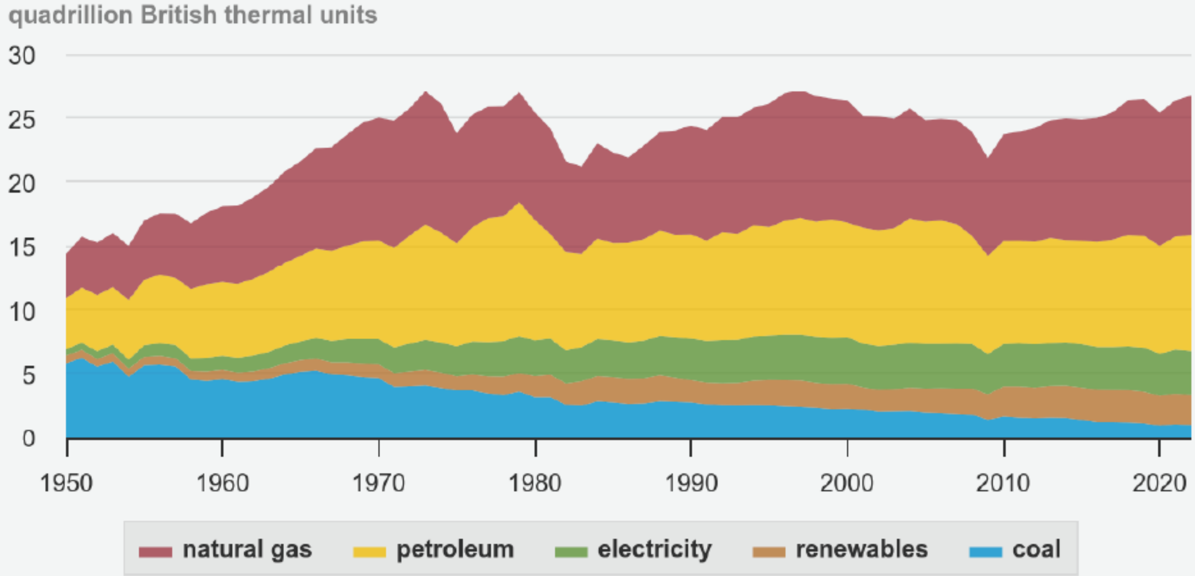
Economic Barriers: Analysis

While each potential use of nuclear produced heat has unique economic considerations, they share a common link to the natural gas market. This link is used to provide technical analysis of economic scenarios where nuclear reactors may be adopted for heat production or cogeneration.

The profitability of nuclear produced heat is always compared to the next best alternative. Where the same quantity of thermal energy can be produced using natural gas at a lower price, nuclear produced heat is subeconomic. This is true even if a nuclear reactor can operate at a profit from an accounting perspective. Consider an oil refinery that requires a set quantity of heat to process oil. By replacing aging heating equipment, engineers expect that $20 million in expected long run profits would be maintained. If a nuclear reactor can fill this need for heat for at a cost of $2 million dollars, the endeavor will generate $18 million in profit for the refinery. However, if an equivalent natural gas facility would cost a total of $1 million, then total profits would be $19 million. Even though a nuclear reactor would create profits on paper, $1 million dollars is left on the table by selecting the nuclear reactor project over the natural generator. The economic feasibility of nuclear reactors is directly tied to the substitute heat sources available on the market.

After the hydraulic fracturing boom of 2014, natural gas has become the lowest marginal cost source of energy in the U.S. Existing coal and nuclear power plants with high upfront cost and low operating costs remain in operation, but retired generation capacity tended to be replaced with low-cost natural gas. Since 2010, the share of electricity produced by natural gas in the U.S. has increased from 24% to 43% (EIA, 2012, pp. 1949–2011, 2024d). The energy use of industry has shifted away from coal to natural gas and petroleum as early as the 1970’s (see Figure 2)

Figure 2:
U.S. Industrial Sector Energy Use by Source (EIA, 2023d)



This same switching decision is faced by purchasers of heat for industrial uses. As natural gas prices have declined, the relative value of installing other sources of heat, including nuclear have dropped. This is referred to as an opportunity cost. The opportunity cost of installing a SMR for heat production is the difference in profits that would be acquired by instead installing a natural gas facility. The opportunity cost is added to a profit equation to establish total economic profits, meaning that if there are unused lower cost alternatives economic profits are negative.

Therefore, the adoption of nuclear cogeneration depends both on the cost of nuclear reactors and natural gas. Holding reactor costs constant, a natural gas price threshold can be predicted where new industries will prefer to construct nuclear sources of heat instead of utilizing natural gas.

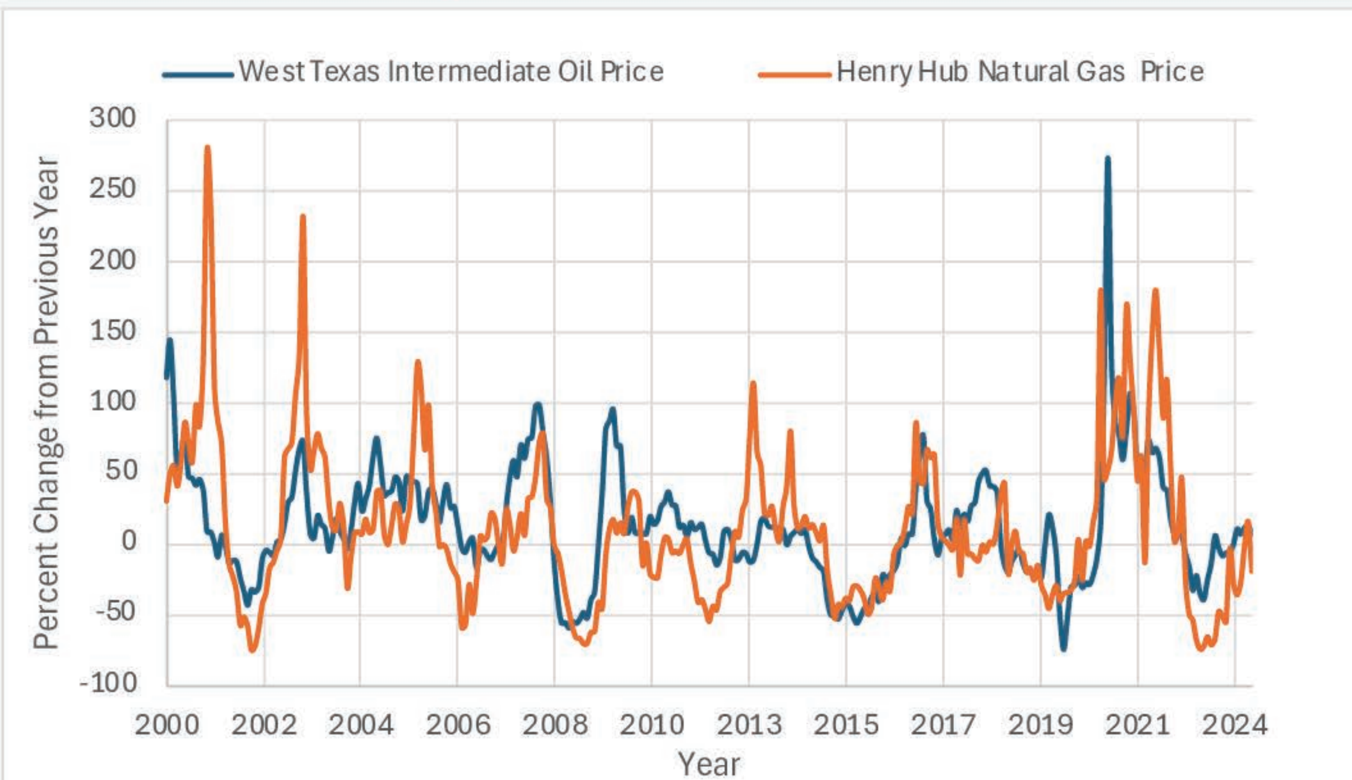
This breakeven point is identified for industrial applications, hydrogen production, and kerogen rich oil shale extraction. This is then compared to possible natural gas price scenarios in the future to establish the significance of the economic barriers in Wyoming.

We begin with industrial uses of direct nuclear heat. A survey of industry determined that most companies applying industrial heat were unwilling to switch energy sources unless there were cost savings (EIA, 2018). The most cited reason for not switching energy sources was that existing equipment could not operate on any other fuel type (EIA, 2018). Because of the sunk cost in equipment and operations training, switching to SMR or microreactor generated heat is more feasible over the course of many years. As industrial heating equipment is retired, if nuclear technology is economical, existing heat sources can be displaced. For this to happen, nuclear produced heat must be cost competitive with natural gas heating at the time of these retirements.

A recent analysis of switching costs from natural gas to SMR nuclear heat is leveraged. The findings suggest that for SMRs to be deployed for industrial heat applications, natural gas prices need to remain above $6.78 per MMCF. However, this price point drops if the facility can coproduce electricity and heat, allowing the reactor to sell electricity to the grid during peak demand periods. These estimates are based on a market model where a demand schedule is fulfilled by five different SMR designs[14]. Real world price data is used and a model from the Electric Reliability Council of Texas (ERCOTT) and Southwest Power Pool (SPP) is balanced. The most profitable energy source for heat is utilized based on the regional demand for industrial heat, and the alternative price of electricity. While this model includes simplifying assumptions, the market structure analysis accounts for the total system cost affecting deployment choices. (Vanatta et al., 2023)

The other two use cases for nuclear direct heat, kerogen rich oil shale, and hydrogen production also have links to the natural gas market. Oil and natural gas prices are correlated because the two are coproducts. And since both oil and natural gas generate energy, a large price differential leads to a convergence as markets adjust from a disequilibrium (Brown, 2005). See Figure 3 for a comparison of oil and gas price changes over time.

Figure 3:
Oil and Natural Gas Price Dynamic[15]



14 Three HTGR, a iPWR, and a IMSR design based on available costs data.

15 Data source used to create Figure 3 include (EIA, 2024a; Federal Reserve Bank of St. Louis, 2024)

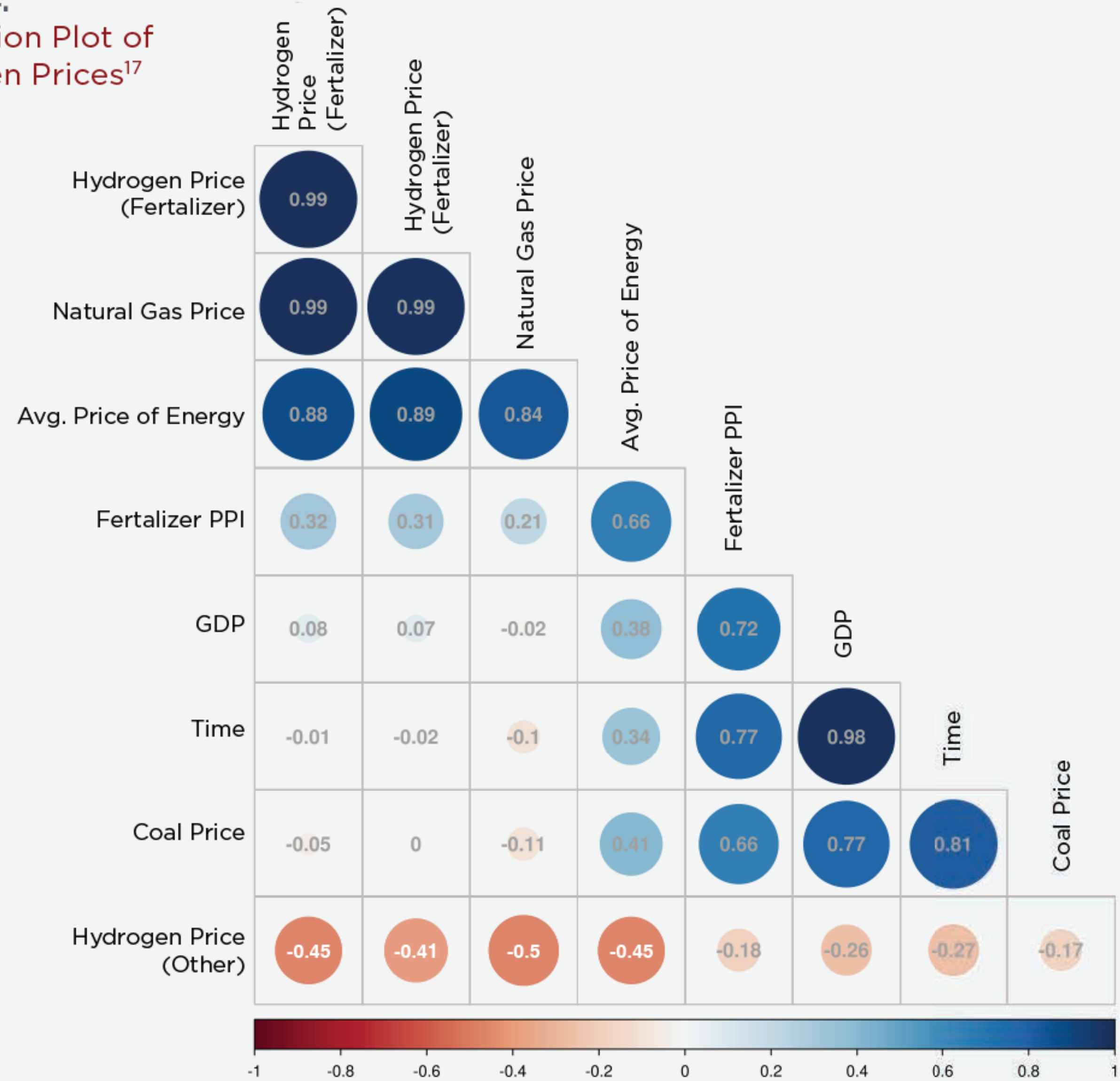
An economic analysis of available oi shale recovery methods estimates the break-even price point to be between $115 and $148[16] per barrel of oil (Bartis, 2005). Based on the correlation between natural gas and oil prices, if the price of oil enters this range, then natural gas prices will be high enough for nuclear heat sources to be economically viable. Assuming that oil prices achieve this price threshold, there is economic potential for nuclear heat processes to support extraction in Wyoming.

The largest difficulty in developing the kerogen oil shale industry in Wyoming is alternative oil sources. Mature oil produced from shale is less costly to extract than kerogen heavy oil. Any produced oil shale requires the kerogen to be processed into oil, adding one additional cost. Further, oil sands in Canada and Venezuela also require heat to be extracted but these processes are more cost effective. Current tar sand operations are being run profitably in Canada, while oil shale projects remain at a standstill (Han et al., 2024). The extensive resources available from shale plays and tar sands act as a backstop price on oil, restricting the upper range of potential prices. If oil prices increase to the $130 per barrel level necessary to recover oil shale in Wyoming, then drilling will increase in these other sources of oil. Eventually, this will bring oil prices back down to the marginal cost of producing from shale. This creates a *severe obstacle* to kerogen oil shale production in the economic category. Without technological innovation that lowers production costs, the State will not expand recovery operations.

Like oil shale, hydrogen is linked to the natural gas market through inputs. The most common method of producing hydrogen is steam methane reforming, which uses natural gas as a feed stock (Jechura, 2015). Further, natural gas is used to generate heat during hydrogen production. While many supply and demand factors effect price, the price of hydrogen sets a floor for producers, making it the most correlated component of price formation. A correlation matrix of factors that are plausible drivers of hydrogen price is provided in Figure 4.

[16] Inflation adjusted from 2005 (the time of the report) to 2024.

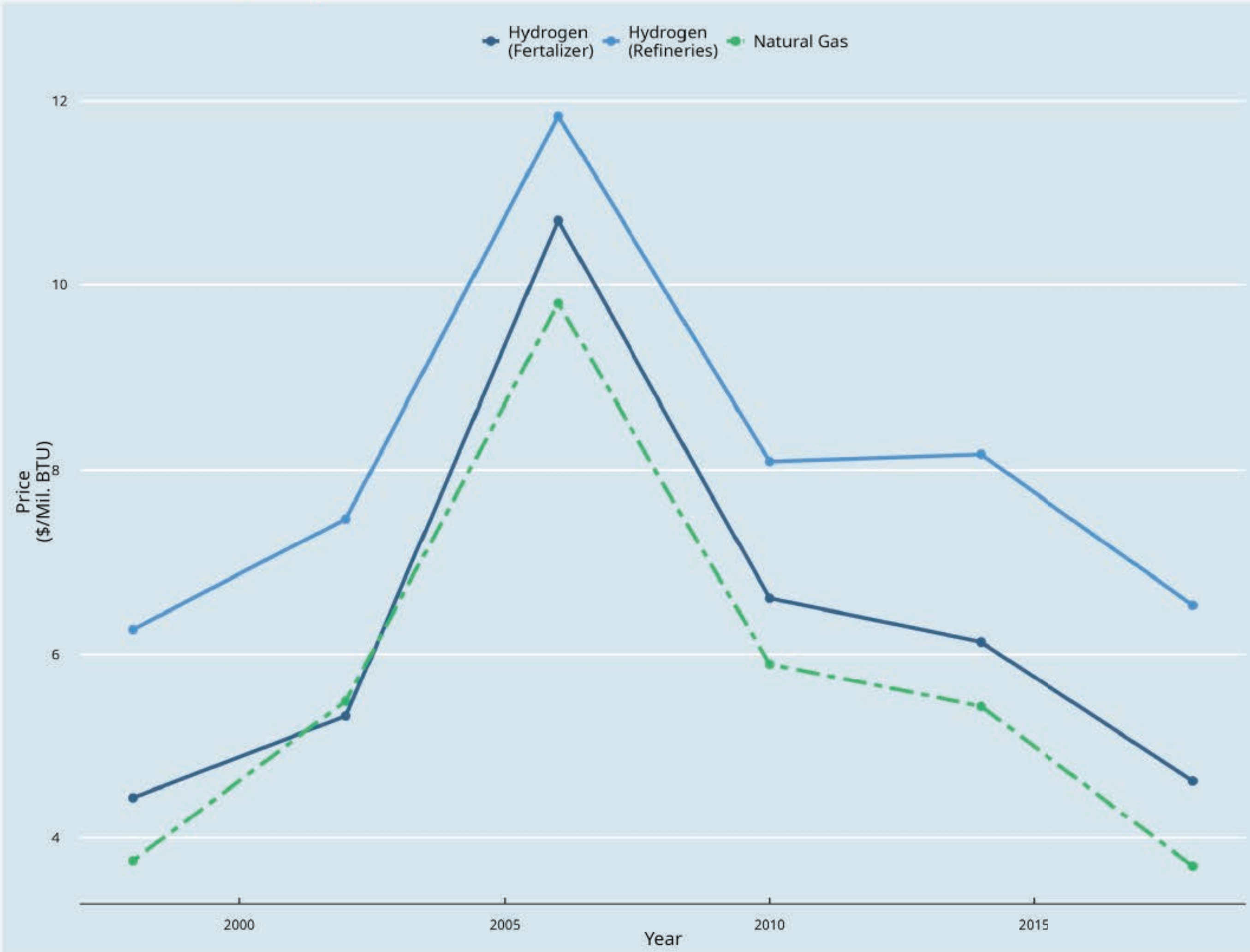
Figure 4:
Correlation Plot of Hydrogen Prices[17]



The relationship between hydrogen prices and natural gas prices across time is provided in Figure 5.

[17] The data used to create the correlation plot in Figure 4 come from multiple sources. The Manufacturing Energy Consumption Survey includes all Hydrogen prices (fertilizer, refineries and other), and the average energy price paid in term of BTU(EIA, 1994, 1998, 2002, 2006, 2010, 2013, 2017, 2021). The fertilizer producer price index (PPI), gross domestic product (GDP), natural gas price, and price of coal were collected using the Federal Reserve of Saint Luis database(EIA, 2024a; Federal Reserve Bank of St. Louis, 2024; International Monetary Fund, 2024; U.S. Bureau of Economic Analysis, 2024; U.S. Bureau of Labor Statistics, 2024b, 2024a).

Figure 5:
Price Trend of Hydrogen and Natural Gas[18]



This correlation between observed hydrogen prices and natural gas prices allows for hydrogen prices to be predicted during unobserved periods. The price of commodities such as hydrogen, are set by the marginal cost of production. Under current market conditions steam methane reforming using natural gas is the marginal production method. Based on this, an estimated hydrogen price is produced using natural gas data. This estimate was created with a regression analysis provided in Appendix (C). This establishes the expected price received for hydrogen production independent of the technology used since the price is global[19].

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18 Ibid

19 There may be deviation in the market price for hydrogen within regional markets due to transportation costs, but the global average hydrogen price sets bound on the local deviation possible. Further, natural gas prices drive electricity prices in the U.S. which in turn affects the operating cost of electrolysis.

Due to the importance of natural gas in all the use cases of heat from nuclear energy, forecasts of natural gas prices are used to determine cutoff points for economic viability. This model is an autoregressive time series model which predicts future prices based on lags of the price of natural gas and historic variance. The model also includes a variable of unforeseen temperature variations[20]. The price of natural gas is transformed to be optimally trend stationary and then differenced[21]. This roughly correlates to an estimation of a change in natural gas price in terms of percentage change from the previous month. Based on the Akaike Information Criteria (AIC), no lags are added to the model (Akaike, 1974). Appendix (B) provides more details about the rationale for the model applied and data validation test results.

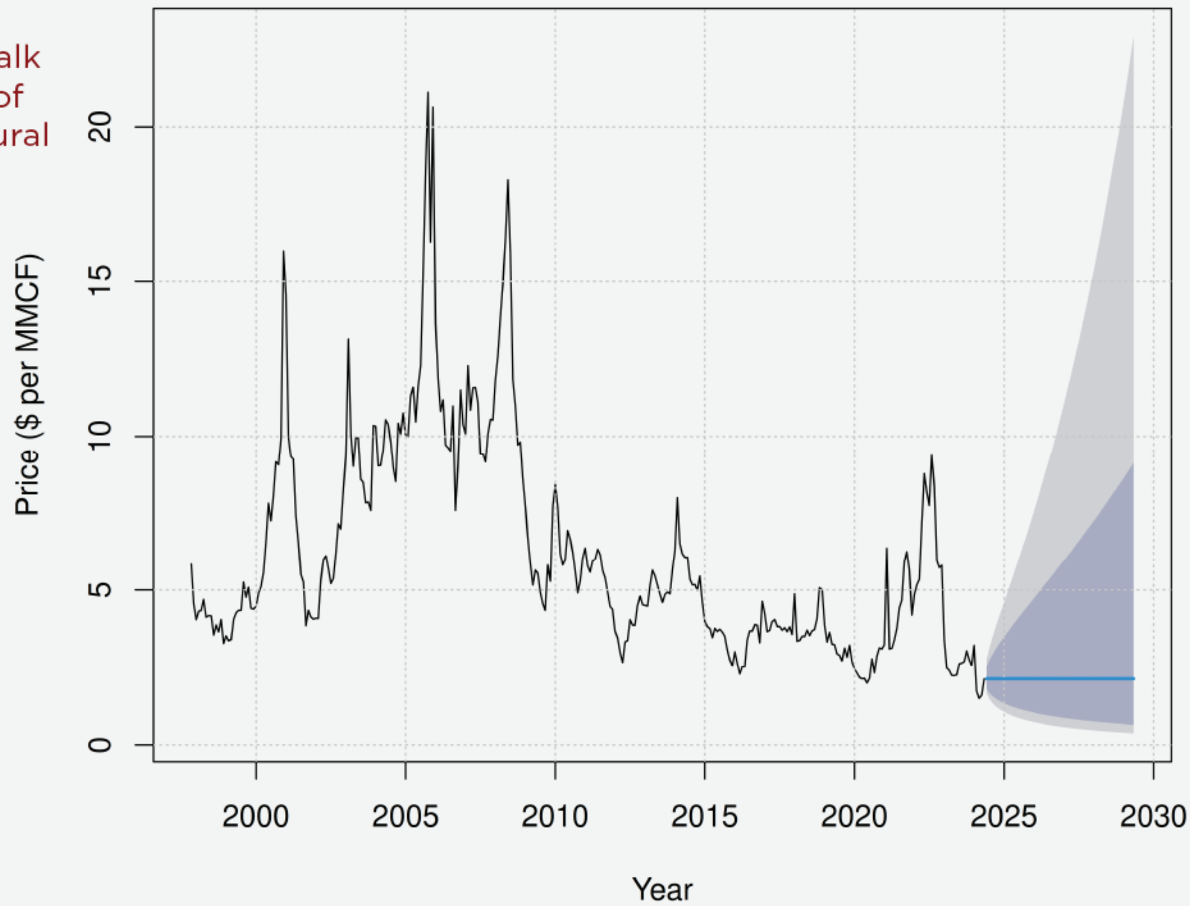
This form of model is a random walk price model. After accounting for temperature changes, the percentage change in price of natural gas is not correlated with the previous month's change. This fits expectations of market dynamics. The price of natural gas remains stagnant unless there is an unforeseen shock in demand or supply factors. After this shift, the price is expected to remain at that level. For example, the hydraulic fracturing boom of 2014 significantly reduced natural gas prices. After this shift, prices have remained lower than historic levels. The price of natural gas as forecasted by this model is provided in Figure 6. The confidence bands are 80% and 95% respectively[22].

[20] This variable is the cumulative 12-month residuals of a regression that predicts the number of populations weighted heating degree days, using dependent variables of a time trend, and month dummy variables. This represents the unexpected change in weather over the last year, since monthly variation and long-term trends are well understood by companies buying natural gas futures. Leaving out this control yields similar model outcomes.

[21] Lambda value of the transformation found using the box-cox method (Box & Cox, 1964).

[22] An 80% confidence interval means that if the model is correctly specified, then the actual price will fall outside of this band 20% of the time due to chance.

Figure 6:
Random Walk Prediction of Future Natural Gas Prices



Based on this forecast, it is unlikely, but not impossible that natural gas prices will rise to the $6.78 minimum price point necessary to deploy SMRs for industrial heat use. The most likely future natural gas price is the current price, which is well below the necessary natural gas price. The random walk model predicts that half of all price paths end in a price less than $2.50 per million BTU far into the future. As time increases it becomes feasible for high prices to be achieved as more positive shocks to price can be accumulated by chance. By 2030, historically high prices are within the 95% confidence interval. The farther you go into the future, the more probable it is that natural gas prices can achieve pre-2010 levels, because the range of possibilities expands. However, it should be noted that even after 2050 there is less than a 50% change to achieve a $6.78 minimum price. This model demonstrates the intuitive result that natural gas prices are more uncertain across time. In the short term it is unlikely that reactors will be cost competitive with natural gas, but with enough time this outcome becomes a coin flip.

However, there is evidence that nuclear reactors for industrial heat production will be able to enter the Wyoming market even at lower natural gas prices. There are multiple tax exemptions at the state and federal level for SMRs in Wyoming (see Section 3.6) and additionally, direct support has been provided to encourage SMR development in the State (BWX Technologies, 2023).

Two other cost considerations assist in establishing cogenerated heat SMRs and micro reactors. First, the natural gas breakeven point is assessed based on current SMR prices. SMR learning rates have the potential to reduce overnight capital costs by 50% after 2050, with 35 GW of capacity deployed (Lohse et al., 2024). Under such a cost reduction, the break-even price would be closer to $3.50 per million BTU. This price point has been reached post-2014 and is in the realm of immediate price possibilities of natural gas. Finally, adding the option to sell excess electricity on the market can improve the economics of SMR heat generation (Vanatta et al., 2023). While this estimate depends on assumptions about multiple unknown cost factors, it becomes feasible that SMRs will be applied to industrial heat in the future.

The deployment of SMRs in Wyoming for industrial heat uses is placed as a *moderate obstacle* in the economic scoring criteria. Current industrial heat applications have an incentive to operate using existing equipment running natural gas. Further, any industries that retire industrial heat equipment will install natural gas generators to maximize profits. On the other hand, reasonable reductions in SMR costs coupled with federal and State incentives can propel SMR industrial applications in the future.

Finally, this model of natural gas prices can be reworked to perform a similar analysis of hydrogen prices. Break-even price points of producing hydrogen using nuclear produced heat and electricity[23] have been estimated to range from between $2.6 per kilogram to $4.7 dollars per kilogram (Soja et al., 2023a). A price forecast of hydrogen with these costs plotted as horizontal lines is provided in Figure 7. The red line is the minimum viable price of $2.6 per kilogram of hydrogen, and the green line is the upper bound viable price of $4.7 per kilogram of hydrogen. In between these two plotted lines, is the expected cost of $3.3 per kilogram for a high temperature steam methane facility using the Prairie Island nuclear power plant (Soja et al., 2023b).

[23] Including both electrolysis and high temperature electrolysis

Figure 7:
Random Walk Prediction of Future Hydrogen Prices[24,25]

The results suggest that hydrogen production from nuclear is less market ready than industrial heat. Natural gas prices would need to reach levels above the pre-hydraulic fracturing boom to be viable without State financial support. To close this gap technological innovations are necessary (see Section 3.7). Under ambitious cost reductions goals the DOE seeks to decrease the cost of hydrogen produced by nuclear to $1 kilogram (DOE, 2021b). This would make nuclear produced hydrogen competitive with natural gas sourced hydrogen by 2030 in more than 30% of the hydrogen price path simulations from the model but necessitates continued technological development. Under current market conditions, economic factors are considered a *major obstacle* for producing hydrogen with advanced nuclear reactors in Wyoming.

[24] Ibid

[25] Price cutoff ranges selected based on the (Soja et al., 2023a)

Effect of Carbon Pricing

Many academic studies and federal programs about direct heat uses of nuclear reference carbon reduction targets as a motivation of analysis (Dabbaghi et al., 2024; DOE, 2022a, 2022b; El-Genk et al., 2021; Gulli et al., 2023; Peakman & Merk, 2019; Safari & Dincer, 2020; Shobeiri et al., 2023; Stewart et al., 2021; Vanatta et al., 2023). This interest in using nuclear energy to produce direct heat and hydrogen as a low emission energy source provides an additional incentive to development. The effect of encouraging nuclear heat production can be evaluated with economics to determine if a premium paid for low carbon energy sources will make direct heat applications of nuclear economically viable.

Economic tradeoffs remain relevant when considering carbon dioxide reduction goals. A low carbon premium paid for nuclear power reduces the profitability gap between natural gas and nuclear heat sources. While such a policy would create a shift towards lower carbon energy sources, the effect on nuclear sourced heat is uncertain. Depending on the assessed value of carbon dioxide reduction, natural gas sources of industrial heat may still provide more economic welfare than higher cost nuclear heat sources. To determine if a range of proposed federal standards would reduce the economic barriers to entry of nuclear produced heat a market model of natural gas under these proposals is developed.

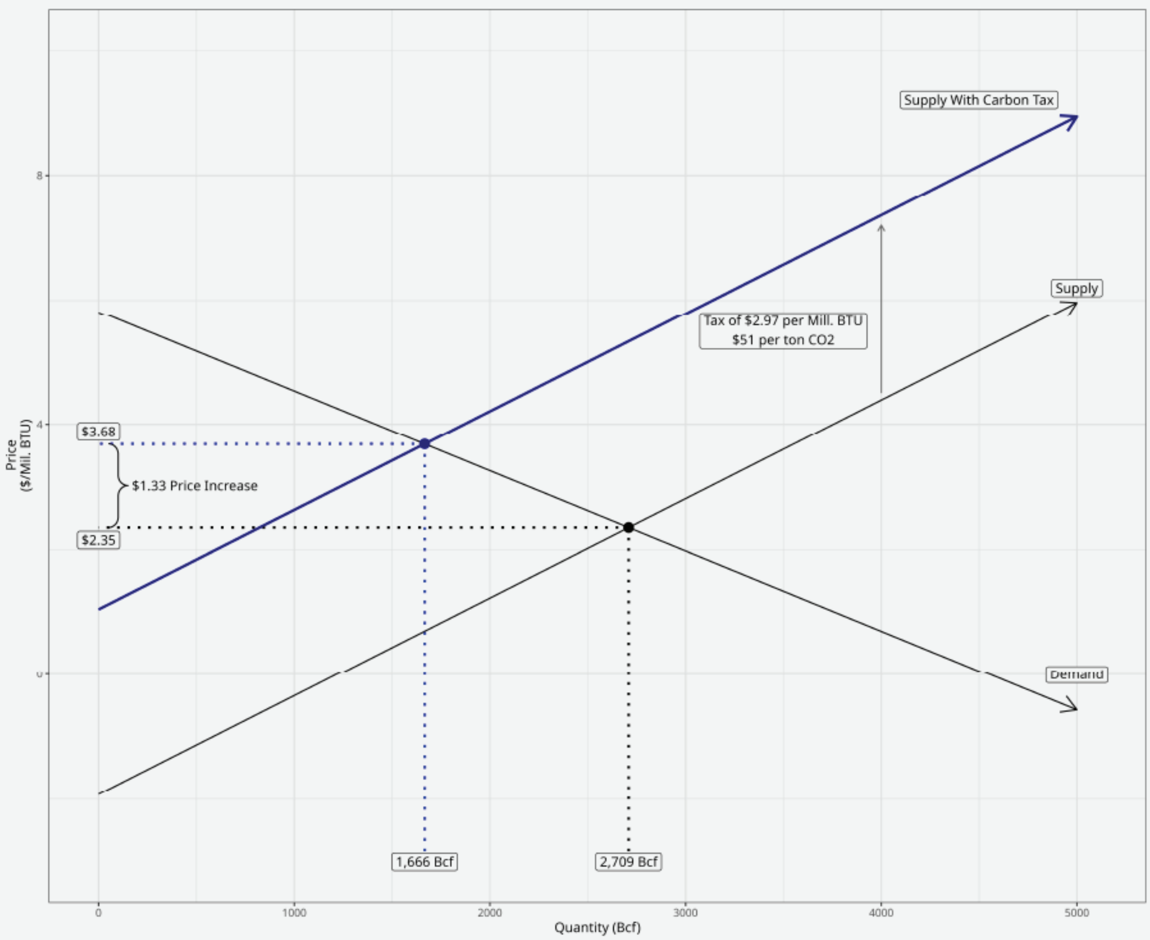
The EPA estimates the social cost of producing one ton of carbon dioxide. Climatology forecasts are integrated with economic models of future costs and benefits of the climate models, which provide an estimate of the welfare gains from carbon reduction. Notably such forecasts rely on certain value judgments. For example, some models have treated the discount rate (time value of money) for society independently from market rates placing future cost at under 2%, while other models integrate private market discount rates valuing future costs at 4.3% (Nordhaus, 2007)[26]. Other considerations include whether global, federal, or state social values should be considered in policy analysis. For more details about these policies see Appendix (A).

The present analysis considers outcomes under two proposed carbon pricing mechanisms, the current EPA evaluation of $51 per ton of carbon dioxide implemented under the Biden administration, and the previous social cost of carbon of $4 per ton under the Trump administration (Asdourian & Wessel, 2023; Goulder & Iii, 2012; *Social Cost of Carbon, December 2015*, 2015). A social cost of carbon estimate produces an implicit tax on carbon, for consideration by legislators. The following analysis applies these social costs of carbon, to determine if this specific standard has the potential to adjust the nuclear produced heat market in Wyoming.

[26] Small changes in these values can create major changes in predicted carbon values. For example, a recent estimate of the social cost of carbon predicts a cost of $80 per ton at 3.0% discount rate, but $308 per ton with a 1.5% discount rate (Rennert et al., 2022).

The alternative to nuclear produced industrial heat is natural gas produced heat, so a simplified supply and demand model of the natural gas market is developed. The effect of a carbon reduction policy from the possible EPA standards is modeled as a supply shift in natural gas based on the total volume of carbon per million BTU (EIA, 2023b)[27]. Based on this, a million BTU of natural gas, would have an added cost of $2.97 under Biden carbon policy, and $0.23 under Trump policy. The demand and supply elasticity (how much a price increase changes consumption), is taken from econometric models[28]. The 2023 equilibrium points of gas consumption and price are used as a reference point[29]. The supply and demand curve are assumed to be linear within the range of policy implications. Figure 8 and Figure 9 are supply and demand diagrams of the natural gas market with these two carbon pricing mechanisms.

Figure 8:
Effect of natural gas price and quantity under EPA Social Cost of Carbon Pricing.[30]



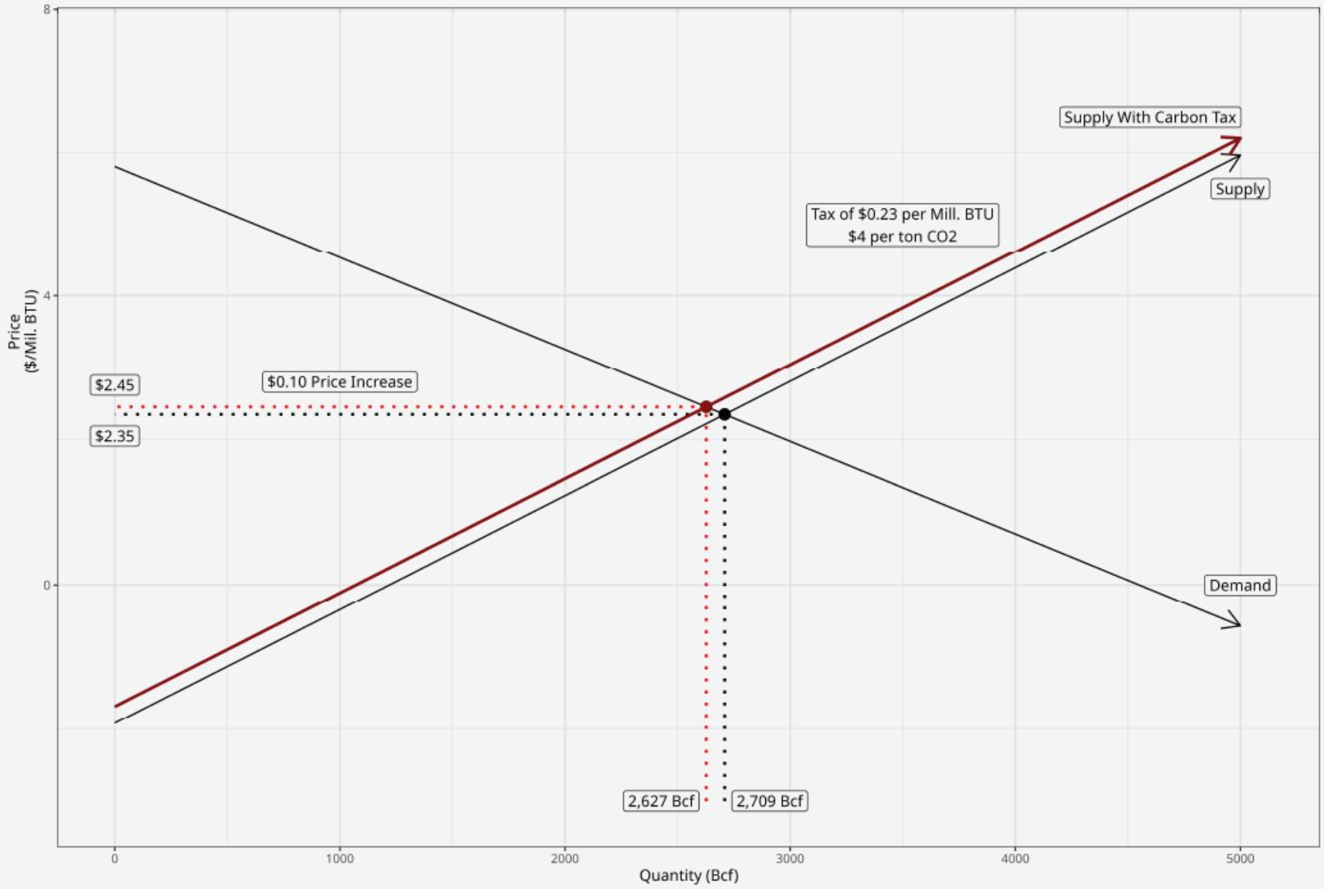
[27] 116.65 pounds of carbon dioxide emitted per million BTU burned of natural gas (EIA, 2023b). 2000 pounds per ton. 0.058325 tons of carbon dioxide per million BTU.

[28] Long term natural gas demand elasticity of -0.68 (Labandeira et al., 2017), and supply elasticity of 0.55 (Gebben, 2025).

[29] In 2023 total us natural gas consumptive use was 2723.5 billion cubic feet, with 1038 BTU per Mcf (EIA, 2024g; U.S. Bureau of Transportation Statistics, 2024). Price of $2.35 per Million BTU near 2023 (EIA, 2024a).

[30] Ibid.

Figure 9:
Effect of natural gas price and quantity under previous EPA Social Cost of Carbon Pricing.[31]



These models provide a starting point to determine if potential future carbon dioxide pricing policy changes will affect the economic viability of nuclear heat production in Wyoming. If a tax was implemented based on the current EPA carbon social cost estimates nuclear power does not gain a large enough price premium to compete with natural gas in Wyoming. The shift in supply of natural gas would result in the price paid by consumers increasing by $1.33, and a decrease in total natural gas consumption. This would raise the price of natural gas to $3.68 cents which is lower than the $6.78 threshold for nuclear power to replace natural gas in industrial uses.

Under current economic conditions, carbon considerations are not enough to induce SMR industrial heat use in Wyoming. However, under the previously identified future cost reductions by 2050 such a policy would decrease the time to market for SMRs. The same cost considerations are relevant to hydrogen production which has a higher market entry barrier. This policy would have the largest dampening effect on oil shale applications since this decreases the value of oil extraction.

[31] Ibid.

A tax based on the previous carbon pricing estimation would produce a minor price increase of 10 cents per million BTU, having a marginal effect on the relative profitability of nuclear produced heat.

These figures provide the effect under the assumption of a linear supply and demand curve and the numerical results are sensitive to this constraint. An alternative simplifying assumption is that the supply curve has a constant elasticity, in this case the magnitude in price is constrained as the supply shock becomes large. However, this starting point provides valuable information about the probable impact a carbon pricing policy could have on the market for reactors when applied to industrial heat.

The EPA has proposed new guidelines which would increase the social cost of carbon to $190 per ton (*National Center for Environmental Economics, 2023*). This introduces a new policy consideration which would have consequential effects to the market for nuclear reactors. One reason for this substantial increase in estimated carbon cost is a change in discounting methods. Rather than using a constant discount rate, future rates decline across time leading to less discount of future expected costs (*National Center for Environmental Economics, 2023*). This is done to account for uncertainties in future economic growth, with more uncertainty far in the future (*Arrow et al., 2013; Freeman & Groom, 2016*).

If this cost of carbon were applied as a tax, it would be equivalent to charging an additional $11 per million BTU of natural gas, which is 464% of the current market price. However, the effect of such a policy would be constrained by alternative carbon reduction methods. For example, total carbon output is neutral when a natural gas power plant emits one ton of carbon, and one ton of carbon is sequestered at another location. If a $190 price of carbon is accounted for, then the resulting cost increase to operate a natural gas facility is the next lowest cost of reducing carbon dioxide.

The actual cost added to natural gas purchases under this tax would depend on the state of alternative carbon reduction options, and carbon markets. For example, removal of carbon from the air costs between $126 and $350, which would not significantly reduce natural gas added costs (*IEA, 2020*). However, reforestation efforts can capture carbon at a price of between $5-$100 per ton and could reduce the policy effect on natural gas facilities (*Austin et al., 2020*). Alternatively, carbon reduction could be purchased on the market. The market price of carbon in the European Union Carbon permit system is $72 per ton (*Trading Economics, 2024*). While economic conditions will evolve if this carbon policy is implemented, if this price of carbon were applied to energy production today the carbon credit market would allow natural gas facilities to operate with an additional fee of $4.17 per million BTU.

Under a federal policy that places $190 per ton value of carbon reduction, SMR produced heat would become cost competitive with natural gas. The ability to switch into nuclear produced heat reduces the risk of policy changes for Wyoming firms. Under this policy outcome some of the welfare loss associated with reduced coal, oil and natural gas production in Wyoming would be compensated by an increase in nuclear produced power, including industrial heat uses.

For this analysis, potential federal policy changes that apply EPA carbon price standards would not reduce the identified obstacle scores, absent a reduction in nuclear reactor costs. An approximate increase in natural gas price of $1.33 per mill BTU is not enough for nuclear produced heat more cost effective. However, a policy based on the proposed EPA social cost of carbon could decrease this score, depending on the final market price of sequestration technology.

EXISTING INDUSTRY

Existing Industry: Scoring Criteria

Industrial Heat	Hydrogen	Oil Shale
Minor Advantage	Minor Advantage	Major Obstacle

Existing industries are found to be a *minor advantage* for industrial heat applications of nuclear energy in Wyoming. Wyoming has industries that are candidates for sourcing heat from nuclear reactors. Both trona mines and oil refineries are Wyoming sectors that have economic incentives to develop SMRs as part of the industrial processing. However, there are only a few Wyoming based sectors with production processes that are amenable to the use of nuclear produced heat. Industries like paper mills and ethyl alcohol are slated to test SMR heat, but these sectors are absent in the State.

Hydrogen production has a similar incentive structure to industrial uses. Refineries and fertilizer producers are the top two consumers of hydrogen. Both exist in Wyoming, providing a potential demand source for hydrogen produced with SMR heat. This puts the existing industry score as a *minor advantage* for hydrogen production.

Since no kerogen oil shale operations exist in Wyoming, existing industries are scored as a *major obstacle* to applying nuclear heat to oil shale extraction.

Existing Industry: Analysis

Existing industries in Wyoming create a source of demand for nuclear produced heat in the State. To quantify the potential development in the State, companies already using industrial heat in a manufacturing process were reviewed.

The primary source of data used comes from an Idaho National Lab study, which applies survey data collected as part of the EPA's greenhouse gas reporting program (EPA, 2014; McMillan & Ruth, 2018). The data includes company information for any operation that emits at least 25 thousand metric tons of carbon dioxide in a year. This methodology excludes most companies that use industrial heat but is appropriate for the study of SMR potential deployment as operations only using small quantities of heat will be subeconomic for nuclear reactor applications.

Microreactor scale projects (under 300 MW) are not included in the current analysis, due to significant cost barriers, and data limitations. Current levelized costs for micro reactors average $313 per MWh, which can be compared to the average levelized cost of SMR and larger projects of $100 per MWh (Abou-Jaoude et al., 2023)[32]. This makes microreactors cost competitive with diesel generators but not with electricity sourced from the grid (Westinghouse & Bruce Power, 2021). We assume that any industrial facility with access to the grid won't deploy microreactors over the study period. Nevertheless, future innovations in microreactor technology could change this as the technology matures. For example, the State funding provided to test the BANR microreactor at Wyoming trona mines could reduce these barriers to entry (Wolfson, 2023). With continued technological development, SMR technology can become competitive with recently deployed technologies, which have levelized costs of between $44.6[33] and $65.8[34] per MWh (EIA, 2022). Therefore, the focus of the existing industry analysis is on large industries which both provide the highest potential economic benefits from reactor utilization and can most easily utilize SMR designs in the future.

The Idaho National lab data is used to identify the industrial heat output of Wyoming firms, their location, and the industry they are involved in. Summary statistics of the Wyoming industries are provided in Table 3.

Table 3:
Industrial Heat Use in Wyoming by Industry (Terra-Joules per Year)[35]

Industry	<300 deg C	<600 deg C	Total	Percentage
Trona	70,100	70,100	70,100	68.0%
Refineries	11,600	27,700	27,700	27.2%
Fertilizer	800	800	2,500	2.5%
Lime	0	0	1,500	1.5%

[32] Values are inflation adjusted from $250 per MWh and $80 per MWh in 2019 to 2024 respectively (U.S. Bureau of Labor Statistics, 2024a).

[33] Natural gas LCOE inflation adjusted to 2024 dollars.

[34] Solar LCOE inflation adjusted to 2024 dollars.

[35] Table 3 data was aggregated from greenhouse gas reporting program (McMillan & Ruth, 2018)

Trona and soda ash processing provide the largest potential application of nuclear sourced industrial heat in the State. All heat demand in this sector is at or below 300 degrees Celsius. This is important for a development pathway because lower temperature requirements increase the range of SMR designs which can be employed at the trona mine, without heat augmentation. This is enough heat demand to operate 2.65 SMR reactors in Wyoming[36,37].

Oil refineries are the next largest demand source for industrial heat. Refineries apply heat for a range of processes, including cracking complex oil chains into lighter components or to decrease viscosity. This leads to a split in required temperatures, and only 42% of heat used is supplied at less than 300 degrees Celsius, with all other heat needs falling in the range of 301 to 600 degrees. This precludes some light water reactor designs from supplying the necessary high temperature directly, but liquid metal cooled, or high temperature gas-cooled reactors can supply these temperatures without augmentation. As explored in Section 3.7, these higher temperature reactors face more technological challenges that make LWR more profitable in the near term. Even excluding this higher temperature range in refineries, the sector still uses the second most industrial heat of any Wyoming sector. The total sector provides enough energy demand to support 1.35 SMRs[38]. There are four operating oil refineries in Wyoming, so this capacity would need to be split across multiple microreactors (EIA, 2024c).

The chemical reaction used to produce nitrogen fertilizer is accelerated when completed in a narrow temperature range. Fertilizer production facilities in the State could apply SMR produced heat rather than the typical natural gas production.

In addition to requiring industrial heat, fertilizer production and oil refineries are the largest demand sources for hydrogen (EIA, 2024e). One potential future area of research is to evaluate cost savings of collocating hydrogen production with these industries. Since hydrogen production and the fertilizer plant or oil refinery need processed heat, a larger deployed set of SMRs can be used to supply the needs of these industries simultaneously. This reduces transmission costs and allows for economies of scale.

Finally, lime and cement processing have the lowest identified demand for industrial heat in the State, and exclusively requires temperatures above 600 degrees Celsius. This ranks the industry as the least likely to adopt nuclear produced industrial heat, requiring HTGR to be produced with additional heat augmentation. Future technological development and cost savings will be necessary before this application is feasible.

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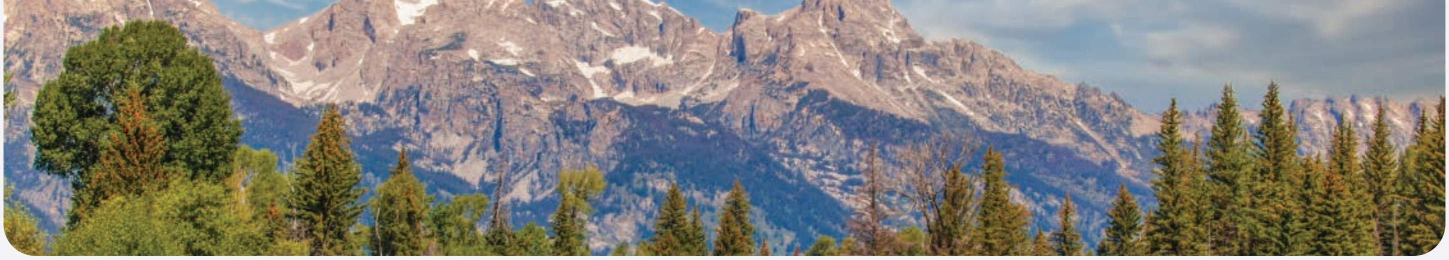
[36] Assuming a 300 MWe SMR with 93% capacity factor and 33% thermal efficiency (Lohse et al., 2024; NuScale Power LLC., 2022) then then a demand of one Terajoule per year of thermal energy requires:

$$\frac{3.786\ 10^{-5}\, SMR}{\text{Terajoules}\ per\ year} = \frac{70{,}100\ \text{Terajoules}}{Year} * \frac{277\ MW\!-\!hours}{\text{Terajoules}} * \frac{Year}{8766\ hours} * \frac{SMR}{300\ MWe} * \frac{1\ MWe}{3\ MWt} * \frac{1}{0.93\ Capacity\ Factor}$$

[37] $2.65\ SMRs\ for\ trona\ mining = \frac{3.786\ 10^{-5} SMR}{\text{Terajoules}\ per\ year} * \ 70{,}100\ Terrajoules\ per\ year$

[38] Since some electricity must be produced to increase temperatures above 300 degrees Celsius, we assume the ratio of MWe capacity to MWt of production is 50% instead of 33% for the 600 degree uses.

$$1.35\ SMRs\ for\ oil\ refinery\ use = 11{,}600 * \frac{3.786\ 10^{-5} SMR}{\text{Terajoules}\ per\ year} + 16{,}100 \frac{5.679\ 10^{-5} SMR}{\text{Terajoules}\ per\ year}$$



There are also opportunities for Wyoming sugar beet processing facilities to utilize microreactors. There are two sugar beet processing plants in the State, which require generators to supply thermal output with temperatures of 70 degrees Celsius (Ames et al., 2021; Staff, 2010; Wyoming Sugar Company, 2019). A 10,000 ton per day beet facility could require up to 264 MW to operate (Lorenz, 2008). Since this output would be supplied as thermal energy the required reactor capacity of the facility would fall into the micro reactor range at 88 MWe[39]. With additional cost reductions of microreactors, beet manufacturing could become an intriguing application of nuclear produced heat in the State but does not reach the capacity threshold for inclusion in this analysis.

This data is aggregated by county, to represent where the economic benefits of industry growth will accrue. This is provided in Table 4.

Table 4: Industrial Heat Use in Wyoming by County (Terra-Joules per Year)[40]

County	<300 deg C	<600 deg C	Total	Percentage
Sweetwater	70,100	70,100	70,100	68.0%
Carbon	7,900	13,100	13,100	12.9%
Laramie	800	9,100	10,800	10.6%
Weston	900	2,800	2,800	2.8%
Natrona	2,000	2,400	2,400	2.4%
Park	0	0	1,500	1.5%
Uinta	600	700	700	0.7%
Converse	0	300	300	0.3%

Development of SMR applications is most likely to occur in Sweetwater County due to the centralization of trona mining. Oil refining operations are more dispersed throughout the State, which results in a mix of counties with potential SMR growth.

Statewide industrial uses from trona mining and oil refining could support up to four 300 MWe small modular reactors. However, regional clustering of industrial demand for heat improves the economics of deployment. This is referred to economies of multiples, and is driven by such factors such as modularity, learning rates and experience deploying the same design.

Sweetwater is likely to be the first mover in the industry, having both trona mining and oil refining. There is more potential for regional clustering due to demand from existing industries. Further Sweetwater industries require a low outlet temperature potentially reducing the cost of deployment, and increasing the range of reactor designs capable of supplying heat without augmentation. In fact firms in Sweetwater are investigating the potential for microreactors to assist in trona processing (Wolfson, 2023).

39 Assuming a three to one MWe to MWt ratio.

40 Ibid.

Total potential demand in Sweetwater is equivalent to 2.65 300 MWe SMRs. Carbon County demand sources can support 150 MWe of SMR capacity such as two NuScale modules (NuScale Power LLC., 2022). Industries in Laramie County can source 122 MWe of SMRs. No other counties are likely to attract SMRs based on industrial demand sources, without future sector growth.

These existing industries provide a *minor advantage* for developing nuclear projects. Existing trona mines, and oil refineries require enough heat to utilize up to four SMR. Hydrogen production is encouraged by the existence of oil refineries and fertilizer producers in the State. Only kerogen oil shale faces an *major obstacle* to development since no oil shale projects are active in the State.

TAX STRUCTURE

Score

Major Advantage

Tax: Scoring Criteria

Wyoming's tax code and the federal government provide a *major advantage* for siting nuclear heat production in the State. This applies equally to all nuclear applications reviewed. At the federal level, the Inflation Reduction Act of 2022 provides tax incentives for energy communities such as Wyoming. The State has exempted advanced nuclear reactor projects from all applicable taxes.

These programs produce significant cost savings for the nuclear industry, which encourages development. These cost savings are unique to the State, providing a direct incentive to locate projects in Wyoming. This places the tax score as a *major advantage*.

Tax: Analysis

Wyoming provides tax advantages for cogenerating heat for industrial uses. While the State does levy an excise tax of $5 per MW of electricity produced by a nuclear reactor, this tax is unlikely to affect new cogeneration facilities. Wyoming Statutes (2024) 39-23-101, part C provides an exemption stating.

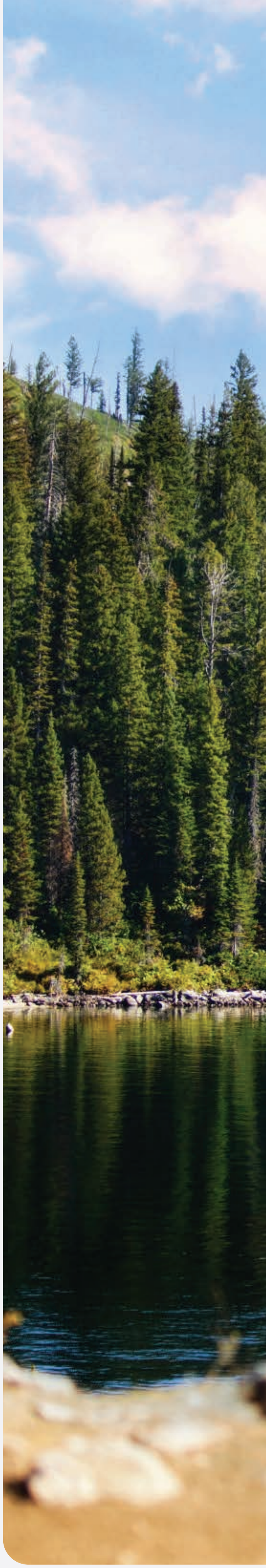
> *"Except as otherwise provided in this subsection, no tax shall be imposed on any advanced nuclear reactor operated in accordance with W.S. 35-11-2101. Beginning July 1, 2035, a taxpayer shall only qualify for the exemption authorized under this subsection for any month that not less than eighty percent (80%) of the advanced nuclear reactor's uranium used for producing electricity was sourced from uranium mines located in the United States."*

The 80% requirement is not a disadvantage for advanced reactors at current uranium prices, but different economic conditions are worth considering. There are two possible scenarios: 1) Uranium produced in the U.S. exceeds total quantity demanded in Wyoming; and 2) Uranium produced in the U.S. is lower than the total quantity demanded in Wyoming at market prices.

In the first scenario, Wyoming nuclear power plants would be willing to pay a premium for U.S. sourced uranium, but other producers are neutral. This means that all uranium produced in the U.S. will be purchased by Wyoming power plants, but uranium prices will remain the same. The policy will not increase U.S. uranium production or change the relative price. This assumes that global arbitrage will stabilize uranium prices. However, if mines are able to price discriminate, charging more to local Wyoming power producers through contract negotiation, then there will be an added cost for nuclear power plants operating in the State (Nauleau et al., 2015; Taylor & Yokell, 1979).

In the second scenario, global market prices are not high enough to induce local production to fully cover the quantity demanded in Wyoming. In that case, the effect of the policy is to raise the operating costs of nuclear power producers in the State and increase U.S. uranium production. This shifts some economic benefits from Wyoming nuclear electricity producers to U.S. uranium miners. Additionally, there is an economic deadweight loss, where the total benefits of the uranium producers are less than the reduction in profit for electricity producers (Ricardo, 1819). This is because uranium is being produced at a lower cost in other parts of the globe, so more resources are spent to extract the same quantity of uranium domestically. The added cost to produce the Wyoming uranium compared to the global cost constitutes the economic loss.

Based on the supply elasticities found in previous research (Gebben, 2024) and the market structure of nuclear energy, the most likely outcome is that all Wyoming power producers will continue to purchase U.S. sourced uranium. A trend encouraged by projects designed to develop domestic uranium infrastructure through the Inflation Reduction Act of 2022 (DOE, 2024b). Since uranium is a small portion of the total cost of nuclear power production compared to capital, the added fuel cost will be more than offset by this tax credit. A 1% increase in price paid by the Wyoming power producers will induce 0.66% uranium production (Gebben, 2024). So long as this cost escalation is less than the tax benefit, 80% of uranium used in the country will also be produced locally.



While the State nuclear produced electricity tax is mitigated by current statutes, additional tax advantages are available to reactors applied for direct heat. Wyoming and South Dakota are the only two states that do not levy either a corporate income tax or a gross receipts tax (Loughead, 2024). This encourages the development of nuclear reactors operating in the State. Further, typical sales tax burdens for direct heat applications are reduced through Wyoming Statute (2024) 39-15-105 which provides an exemption of sales taxes for:

> *"Sales of power or fuel to a person engaged in the business of manufacturing, processing or agriculture when the same is consumed directly in manufacturing, processing or agriculture."*

This reduces the State taxes paid for direct heat applications of nuclear reactors compared to utility scale electricity production. In the context of the present analysis, this tax structure constitutes a significant advantage for Wyoming nuclear power operations.

A second tax advantage comes from federal programs. The Inflation Reduction Act applies tax credits to low carbon energy sources and some of these credits can be applied to nuclear energy.

Importantly, this tax credit is increased in specific regions. A bonus credit of up to 10% can be applied for designated energy communities[41]. This tax credit can be applied as either a production tax credit or an investment tax credit. Based on the project specifics, a company can choose to receive the benefits as a fraction of capital investment or in net production.

One way to qualify for this credit is if the project is in a census tract[42] where a coal mine was closed after 1999 or a coal-fired electric generation unit retired after 2009. A map of counties qualifying for this tax credit is provided in Figure 10. Much of Wyoming can qualify for this added tax incentive due to the long-standing coal industry in the State.

[41] See (The Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization, 2024)

[42] Or an adjoining census tract.

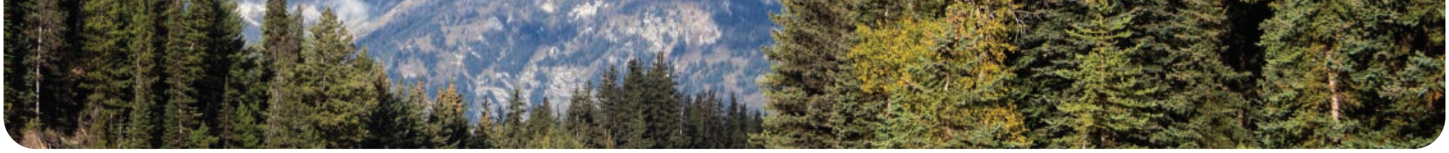
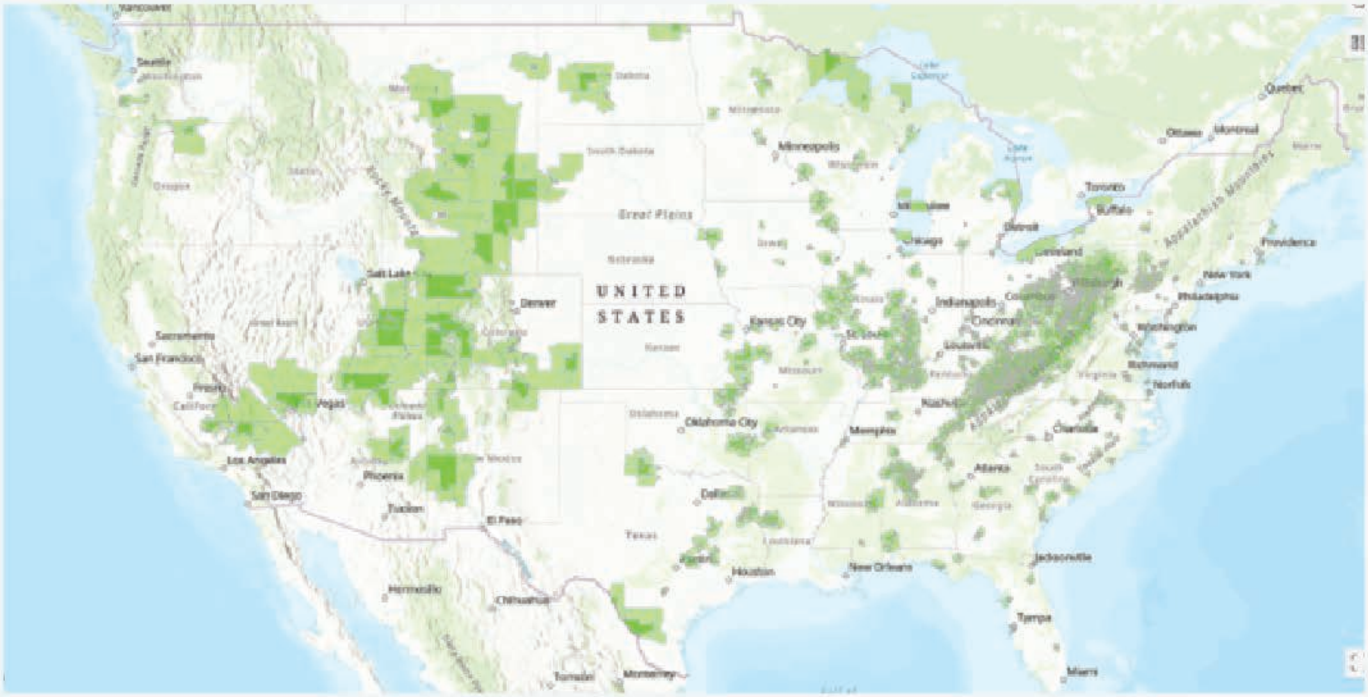


Figure 10:
Coal Closures in the Continental U.S. (DOE, 2024a)



The combination of possible federal tax credits can reduce overnight capital costs[43] of SMRs by as much as 37% (Lohse et al., 2024). The significant federal tax incentives for SMR production, with special benefits to Wyoming projects, further adds to the *major advantage* tax score.

TECHNOLOGY

Industrial Heat	Hydrogen	Oil Shale
Minor Obstacle	Minor Obstacle	Moderate Obstacle

Technology: Scoring Criteria

Technology scores as a *minor obstacle* for applying heat produced from nuclear energy for industrial applications. All planned advanced reactors designs will be able to produce heat applicable to Wyoming industries, such as trona mining. However, future advancements in reactor designs are expected to decrease costs. Without these cost savings, nuclear reactors will be less attractive than alternative power sources, limiting market access.

[43] Overnight capital costs are the total construction costs, without including interest paid on loans.

Similarly, hydrogen producers can source energy from low temperature advanced nuclear reactors. This is accomplished by using some of the electricity produced by the reactor to increase the temperature of the hydrogen generation process above the outlet temperature, or by using the electricity in an electrolysis process[44]. As an emerging industry, hydrogen production with nuclear reactors has more technological challenges than industrial heat use. Nevertheless, the technology score remains a *minor obstacle* since available reactor designs can supply this sector with heat.

Finally, kerogen oil shale extraction is assigned a *moderate obstacle* score. Unlike hydrogen or industrial applications, there are no established oil shale operations in Wyoming. Available technology limits oil shale extraction, adding additional barriers to integrating nuclear produced heat.

Technology: Analysis

The type of nuclear technology selected for industrial uses is dependent on the required cogeneration operating parameters. For example, a cogeneration microreactor used for methane reforming would need to be capable of supplying between 700°C and 1,000°C process steam. These operating parameters limit the choice to either a HGTR or MSR nuclear unit unless augmentation is implemented. Generally, the following nuclear design concepts have been used, or proposed, for cogeneration applications:

- Light water reactors (LWRs),
- High temperature gas reactors (HTGRs),
- Liquid metal fast reactors (LMFRs),
- Molten salt reactors (MSRs), and
- Heat-Pipes.

A summary of these technologies is provided, establishing the relative technological benefits of each reactor. Later, the technological readiness of advanced reactors designs is explored to identify the technological score for each nuclear heat application.

Each of these technologies can achieve higher temperatures when heat augmentation technology is applied. Electric, chemical or mechanical heat pumps can be used to increase the outlet temperature of the reactor (Worsham, 2023). Various heat augmentation methods for nuclear reactors are currently being developed (Singh & Sharma, 2021; WNN, 2023). Development of such technologies could reduce the technical obstacles associated with the temperature limits of any one reactor design.

[44] Either standard electrolysis or HTSE.

Light Water Reactor Technologies

Light Water Reactor (LWRs) SMRs are smaller versions of the current U.S. power reactor fleet. These reactors require a reactor pressure vessel, operating between 1,200 psi and 2,500 psi, use 3% - 5 % enriched Uranium-235 (U^{235}), and generally have the same operating characteristics and safety issues of the Generation III[45] power reactors. While newer advanced LWR designs use more passive safety features, post shutdown decay heat must be managed to prevent core damage.

Light water SMRs use one of two basic design concepts. One concept is the boiling water reactor (BWR) where steam produced in the reactor is directly used to provide cogeneration process heat or electricity generation. In contrast, the pressurized water reactor (PWR) operates at a high enough pressure to prevent steam voids in the reactor coolant system. The PWR uses an intermediate loop[46] between the reactor and the industrial application. About two-thirds of the energy produced in LWRs is rejected to the environment. Several countries have reclaimed this rejected energy for co-generative processes.(Constantin, 2024)

High Temperature Gas Cooled Reactors

The HTGCR was developed in the 1950s and was used for the Peach Bottom 1 SMR (Pennsylvania; 200 MWth; 1966-1974) and the Fort St. Vrain (Colorado; 842MW^{th}, 1979-1989) commercial generation facilities. The HTGCR, coupled to a hydrogen production plant, uses a graphite moderator rather than water to slow down fission neutrons to sustain the nuclear reaction.

The HTGCR has the advantage of supplying process heat in the temperature range between 700°C and 1,000°C. These high temperatures support a variety of industrial applications. For example, several thermochemical looping technologies can produce hydrogen directly from water at 800 °C, with greater thermal efficiency than methane reformation (Peck et al., 2013).

TRISO nuclear fuel particles consist of various UOX chemicals, such as UO2, which have been coated with four layers of three isotropic materials deposited as a protective kernel. These four layers include a buffered PyC layer, inner PyC layer, and silicon carbide layer outer PyC layer. TRISO nuclear fuel particles, about the size of a ballpoint pen, show promise, pending NRC review and approval.

[45] AP1000, Generation III+, Vogtle units 3 & 4.

[46] Steam generators

Fast Reactors

Fast reactors directly use fast fission neutrons to transmute U^{238} into Pu^{239}. These reactors use depleted uranium (U^{235}) around the core. Fast neutrons are captured by U^{238} and decay to Pu^{239}. Over time, the Pu^{239} supplies most of the reactor power. The number of neutrons produced by Pu^{239} fission has about a 25% greater efficiency than U^{235} thermal fission. Additionally, fast neutrons are more efficient breeding[47] Pu^{239}. Rather than water, these reactors typically use a liquid metal coolant, such as sodium or lead, and operate at low pressure. For example, the proposed Natrium Reactor in Kemmerer will operate at just slightly higher than atmospheric pressure, eliminating the need for a reactor pressure vessel.

Some fast reactors have been operating since the 1950's. In addition, the DOE operated the Fast Flux Test Facility for breeder reactor material research[48] and France operated the world's largest fast reactor[49]. (Allen, 1977; WNA, 2021a)

Molten Salt Small Modular Reactors

A subset of molten salt reactors (MSR) are fast reactors where the fuel is dissolved within the coolant, usually in a molten fluoride salt. Recently, MSRs have come back into interest due to their compatibility with the thorium fuel cycle used to breed U^{233}. Molten salt reactors were first developed in the 1950s. Several early experimental reactors had extended run times. However, the MSR approach was abandoned in the 1970s in favor of uranium fuel.

Molten salt reactors have exceptional thermal stability. This physical characteristic allows high temperature operations at low-pressure, allowing greater use of passive safety features. The reactor also has higher efficiencies and lower spent fuel generation compared to other technologies. The MSR is uniquely suited for supplying cogeneration industrial process heat. However, MSR corrosion issues have not yet been successfully resolved. Southern Company and TerraPower are experimenting with SMR MSR designs, as well as China, Canada, Denmark, Netherlands, Japan, Indonesia, and the United Kingdom. (WNA, 2021b)

Market Readiness

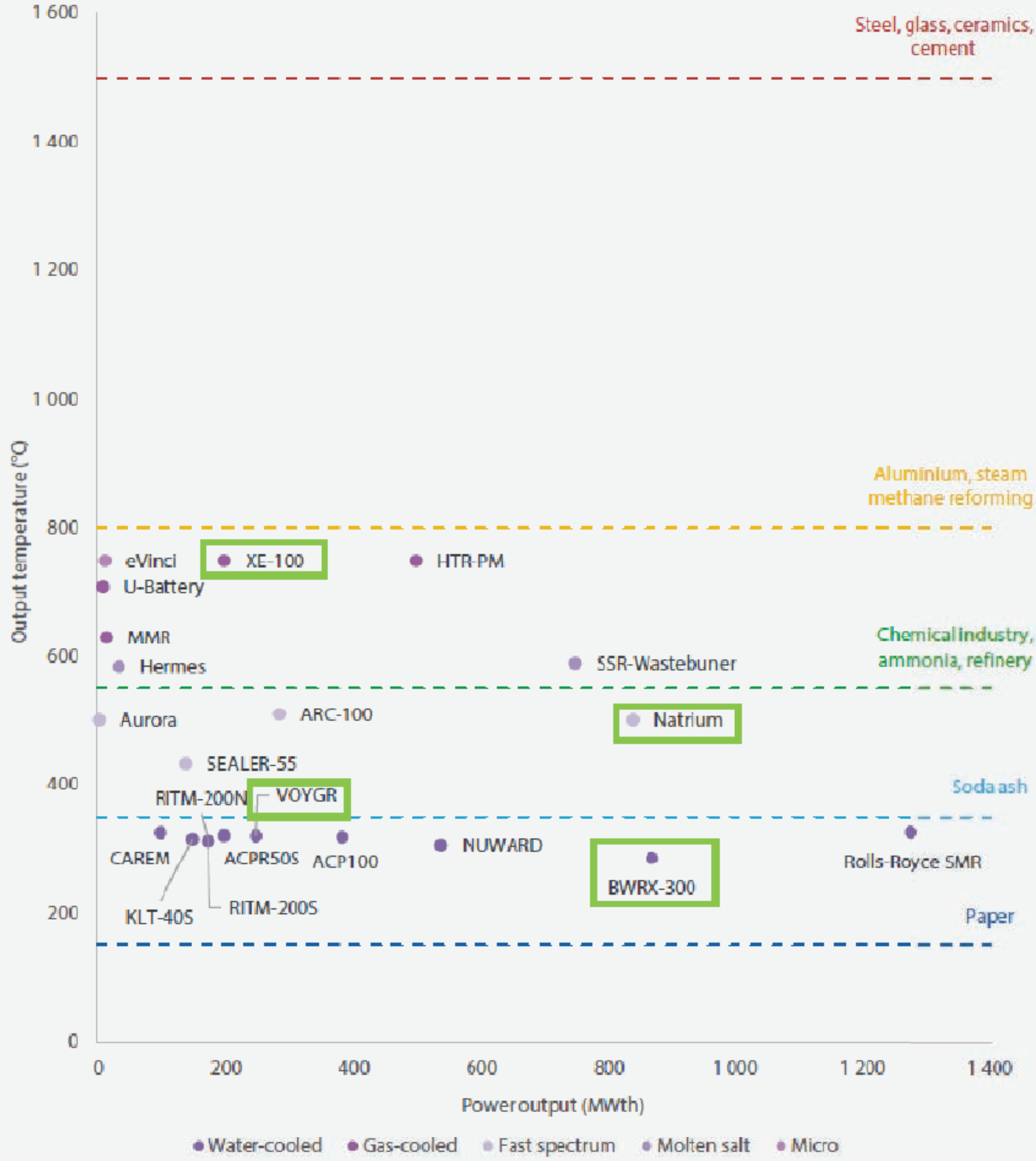
To assess whether current technology promotes industry development in Wyoming, the state of each technology needs to be evaluated. This requires two steps, identifying the industrial applications of the various reactor designs and an assessment of the current state of the technology. Figure 11 shows the types of direct heat uses applicable to specific SMRs designs under development.

[47] LWRs also rely on U^{238} fast neutron capture, but at a less rate. Generally, about 1/3 of a LWR reactor power is generated by Pu^{239} fission during the last third of the fuel cycle.

[48] 400 MWth; 1980 1992

[49] Superphenix; 1985 - 1998, 1,242MWe

Figure 11: Market Application of SMR designs (Coffey, 2023).



Under current technological and economic constraints (see Section 3.4), advanced reactor designs face challenges for being deployed in industrial heat applications. However, some technologies for industrial applications are more viable than others. A survey of industry experts used to rank the importance of deployment factors, such as siting and fuel availability, identified the NuScale VOYGR and the GE-Hitachi BWRX-300 to be the top designs ready for industrial heat use (Coffey, 2023). Other models support this finding, indicating that at current technological development levels, low temperature applications of SMRs provide the most deployment potential (Vanatta et al., 2023). Both reactors are suited for low heat industrial applications, although the NuScale design is marginally able to process soda ash. This indicates that low temperature applications are the most technologically able to be deployed.

Future innovation and learning will be required to promote industrial heat applications in Wyoming. A learning rate of between 5-10% per doubling of output of SMRs has been identified in the literature (Steigerwald et al., 2023). However, this learning rate is likely to be closer to the upper portion of this range at 9.5%, when accounting for the fact that most SMR designs are first-of-a-kind design (Lohse et al., 2024). Some of these cost savings come from duplicating specific design elements, with a first-of-a-kind nuclear reactor costing 19% more than reactors with previous deployment[50] (Lohse et al., 2024). This has two potential effects. First, increased learning rates will lower SMR cost generally incentivizing a range of direct heat applications. On the other hand, the learning rate driver encourages specialization with the industry continuing to invest in the lowest cost reactor design. Since the temperature output of the reactor varies by design, an industry standard design may lead to a difficult to reverse nuclear reactor template (David, 1985). As a result, the learning rate may limit the future heat applications of SMRs by narrowing the available range of temperatures on the market. Whether the generalized SMR cost reduction, or the specialization effects dominate is not discernible until the technology develops further.

While many uses for industrial heat from nuclear are technically feasible, additional development is required to bring these innovations to commercialization. The exact temperature of the reactor design limits which industrial applications are amenable to cogeneration. The most likely future uses of nuclear produced heat in Wyoming are in a low temperature range, suitable for soda ash processing and some oil refining. This places the technological score as a *minor obstacle*. All else equal, further research and development is necessary to establish industrial uses for nuclear in the State, but Wyoming is not uniquely challenged by this. The major industries in Wyoming will require heat under 300 degrees C (see Section 3.5), which is feasible with most advanced reactor designs being developed.

The technological challenges are not identical across nuclear applications. Kerogen oil shale extraction is an immature industry, with at least 20 different retorting methods being investigated to process the kerogen rich oil (Speight, 2012a). The interaction between this uncertainty and the rapid development of nuclear technology increases the technological barrier of oil shale extraction above a simple average of the two technological limitations.

Extraction processes, such as the Galoter retort method, would require temperatures of 700-800 degrees C, while other in situ processing methods are expected to use temperatures of 343 degrees (Speight, 2012a, 2012b). This creates uncertainty about which reactor designs can support this extraction industry. Current reactor designs can produce most of the possible temperatures for oil shale recovery expected in the literature, but the average temperature is higher than applications such as trona mines. Unlike industrial heat, the technology of oil shale extraction requires additional technologic developments to feasibly purchase nuclear produced heat. This elevates the technological score to a *moderate obstacle*.

[50] Log-log the coefficient of a nth of a kind reactor dummy predicting overnight capital costs is -0.22. Which translates to a 19% decrease in costs.

Hydrogen production is found to have a technological score of a *minor obstacle*, although more challenges exist than in industrial heat processes. Three commercially available hydrogen production processes require direct heat including steam methane reformation, partial oxidation, and biomass gasification (Pinsky et al., 2020). Each of these technologies requires the application of between 700-1000 degrees C of heat, which exceeds the produced outlet temperature of all but molten salt and gas cooled fast reactors (Pinsky et al., 2020). This technological limit does not preclude advanced reactors from producing hydrogen. For example, the NuScale project planned to produce hydrogen by redirecting a portion of the electricity produced to generate heat, elevating the applied heat above the 300-degree starting point up to 860 degrees (Szondy, 2020). Using produced electricity relaxes the design limitations of nuclear reactors as applied to required temperature outlets.

However, applying electricity from a reactor contributes to operating costs. The generation of heat from nuclear produced electricity takes a circuitous energy route as nuclear energy is converted to thermal energy, which is then transformed into electrical energy, and finally back to heat. Applying nuclear heat converts chemical energy directly to heat, skipping the intermediate steps, and decreasing system losses. Applying nuclear produced heat in this direct manner generates a cost advantage compared to other electricity generation sources. However, this advantage of direct heat applications is dimensioned if the nuclear energy must be converted from heat to electricity prior to being applied. Advancement in high temperature reactor designs will therefore improve the economics of producing hydrogen with nuclear reactors.

Alternatively, electrolysis processes may become a demand factor for advanced nuclear reactors. SMRs can be deployed at the hydrogen production facility, providing a steady flow of electricity. Electrolysis process is agnostic towards the outlet temperature of the reactor and can produce hydrogen from any electricity source. Demand for nuclear electricity could take the form of high temperature steam electrolysis (HTSE). HTSE can reduce the electricity required to produce hydrogen by 35% by changing the phase of the water (Smolinka et al., 2022). Cost calculation of nuclear hydrogen production, place this method as the lowest total energy requirement of hydrogen generation (IAEA, 2017; Soja et al., 2023a). However, HTSE is found to be the second lowest cost hydrogen production method from a suit of potential projects due to elevated capital costs of the system designs (Soja et al., 2023a). When using these methods electrolysis of HTSE circumvents the need for additional grid transmission infrastructure minimizing costs.

Alternative electricity sources are a relevant consideration. Importantly, nuclear reactors can produce electricity at a steady rate, which provides technical advantages over intermittent resources such as wind or solar (Farhana et al., 2024; Olateju et al., 2016). The most direct competition with nuclear energy sources in this respect comes from natural gas or petroleum generators. The main challenges of deploying nuclear for electrolysis process are these opportunity costs as elaborated in Section 3.4, and hydrogen production from electrolysis is only minimally affected by technological limitations of nuclear reactor designs.

Unlike kerogen rich oil shale production, hydrogen production is an established industry which can apply existing nuclear technology. Current nuclear systems have the physical capacity to serve this market, although innovation is needed for nuclear produced hydrogen to supplant the dominate steam methane reformation[51] method of generation. This places technology as a *minor obstacle* for the application of nuclear reactors in hydrogen production.

LOCATION

Industrial Heat	Hydrogen	Oil Shale
Minor Obstacle	Minor Obstacle	Major Advantage

Location: Scoring Criteria

The reactors deployed in different regions of the country may incur different total costs, due to location specific considerations. Large portions of Wyoming have location cost advantages due to low population density and reduced flooding risk. On the other hand, water availability and steep terrain increase nuclear costs in the State. While some areas of the State are unaffected by these considerations, much of the territory has at least one location consideration that adds to nuclear reactor costs. This places industrial and hydrogen applications of nuclear in the *minor obstacle* scoring range.

The Mountain West is one of the only regions in the world with significant kerogen oil shale reserves. The U.S. has the more oil shale resources than any other country, and these resources are concentrated in Southern Wyoming and Northern Colorado. Wyoming oil shale resources alone are larger than any other nation. This places location factors for oil shale production with nuclear heat in the *major advantage* category for the State.

Location: Analysis

SMR designs have a small footprint, which allows them to be deployed modularly across the nation in order to meet industry needs (Black et al., 2021). This provides flexibility in location for industrial heat uses of nuclear not available for large scale light water reactor projects.

Since the advanced reactors used for alternative uses, such as industry heat, and hydrogen production will typically fall into the SMR or microreactor size range, there are few physical limits to location selection. The main identified location considerations come from the Nuclear Regulatory Commission siting process. Some of these factors make Wyoming based industry heat SMR projects more feasible, while others restrict options in the State.

An Oakridge Laboratory report identified spatial attributes which create challenges for SMR siting in Wyoming (See (Belles et al., 2012). These include.

1. Land with a population density greater than 500 people per square mile
2. Wetlands and open water.
3. Protected land, national parks, historic areas, wildlife refuges.
4. Land with a moderate or high landslide hazard susceptibility.
5. Land that lies within a 100-year floodplain.
6. Land with a slope greater than 18%
7. Land that is more than 20 miles from cooling water makeup sources[52].
8. Land too close to fault lines.
9. Land located in proximity to hazardous facilities[53].
10. Land with safe shutdown earthquake peak ground[54].

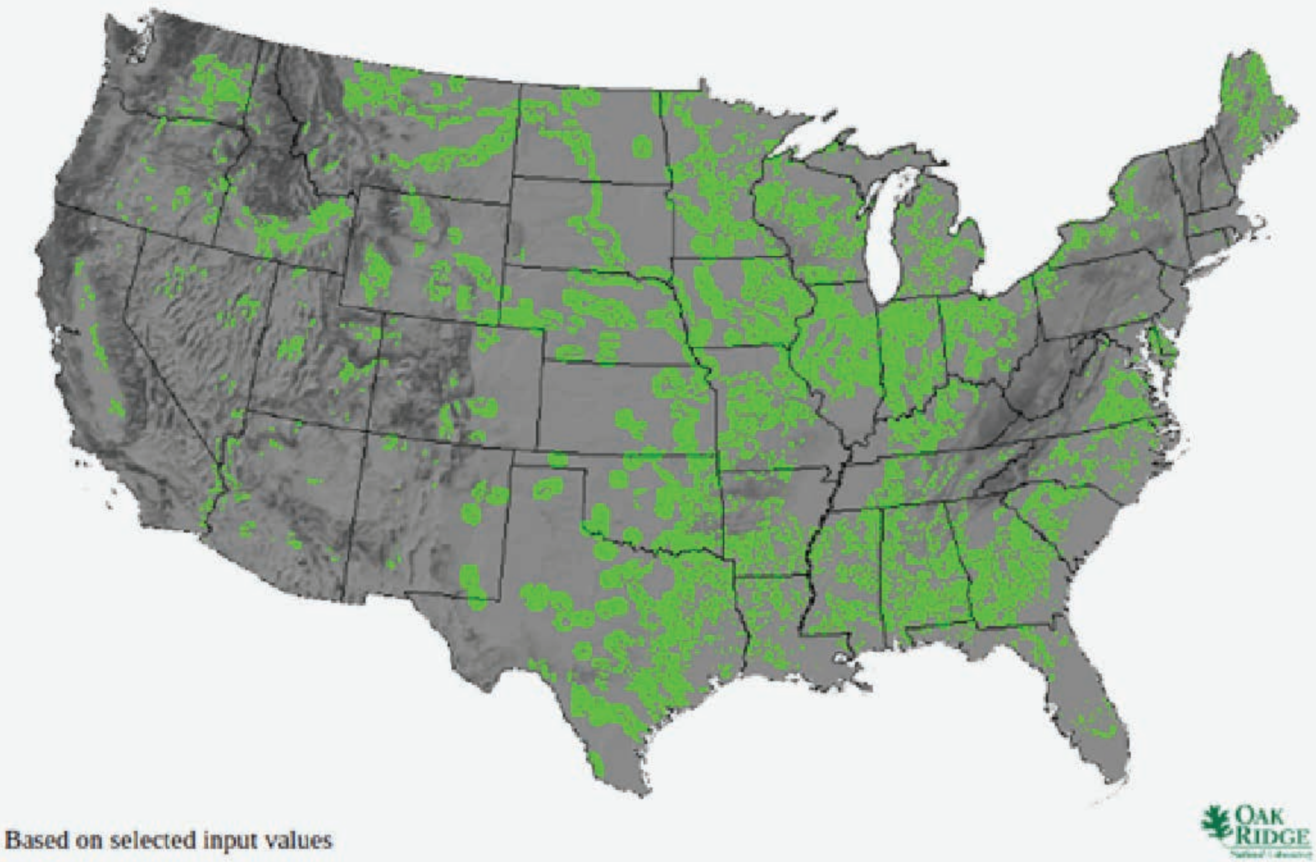
These location issues can be overcome with proper engineering but are relevant to the economic feasibility of an SMR project. For example, reducing the risk of a natural disaster lowers insurance costs, as well as reducing licensing costs.

Of these attribute considerations, Wyoming locations are advantaged in the categories of population, wetland, floodplains, and earthquake sensitivity. The obstacles which affect the most surface area in Wyoming are access to water cooling sources, protected land, such as Yellowstone National Park, and steep terrain grade. The individual map extents of these factors are provided in Appendix 3.

Figure 12 provides a map of areas of the country that face none of the identified location obstacles. The easiest regions to site an SMR are located east of the Rocky Mountains, where water is more abundant, and elevation is stable.

[51] That also uses natural gas as a heat source.
[52] With at least 65,000 gpm
[53] Examples include airports and oil refineries
[54] A 2% chance in a 50-year return period greater than 0.5 g is excluded

Figure 12:
Regions With No SMR Siting Difficulties (Belles et al., 2012)



Even though much of Wyoming is deemed to have at least one siting challenge by this analysis, the unique attributes of direct heat use reduce some of these location challenges in the State.

The single factor that removes the most land in Wyoming from SMR siting consideration is access to water, which is required to operate the electricity generation and provides enhanced safety measures. However, this analysis only reviews SMR designs using a closed-cycle mechanical-draft cooling tower. Many of the industrial use cases for nuclear heat will require alternative designs, such as high-temperature gas reactors or molten salt reactors, which reduce water consumption (Belles et al., 2012; Foley, 2017). Further, the use of heat for industrial applications will decrease water loss. The water used in industrial applications needs to be cycled to prevent mineral buildup or replaced due to leaks (Guyer, 2014). Nevertheless, capturing the heat for direct use reduces the water consumption rate by circumventing the need to expel steam in the electricity generating process.

Based on these factors, it is worth considering how the SMR siting challenges of Wyoming compares to other regions when excluding the water access constraint. Figure 12 displays the number of identified obstacles without considering water access.

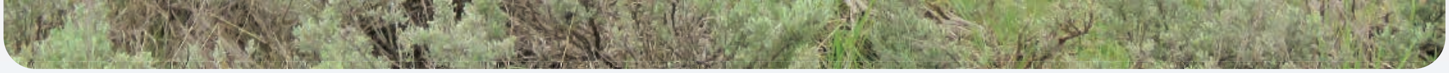
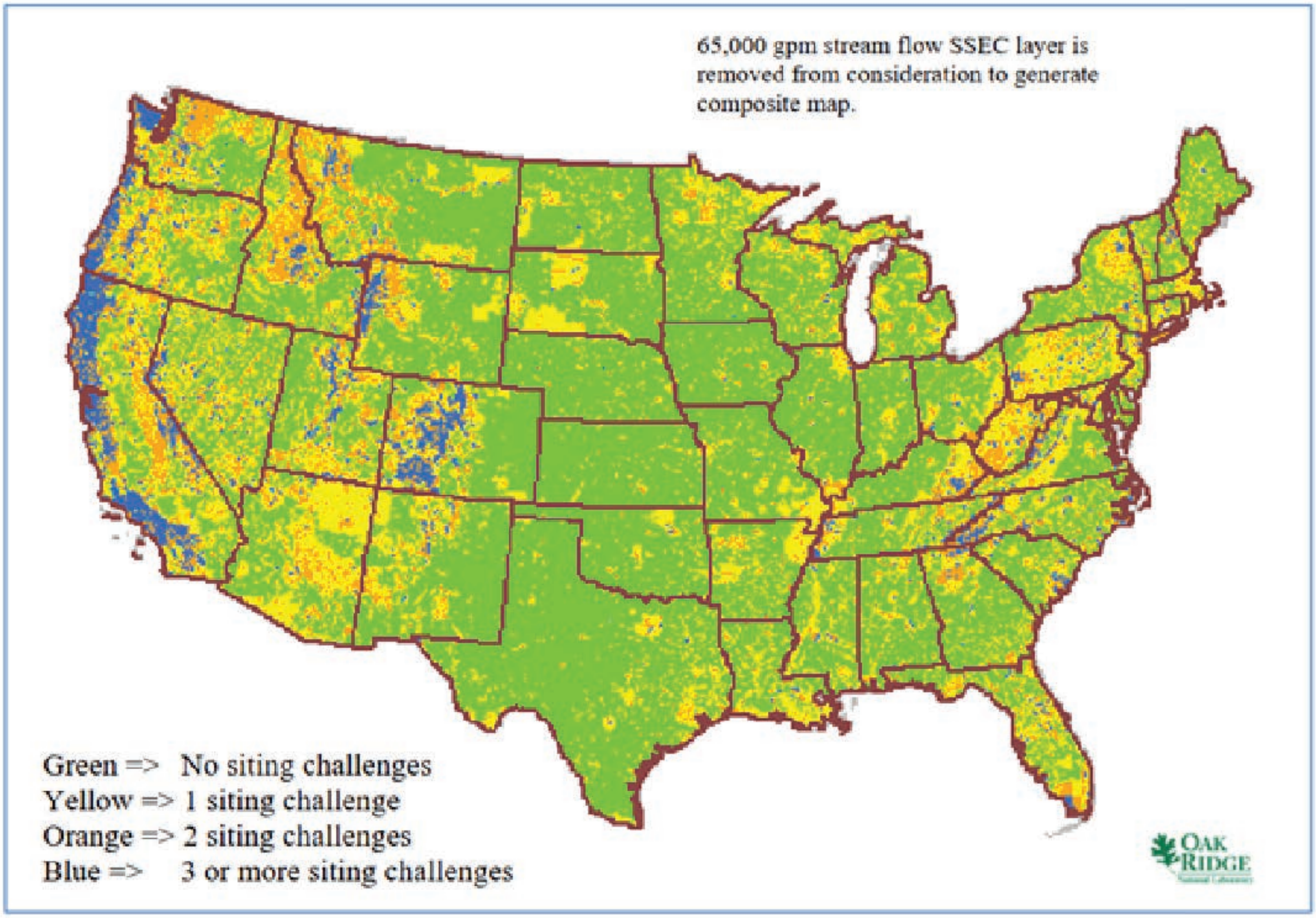


Figure 13:
SMR Regional Siting Challenges Without Water Consideration (Belles et al., 2012)



After excluding water sourcing obstacles from this analysis, most of Wyoming can host an SMR without any licensing difficulties. The primary limitations come from steep terrain and protected land use in northwest Wyoming.

Two factors may diminish the location advantages that are evident in this analysis. First, a SMR malfunction has a small potential radius of impact, which opens new markets for SMR designs. When factoring in this lower radius, SMRs can be deployed in areas with higher population densities and nearer to sensitive facilities (NRC, 2019). Even if the population density standards are reworked, Wyoming has an advantage of being a low population State with high coal capacity. The NRC has identified the current population standards as limiting the number of coal facilities that can be converted to nuclear, because the power plants tend to be located in high population density areas (NRC, 2019). Wyoming's unique combination of expansive energy production and low population provides an advantage in site selection.

Second, water restrictions do affect some of the sources of demand for industrial heat. Notably, hydrogen production requires a steady feed stream of water, which can be challenging to source in Wyoming (E. Holubnyak, personal communication, June 22, 2024). Therefore, the water access limitations in Wyoming create an additional location challenge for this use case, even if the reactor does not require large volumes of water.

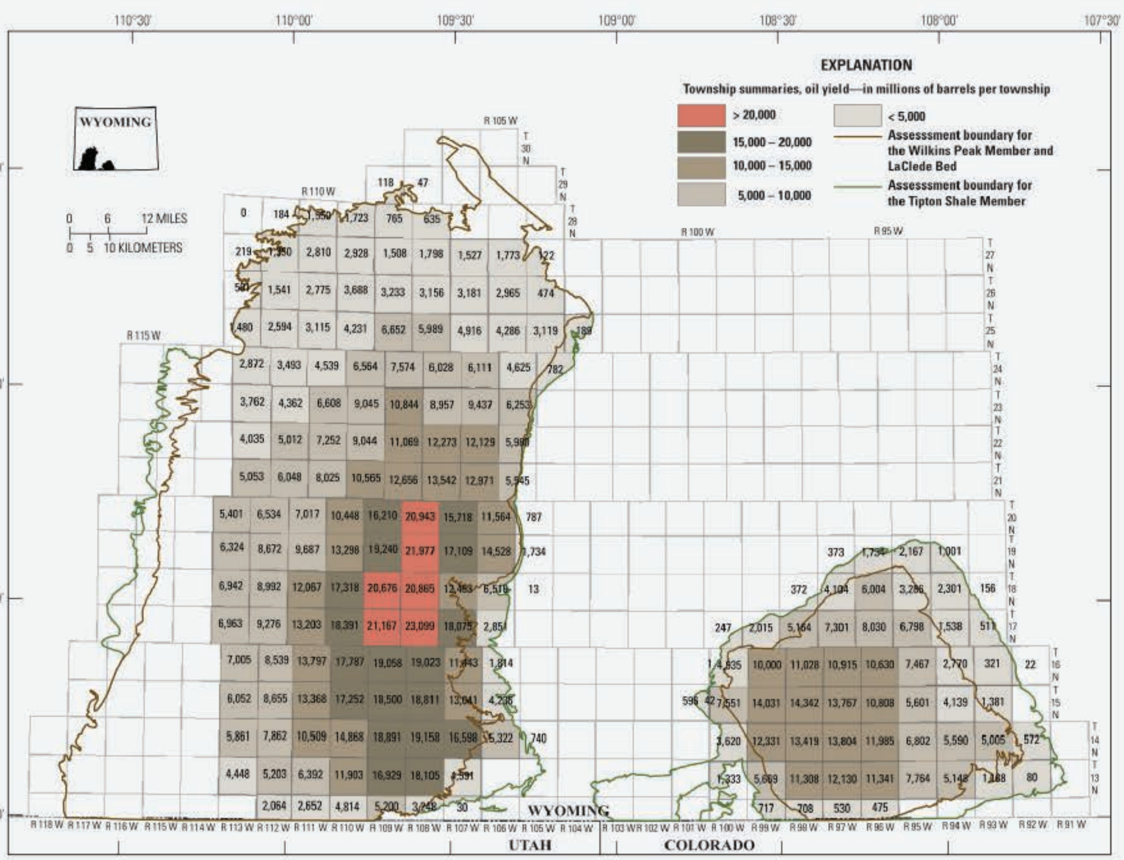
Taken together, the location factors are scored as a *minor disadvantage* for Wyoming. In portions of the State, added regulatory and safety costs would be required to complete a SMR project used for industrial heat. However, this is not true for much of the State and in some locations where industrial applications for nuclear power are in the most demand. Because of this, the location considerations are only a *minor obstacle* and the score is closer to neutral than a *major obstacle*.

There are a few advantages for hydrogen producers to locate in Wyoming, including extant refinery operations and fertilizer producers (see Section 3.5), which are the largest demand sources for hydrogen. However, water constraints become more pertinent to hydrogen production, affecting both the ability to license a nuclear reactor and the ability to provide a feedstock of water for hydrogen production. As a whole, the location considerations of using nuclear energy to produce hydrogen in Wyoming remains a *minor obstacle*. Relative to industrial heat uses, hydrogen faces a smaller obstacle due to the available demand source for hydrogen in Wyoming. However, this is not enough to change the overall classification.

Despite the economic challenges of processing kerogen rich oil shale, (see Section 3.4) Wyoming has a significant advantage in oil shale production worth considering. Technically recoverable resources of oil are estimates of total oil in the ground that can be extracted. Unlike reserves, profitably of recovery is not considered.

The U.S. basins contains 52% of the world's oil shale resources (Dyni, 2006). A breakout of Wyoming oil shale distribution is provided in Figure 13.

Figure 14: Location of Oil Shale Plays in Wyoming (USGS, 2011)



Wyoming technically recoverable resources total 1.44 trillion barrels. Other U.S. reserves include 1.53 trillion barrels in the Piceance Colorado basin, and 1.32 trillion barrels in the Unita Basin split between Utah and Colorado. (USGS, 2011)

This is a *major advantage* for kerogen oil shale production in the State using nuclear fueled heat. If oil prices are ever high enough to induce oil shale production, Wyoming could rapidly expand output.

LEGAL

Score

Minor Obstacle

Legal: Scoring Criteria

Each of the three heat applications of nuclear energy evaluated are reliant on SMR and microreactor design approvals and commercialization. This modifies the compliance cost considerations of nuclear companies targeting these sectors. While the regulatory framework for NRC licensing is the same for small modular and traditional LW reactors, the relative costs are different.

Since SMR designs produce less electricity than large reactors, the same regulatory compliance costs are a higher percentage of expected revenues. Some of the compliance costs can be mitigated through modular production by duplicating technical review. However, not all of these costs scale with production, so small reactors are more significantly burdened by these legal compliance costs. This results in a legal obstacle score of a *minor obstacle* for all categories.

Legal: Analysis

There are multiple legal challenges to operating a direct heat advanced reactor. While there are economies of scale to producing multiple identical units, these do not scale with licensing (Sam et al., 2023). NRC licensing fees for an environmental and technical review of a first-of-a-kind nuclear reactor can cost $10 million dollars (Gebben & Peck, 2023). Initial SMR implementation will face these steep licensing costs, but with significantly lower monetary returns than a large-scale nuclear operation.

As a SMR design is replicated at scale, these licensing costs will be reduced. The technical report costs can rely on the past findings when it comes to component operation and safety systems. However, the environmental report does not scale so easily with replication. Since unique land qualities, such as historic significance, wildlife sensitivity, and economic impact must be studied for each individual project. The NRC has identified challenges in microreactor licensing and categorizes the safety analysis into two categories, those that are generalizable and issues that are site specific with no potential to be streamlined (NRC, 2021).

Since some of the licensing costs cannot be offset by economies of scale, direct heat uses which will usually implement micro or SMR designs, are at a disadvantage. Comparable generation methods, such as natural gas or coal, do not require these costly reviews and large-scale nuclear projects can average the costs over extensive capacity. While insurance requirements are not tailored to SMR designs, this is likely only a moderate cost addition (NEI, 2011).

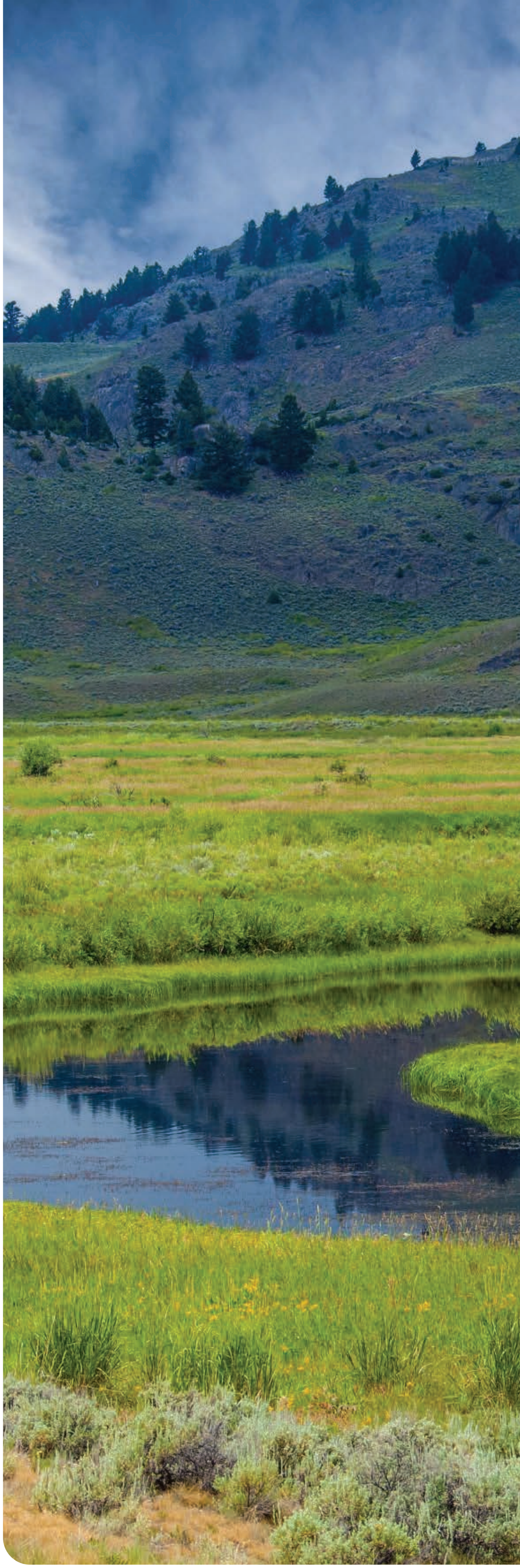
These disadvantages can be minimized by improving the application and associated approval process. While these standards are set by the NRC, hourly rates for compliance and time to completion can be addressed to lower application costs. Wyoming was able to reduce these costs for uranium mines in the State by becoming an agreement state with the NRC, reducing average application costs by $3 million dollars (Gebben, 2024). Wyoming is only an agreement state for the uranium extraction industry and cedes authority for power generation (Nuclear Regulatory Commission, 2018). By applying to become an agreement state, the onus of improving efficiency will be placed on Wyoming, rather than the federal government, which can reduce costs as demonstrated in the uranium industry.

Wyoming operates under a regulated electricity construct, where a utility monopoly is established, providing electricity generation, transmission and distribution infrastructure. The economic rationale for this system is that the provision of electricity is a natural monopoly. In a natural monopoly, economies of scope decrease production costs, so that the most efficient outcome is for one company to manage the entire market. In the case of electricity distribution, creating multiple transmission lines is less cost effective than establishing a single large network, providing a cost advantage to the first firm in the market. In a regulated energy construct, a state allows for a utility monopoly to be established, but approves cost recovery, including authorized rates of return. This vertically integrated structure is advantageous for nuclear power producers because allowable returns methodologies provide an assured cost recovery mechanism, whereas in a deregulated market, nuclear generation is more easily priced out of the electricity market. (Dahl, 2015)

Wyoming's regulated electricity construct could limit the entrance of small nuclear power producers which are not a part of the utility monopoly, but federal rules could conceivably negate this obstacle. In 1978, the Public Utility Regulatory Policies Act (PURPA) was passed, requiring all electric utility companies to purchase electricity from independent producers at avoided cost[55], under certain circumstances. Notably, cogeneration facilities are eligible for PURPA protections, if certain criteria are met. An evaluation of microreactors in Wyoming found that most microreactor designs could qualify (Carlson et al., 2022). The beneficial application of heat in this process means that reactors used to provide industrial heat may be eligible to sell any excess electricity to the utility, which was identified as an important factor in SMR profitability in Section 3.4.

However, this vertically integrated electricity system may create difficulties for cogeneration of heat and electricity from nuclear reactors when the company needs to contract both for electricity and heat. For example, hydrogen synthesis requires both inputs and hydrogen producers may benefit from contracting a nuclear reactor to supply electricity and heat simultaneously. In such a scenario, the SMR firm must sell the electricity to the regulated utility rather than the client.

The State provides an exemption to the requirement that electricity must be sold to the incumbent utility for companies that produce electricity for their own use. However, the nuclear operating licenses and technical requirements make it more feasible to separate the nuclear power generating company from the potential manufacturing company. A specialized nuclear company could provide and manage a SMR more efficiently than having the manufacturing company train staff independently.



[55] Avoided cost is the amount of money the utility company would have to spend to create the electricity themselves.

BENEFITS AND COSTS

ECONOMIC IMPACTS

The benefits and costs of direct heat uses of nuclear power in Wyoming are evaluated using an input-output model (Leontief, 1986). In these models, the inputs of one sector are treated as the output of another industry, and the system of equations are balanced with available data. The model applied comes from IMPLAN[56] which includes sector level data unique to Wyoming, allowing for the economic impacts to be tailored to the unique economic linkages in the State.

The estimates are generated for each potential use case of nuclear. First, the impact of operating a single SMR in Wyoming is estimated. The reference SMR used is a 300 MW reactor operating at 97% capacity (Lohse et al., 2024). The assigned value of the energy produced is 6.89 cents per kWh based on the average price of electricity paid for industrial purposes in Wyoming (EIA, 2023a). An input-output model requires existing industrial data to calibrate. Since no commercial nuclear reactors operate in the State, modifications were made to the model. The model uses the observed expenditure patterns of nuclear reactors in other states for use in Wyoming.

Further adjustments were made to this spending pattern baseline. No uranium expenditure category is available, so this is assigned to coal purchases, since both coal and uranium are energy sources mined in Wyoming for use in baseload electricity generation. Fuel costs are assumed to be 11% of total operating expenditures, based on levelized cost averages of SMR designs (Boarin et al., 2015; Lohse et al., 2024). Further, the electricity infrastructure spending is set to half of the observed IMPLAN parameters since each SMR coproduction plan applies heat on location. After making these adjustments, the remaining cost categories were scaled so that the total is equal to 100%.

[56] For more information on the IMPLAN modeling process, visit IMPLAN.com

The model treats the SMR addition as an increase in electricity generation output of $175.6 million in a year. Finally, the production sales tax is manually set to zero, since the advanced reactor will be tax exempt under Wyoming law.

This single IMPACT estimate is scaled to the expected number of SMRs required under each Wyoming demand scenario.

Industrial Heat

As identified in Section 3.2, there are limited Wyoming-based firms with a clear need for large-scale industrial heat. The biggest opportunity in the State is trona mines, which are currently being evaluated for micro reactor development. This is a key industry to target, and resources are already being placed into gaining further information about the feasibility of microreactor deployment (BWX Technologies, 2023).

Five total industrial heat SMR facilities are assumed to be constructed in the State. Based on the analysis in Section 3.5 just over four 300 MWe SMR facilities can be supported with current industrial demand. This value is rounded up to account for possible growth, and projects that can produce a mix of electricity for retail sale along with industrial heat.

The application of industrial heating from nuclear energy is most economical when replacing retired equipment, instead of existing machinery. This is especially true when nuclear reactors are similarly costed to natural gas heat sources, with the effect of adding a SMR for industrial use is a switching of industries rather than an expansion of manufacturing in the State.

Adding five new 300 MWe SMRs is expected to increase tax revenues by $37 million per year of operation and add 629 direct full-time employees, with a total of 2,545 employees when accounting for indirect effects. This tax total includes induced and spillover tax effects at the State and county levels. Direct taxes are limited because neither produced electricity sold out of state nor produced heat is taxable. We account for this by reducing the direct tax effects in IMPLAN by 90%, allowing for sales taxes associated with purchases for day-to-day operations to be controlled for.

However, retiring five 300 MWe natural gas heating facilities is expected to decrease tax returns by $38 million per year. If natural gas facilities are replaced with SMRs the net effect is a reduction in tax revenues of $1 million per year of operation. These tax differences are within the margin of error, but it is worth considering that replacing existing infrastructure is not an additive process.

Even though the model forecasts are a net reduction in tax revenue, there are other non-monetary benefits to support SMR development which should be considered by policy makers. For example, developing a nuclear sector in Wyoming will help reduce future nuclear costs through learning. This could increase taxes in the future, as other sectors such as uranium mining or uranium recycling increase in the State. It also diversifies the State's energy portfolio which mitigates the long-run risk of shocks to individual industries.

Hydrogen Production

Both hydrogen and kerogen oil shale production are undeveloped sectors in Wyoming. To provide an estimated economic impact, assumptions must be made about future industry development. The impacts are made based on a best estimate of the total change in deployed nuclear reactors, assuming that economic and technological conditions change so that both sectors expand, and nuclear is the lowest cost energy source. This may be considered an upper bound estimate of impacts.

World hydrogen production has the potential to increase by up to 600% by 2050, with the U.S. becoming a net exporter. This is an emerging sector which adds uncertainty to any future forecast. Lower bound estimates of future hydrogen output are only about 20% higher than current levels, although the hydrogen production methods are expected to evolve over this time frame. We apply the median future hydrogen growth path based on current growth rates. This predicts that hydrogen will increase by 150% by 2050. (Gulli et al., 2023).

The impact estimate assumes that the U.S. will match the global average growth rate[57], that Wyoming can acquire 2.5% of the U.S growth, and that nuclear energy sources can produce 150 tons of hydrogen per MW-year (DOE, 2022b). This implies that 8.3 baseline SMRs could be employed for hydrogen production in Wyoming by 2050.

Unlike industrial heat uses, this is a new industry, so the total economic output of the SMR development is treated as additive. The result would be an increase in annual tax revenues of $61 million and 4,224 full-time equivalent employees. Almost all this tax revenue impact is induced in other sectors. By lowering operating costs of the hydrogen facility and increasing local spending, tax revenue is generated by the SMR deployment, even though the project is tax exempt.

Oil shale

Kerogen oil shale production is the least market ready of any evaluated technologies but would have a large economic impact on the State if developed. Under the economic conditions which allow oil shale to be recovered in the State, Colorado and Wyoming would have the most oil reserves in the country (see Sections 3.4 and 3.8). The addition of oil shale to proved reserves would increase Wyoming oil reserves by 1.4 trillion barrels (USGS, 2011). For comparison, current total U.S. reserves are just under 50 billion barrels (EIA, 2024f).

[57] Current U.S. hydrogen production in 10 million tons per year (EIA, 2024e).

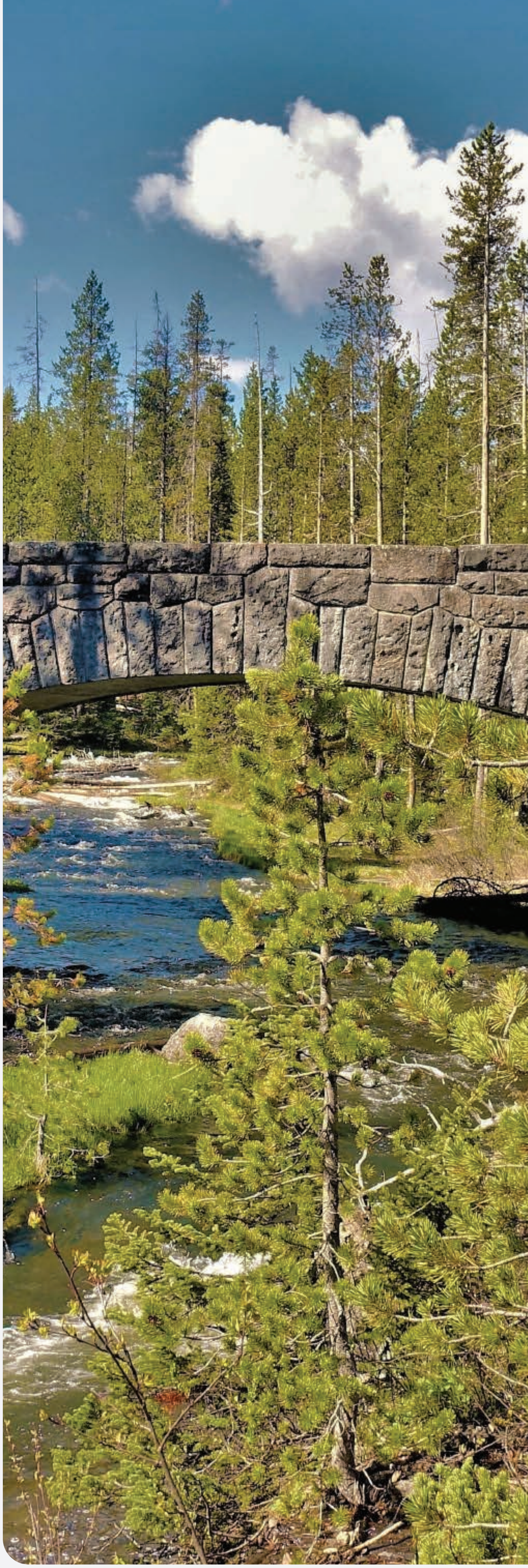
Given the highly speculative nature of this economic outcome, conservative first-pass estimates are used. Increases in the price of oil would lead to significant volumes of oil shale being added to U.S. production but these resources would be more costly to extract. Based on this, it is assumed total U.S. production would double increasing by 13 million barrels a day (EIA, 2024b). This increase would be centered in Colorado, Wyoming, and Utah. We assume 33.56% of the growth would take place in Wyoming based on the distribution of kerogen resources (USGS, 2011). A 300 MWe SMR is treated as having a three to one heat to electricity output capacity, producing 900 MWt.

Tar sand recovery is the closest analogous oil extraction process that is currently operating. Future innovation is assumed to increase the energy efficiency of oil shale recovery to that of tar sand. The energy expended to heat and process tar sands is one third of the amount of energy recovered in the oil (Brandt et al., 2013). Combining this efficiency factor with total oil production output changes yields that 118 SMRs would be required to sustain the oil shale industry. The details of these calculations are provided in Appendix (E).

This would increase tax revenue by $886 million annually and add 61,000 person-years of labor in the State. It is important to note that both the hydrogen and oil shale estimates are using only the tax revenue additions of operating the necessary SMRs and not the total economic impact of the sector development. It also precludes the economic impacts of SMR construction, which may be completed in other States.

Summary

These yearly effects can be summarized as a total value. Table 5 provides a summary of the net present value of the expected tax revenues to Wyoming of each sector. This net present value (NPV) is calculated from the starting date of the reactor operation, as if all reactors are deployed on the same date.



Since NPV depends on the time value of money values are calculated with a range of discount rates. 6% is a common metric for government projects and is selected for the final reported values. These values encapsulate the total NPV of the project if they began operating today and operate for sixty years, representing market potential[58].

Table 5:
Total Tax Wyoming Tax Revenues by Sector

Discount Rate	Application		
	Industrial Heat	**Hydrogen**	**Oil Shale**
0%	$2,253 mill.	$3,741 mill.	$54,026 mill.
6%	$634 mill.	$1,052 mill.	$15,200 mill.
10%	$405 mill.	$673 mill.	$9,713 mill.
15%	$283 mill.	$470 mill.	$6,789 mill.
Employment (person-years)	**2,545**	**4,225**	**61,019**

[58] Further discounting can be applied to estimate the expected value of these projects starting from today. For example, if half of the hydrogen projects are deployed in 10 years, and the other half in 20 years. The total value would be $4.1 million=($4.15 million)/ 1.05 ^10 +($4.15 million)/ 1.05 ^20 . We remain agnostic about the time of deployment, and rather predict the total value added once the operations begin.

CONCLUSIONS

The study evaluated the opportunities and barriers for new non-electrical applications of nuclear energy in Wyoming. Three potential use cases for the State were identified: industrial heat, hydrogen production, and kerogen oil shale extraction.

Tax incentives were categorized as the most significant draw to the State, providing sustained economic benefits to nuclear projects that are uniquely targeted to Wyoming. Future cost reductions in advanced nuclear reactors can spur commercial growth, but currently economic considerations are found to constrain adoption in the near term.

The identified economic factors related to nuclear heat projects are mixed in Wyoming. These factors include:

Factors Supporting Development

1. Tax exemptions in Wyoming for advanced nuclear projects, coupled with federal funding for projects constructed in energy communities present in the State.
2. The existence of trona mines and oil refineries in Wyoming.
3. Wyoming kerogen oil shale deposits and industries that purchase hydrogen provide potential demand sources for nuclear heat in the future.

Barriers to Development

1. Wyoming natural gas is a more cost-effective method of heat generation, unless there are future nuclear cost reductions.
2. SMR and microreactors have higher licensing costs than traditional nuclear projects relative to potential revenue streams.
3. Many advanced reactors are still in a development stage making long-term forecasts of costs and revenues uncertain. Future learning can reduce this obstacle to industry adoption.

The State is well positioned to develop industrial heating applications of nuclear, especially in the trona and oil refining sectors. While constrained by the existing infrastructure in Wyoming, there is a clear development pathway for industrial uses, which can boost technological development and establish a nuclear hub in the State.

The other two use cases for nuclear heat are speculative in the near term. Both hydrogen production and kerogen oil shale extraction require additional innovation to become competitive in the market. However, fostering these innovations could spur nuclear growth in the State.

In cases where nuclear reactors would displace natural gas heat sources, State tax revenues are expected to decline. However, the establishment of new industries, including hydrogen production and oil shale recovery, would bolster new tax sources producing between $61 and $886 million in revenue, respectively.

In addition, advanced nuclear heat applications provide non-monetary benefits to the State including:

1. Promotion of existing and future Wyoming industries (trona, oil refining, hydrogen production, and kerogen rich oil shale extraction).
2. Development as a regional nuclear energy hub.
3. Contribution to cost reductions of nuclear power.

Based on this analysis, the application of nuclear produced heat in Wyoming is situated to expand in the coming years. The Wyoming Energy Authority funding of microreactor applications at trona mines will shed light on the immediate use cases of this technology (Larson, 2023). Future applications of nuclear heat in burgeoning sectors provide an opportunity for continued growth in Wyoming. Both oil shale and hydrogen industries have economic incentives to locate in the State once they reach commercial viability.

Subsequent papers will evaluate other stages in the nuclear supply chain. These include nuclear produced electricity and spent fuel storage. This will provide a standard to compare the advantages, challenges, and the economic impacts across the entire nuclear sector.

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APPENDIXES

APPENDIX (A) CARBON TAX EFFECTS ON HYDROGEN MARKET

The concept of a social cost of carbon is based on economic theory of externalities. Markets are considered efficient by economists when all costs and benefits of a transaction are borne by the parties involved. For example, if a company creates a product without any pollution the market price will produce benefits to the buyer and seller creating economic value. However, if an airport is built near existing homes the noise created by the take-off and landings will create a cost for neighboring homeowners. The airport does not consider the irritation of homeowners when deciding how many planes to fly. As a result, more flights occur during the night than would maximize total economic welfare. If the cost of this noise pollution to homeowners is known, the airport can be charged per flight during night hours at this level. This would reduce the number of flights to an economically efficient level. The private cost of scheduling a flight is raised to be equal to the total social costs. Notably the airport is still allowed to operate if the total profit from a flight exceeds the noise fee the company will maintain operations. Mandating the closure of the airport due to noise complaints would reduce total economic value, since there is a value generated by the flights. By setting a proper noise reduction fee, policy makers can mitigate externalities to homeowners while maintaining the values generated by the industry. This tradeoff leads to the conclusion that there are optimal levels of pollution from an economic perspective. The goal of the policy is to identify the proper level of pollution by industry, not to eliminate pollution entirely. Any fee established to reduce externalities are referred to as Pigouvian tax (Pigou, 1924). While such fees can bring in government revenue the goal of a Pigouvian tax is to align private incentives to pollute with the total costs to society.

Under this approach the EPA was first tasked with identifying the social cost of carbon during the Obama administration which was set at $43 per ton (Isabella, 2021). This estimate is intended to predict the total cost to society from the emissions of carbon dioxide. A future Pigouvian tax on carbon dioxide would be set to this rate creating a new cost to emission while allowing firms to emit where profits are above this rate.

However, estimating the social cost of carbon dioxide depends on underlying value judgments, creating a range of estimates from this number. For example, the value of future costs relative to present benefits can significantly affect the estimated cost of carbon emissions. For example, a recent estimate of the social cost of carbon predicts a cost of $80 per ton at 3.0% discount rate, but $308 per ton with a 1.5% discount rate (Rennert et al., 2022). The ideal discount rate depends on how one values the cost bore in the future, compared to today. This can be challenging when accounting for future population growth, improvements in technology, and fluctuating private discount rates.

APPENDIX (B)
RANDOM WALK MODEL EXPLANATION AND DIAGNOSTICS

An autoregressive (AR) model is used to forecast natural gas prices. An AR model forecasts future price based on the current price of a good, and lags in the price over time. For example an AR(2) model would, forecast next month's price based on this month's price, and last months price.

This model is selected based on the identified market structure of natural gas. The efficient market hypothesis is often applied to the price formation of commodities such as natural gas. This assumption states that any information that is relevant to the future price of natural gas will be incorporated into the current market price.

For example, if a natural gas pipeline is disrupted due to political unrest, traders will account for this in current purchases. Assume this disruption is expected to take place after one month, lowering the available gas supply and raising the price to $3 per MMBTU. In that case an investor can purchase natural gas at the current price of $2 MMBTU and sell it after a month for $3 per MMBTU, receiving a 50% return on investment.

Where the disruption is well known to investors, they will purchase natural gas. In turn this restricts the supply of natural gas today, since it is being set aside for future resale, which raises the price. Investors will continue to purchase natural gas until the current price of natural gas reaches the future price and no profits can be made with current purchases. This raises the current expected price and lowers the future expected price (since more inventories are set aside to be sold in the futures) such that the current price and future price are less than $3 per MMBTU, stabilizing for example at $2.75 per MMBTU.

This process also works in reverse. If the price of natural gas is expected to decrease in the future, profit can be made by selling current inventories and rebuying in the future. Further, companies receiving physical natural gas deliveries contribute to this stabilization. A natural gas powerplant typically mitigates risk of cost overruns by purchasing futures contracts for natural gas based on expectations of future price volatility.

This means that the current price of natural gas incorporates the best available knowledge about present and future market factors of natural gas. An AR model uses this fact to avoid overly complicated models. An alternative regression model could account for a range of factors, including political unrest, technological developments in drilling, population growth etc. However, the AR model greatly reduce this complexity by relying on price signals to capture a myriad of factors that influence price.

Further, it can be reasonably assumed that no additional information could be gathered that will improve the AR model forecast except what can be observed in the price lags. Since the market price reflects all available information known to investors, the key component in the model is the length of time it takes for this information to be disseminated among market participants. In some cases, the current market price will not immediately reflect new information. For example, if geologists discover that total natural gas reserves are larger than previously estimated this can be expected to lower future natural gas price. However, experts in geology may be the only people to understand this, leading to a small price increase when this knowledge is first discovered. Over time, more people will become aware of this fact, leading to market stabilizing. The time it takes for the market to reach equilibrium determines the optimal number of lags included in the model.

Based on this, natural gas markets meet the conditions for the efficient market hypothesis to be applied. Natural gas is a “thick” market, with many contracts traded in a short period of time. These trades include market actors such as power companies, and gas producers each seeking to reduce risk, and traders willing to accept risk for potential future gains. Given the large volume of trades an AR model is ideal for future price projections.

Additional controls are included for shocks to population weighted heating degree days. This can improve model efficiency because it represents the primary unforeseen shock that is not accounted for by market actors. Long term temperature, and population trends are accounted for in future prices, but deviations from this trend are unknown before they occur. An unexpectedly cold winter will decrease natural gas inventories leading to price increases. However, this is unlikely to change the price of natural gas two or three years into the future. By including a variable for temperature shock this factor which does not reasonably change long run prices can be accounted in the month-to-month price prediction.

Given the economic fundamentals of this market an AR model is deemed an efficient time series procedure for forecasting. However, the exact model form is not predefined. Instead, the Akaike Information Criteria (AIC) score is applied to select the terms included (Akaike, 1974). The AIC score balances the fact that including more terms will always improve the precision of a time series model, with the added statistical noise created by adding weakly correlated variables. Technically including any variable to a regression will improve the fit (r^2) but including a variable that does not truly contribute to the dependent variable price formation biases the coefficient estimate.

The AIC metric provides econometricians with a quantitative way to select one model over another, comparing the information acquired by adding a term with a punishment for increased model complexity. This excludes variables from a model when the inclusion provides only a marginal improvement in fit. In the actual model applied, adding a single lag does improve the model fit, but the punishment for overcomplexity leads to a higher (worse) AIC score. As a result, no lags are included in the model. This is a random walk model which suggests that the market adjusts to factors which shift natura gas in less than a month. The data resolution is at the monthly level. An AR model using daily price would likely include multiple lags, but no more than 30 lags can be optimal based on these results at the monthly level.

An AR model is one form of a suit of models. For example, an AR model is the same as an autoregressive integrated moving average (ARIMA) model where the number of moving average terms is zero, and the time series is not differenced. In the ARIMA model the "MA" portion is the moving average price, allowing the average price over a set number of lags to influence the present price. All possible variants of a seasonal ARIMA were tested with up to 12-month dummies and 15 lags of price. A first difference restriction was imposed to maintain stationarity, a necessary condition for the model. The zero-lag model was selected since it had the lowest AIC score of any model. This means that the AR model applied is identical to a ARIMA(0,1,0) which has no auto regressive (AR) terms, one difference, and no moving average (MA) terms.

Diagnostic tests were performed on the final random walk model used in Figure 7 and are provided in Figure 15.

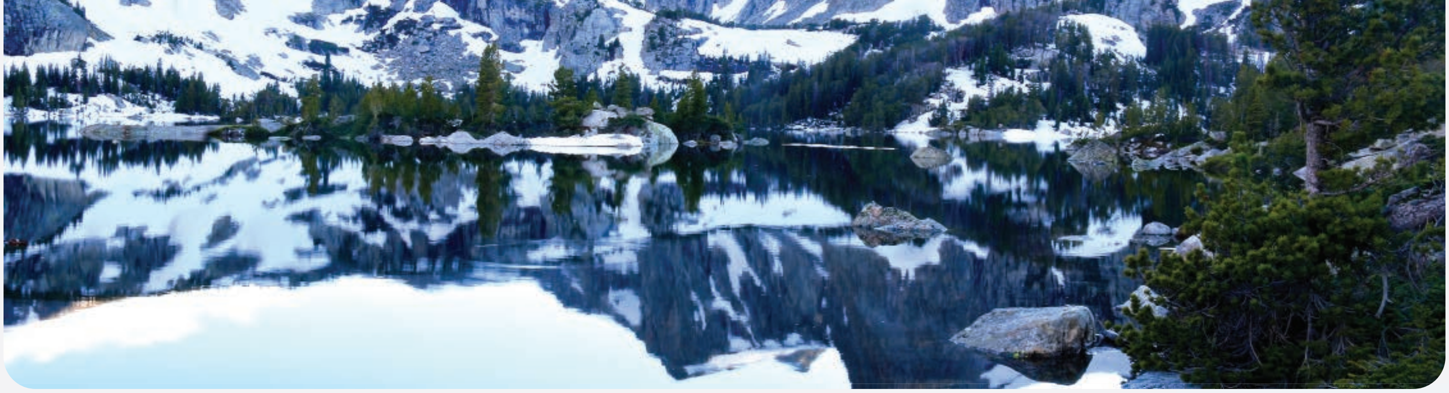
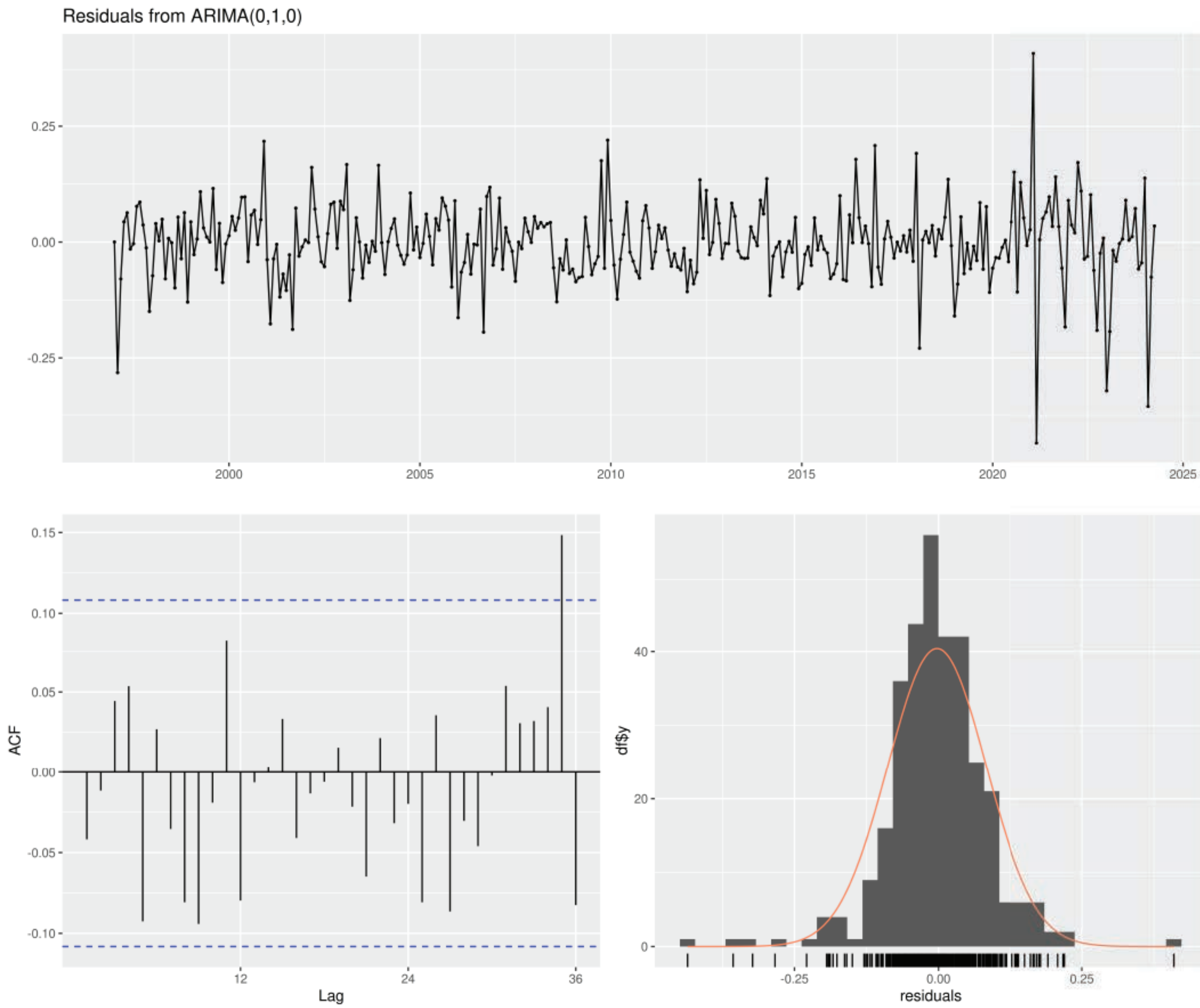


Figure 15:
Residual Diagnostics of Hydrogen Random Walk Model



These validation tests do not provide evidence of serious violations of the time series model assumptions. The residual errors show no signs of serial autocorrelation. Further, errors are nearly normally distributed although there is some left tail skew.

APPENDIX (C)
ESTIMATED HYDROGEN PRICE EQUATION FROM LINER REGRESSION ANALYSIS

Table 6 estimates the relationship between hydrogen price and natural gas price. This simple regression can only apply prices every four years due to data limitations of the Manufacturing Survey (EIA, 2006). In order to create a plausible time series of hydrogen prices, this model is used to fill in hydrogen prices in other time periods, relying on the economic linkage between hydrogen and natural gas prices.

Table 6: Hydrogen Price Estimate from Natural Gas Price

Dependent Variable:	Hydrogen Price
Model:	(1)
Variables	
Natural Gas Price	0.1184***
	(0.0082)
Constant	0.3961***
	(0.0496)
Fit statistics	
Observations	6
R^2	0.98102
Adjusted R^2	0.97627

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

Prices are in U.S. dollars per million BTU.
Prices are inflation adjusted to 2022 using the CPI.
Hydrogen prices are the average price paid by U.S. refineries.
Hydrogen prices come from the EIA quadrennial Manufacturing Energy Consumption Survey.
Natural gas prices are Henery Hub prices.

APPENDIX (D)
TAX EFFECT ABSENT AN ADVANCED NUCLEAR EXEMPTION

Without the existing tax exemption for advanced nuclear, the Wyoming tax structure has a mix of advantages and disadvantages for the direct heat use of nuclear power.

Wyoming has no personal or corporate income tax. A review of theoretical business types operating in all 50 state places Wyoming as having the lowest tax burden for a typical mature company, and seventh for a startup (Fíonta, 2022).

This provides a generalized incentive for companies to locate in the State, but the unique tax structure of Wyoming must be considered to determine the relative advantage for companies producing SMRs.

There are two taxes to consider, property taxes, and sales taxes. Sales taxes average 4.5% while commercial property taxes vary by year based on the state budget balance. 11.5% of all commercial property values are taxable, with an average of 4.2% levies applied, or 48% of the property value.

Wyoming includes all commercial equipment, and capital as part of the property value to be taxed. This means the market value of heat producing SMR can be included in the property tax base. As discussed in the Economic analysis section, the primary barrier for SMR adoption is the relative cost of using natural gas to produce industry heat. This tax structure exasperates this difficulty, by increasing the total cost of SMR heat generation compared to other heat sources.

Because nuclear reactors have a high cost of capital but low operating cost, a tax on capital value disproportionality affects SMR sources. Consider two equal capacity power generators, one is a SMR and the other is natural gas. The natural gas power plant has 25% of its total discounted costs applied to up front capital, with 75% applied to fuel costs. The SMR has 75% of costs applied to capital and 25% to fuel. The upfront investment in capital for the SMR is immediately taxed, while the future fuel cost of the natural gas is not. Total production is the same so sales taxes are identical, but the SMR facility would have three times the property tax compared to the SMR.

An analysis was completed using the reported attributes of 18 SMR designs. The average expected operating life of the facility was 51 years. The value of the facility is assumed to be equal to the overnight capital investment, since interest rates drive capital cost to be equal to the capital returns (Fisher,1909). Assuming an expected return of 5%, and a straight-line depreciation rate the typical SMR facility would face a property tax burden of 7.1% of the total upfront investment. Relative to natural gas facilities with only 25% of cost coming upfront this is a 5.31% increase in costs.

For comparison, the learning rate of technology estimates how quickly cost will decline as an industry develops. The learning rate of SMRs is essential to reach market viability, since the technology is in the preliminary phases of development. Current estimates place the learning rate at between 5-10% per doubling of output of SMRs (Steigerwald et al., 2023). All else equal SMRs will require an additional 50% to 100% increase in development, to become cost effective due to this tax incentive. While this estimate is inexact due to uncertainties in future costs, and learning rates, it demonstrates that the present tax structure will discourage capital intensive investments in industry relative to high operating cost industries.

APPENDIX (E)
NUMBER OF REACTORS REQUIRED FOR OIL SHALE EXTRACTION

In this appendix the number of SMR reactors needed to support a Wyoming oil shale industry is estimated.

To begin, the energy required to produce a barrel of oil from kerogen oil shales is estimated. The amount of energy needed to extract in situ oils can be expressed as a ratio of energy produced. For example, if half a barrel of oil is burned by generators to produce another barrel the recovery ratio would be 50%. Improvements in tar sand recovery methods have reduced this ratio to approximately one to three (Brandt et al., 2013). We assume that this ratio would be achieved for kerogen oils, if economies of production are achieved.

There are 5.684 million BTU per typical barrel of oil (although this varies by grade), and 293.083 Kwh per million BTU(EIA, 2023c). Therefore, the amount of thermal energy from a reactor required to produce a barrel of oil is:

$$0.5527\frac{Mwh}{BBL} = \frac{5.68\ millon\ BTU}{BBL} * \frac{293.08\ Kwh}{million\ BTU} * \frac{Mwh}{1000\ Kwh} * \frac{1\ heat\ energy}{3\ oil\ energy}$$

This means that the reactor capacity required can be determined as a function of the expected oil production rate.

We assume that total oil production in the U.S. will double if oil shales become economically viable. While this is a large increase it is within reason. Between 2010, and 2024 U.S. oil production has increased by 7.8 million barrels of oil per day, from 5.4 million to 13.2 million (EIA, 2024b). This can be mostly attributed to the cost reductions and technical innovations in hydraulic fracturing. Current technically recoverable reserves of U.S. oil shale are 8.5 times larger than current U.S. proved reserves (EIA, 2024f; USGS, 2011, p. 2). It would be a mistake to imply that this means that oil shale extraction will increase total production by 850%. The cost of producing oil shales is significantly higher than other sources, so only a portion of technically recoverable reserves will become viable.

We select a doubling of U.S. oil productions as a first estimate of potential industry growth. This would equate to 1.7 times as much growth in production as was observed in shale boom from 2010 until today. However, given that the U.S. has even more oil shale reserves than shale oil reserves it should be expected that an equivalent “oil shale boom” would result in a larger overall expansion rate. This variable can be adjusted based on more precise projections as oil shale extraction methods mature.

Based on this rule of thumb a doubling of U.S. output total oil shale extraction would reach 13.2 million barrels per day. This would be divided between Wyoming, Colorado and Utah. We assume the production share is equal to the relative ratio of Wyoming's oil shale reserves. So that Wyoming would have 33.56% of the growth[59] (USGS, 2011). This equates to 4.4 million barrels of oil a day in Wyoming.

This is used to calculate the total nuclear energy required to produce the Wyoming shale with:

$$2.448\ millon\ Mwh\ per\ day = 0.5527\frac{Mwh}{BBL} * 4{,}429{,}920\ BBL$$

Finally, the number of baseline reactors needed produce this energy is estimated. The a 300 MW reactor is selected based on available cost estimates (Lohse et al., 2024). This assumption can be modified for alternative reactor designs, but the final economic impact estimate will remain similar so long as the alternative reactor design has a comparable levelized cost.

The 300 MWe SMR is treated as having a three to one heat to electricity capacity as a metric based on published reactor designs (Abou-Jaoude et al., 2023; NuScale Power LLC., 2022). This allows the 300 MWe reactor to provide 900 MWt for heating the oil shale. A capacity factor of 95% is applied slightly above the current 92%, bringing the total capacity to 855 MWt(DOE, 2021a). Over 24 hours this reactor would produce 20,520 Mwh.

This results in the number of SMR reactors required being calculated as:

$$119.3\ SMRs = \frac{2.448 * 10^6 \frac{Mwh}{day}}{20{,}520 \frac{Mwh}{day}}$$

---

[59] 33.56%=(1.44 trillion barrels)/(1.53+1.44+1.32 trillion barrels)

APPENDIX (F)
SELECT MAPS OF OAKRIDGE LAB SMR SITING CHALLENGES

Figure 8:
Nominal, bounding SMR wetlands and open-water SSEC Layer.

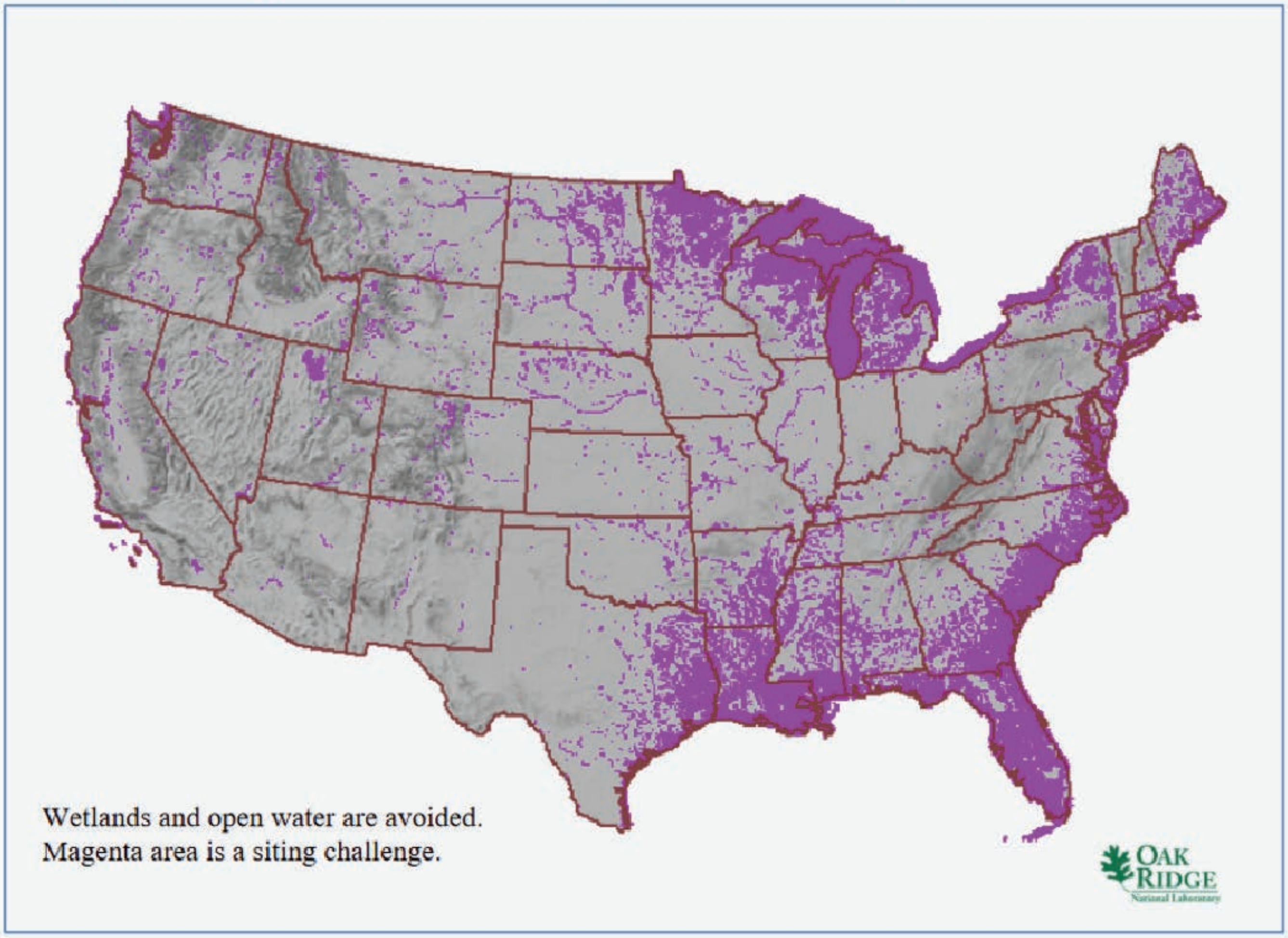


Figure 11: Nominal, bounding SMR 100-year floodplain SSEC layer.

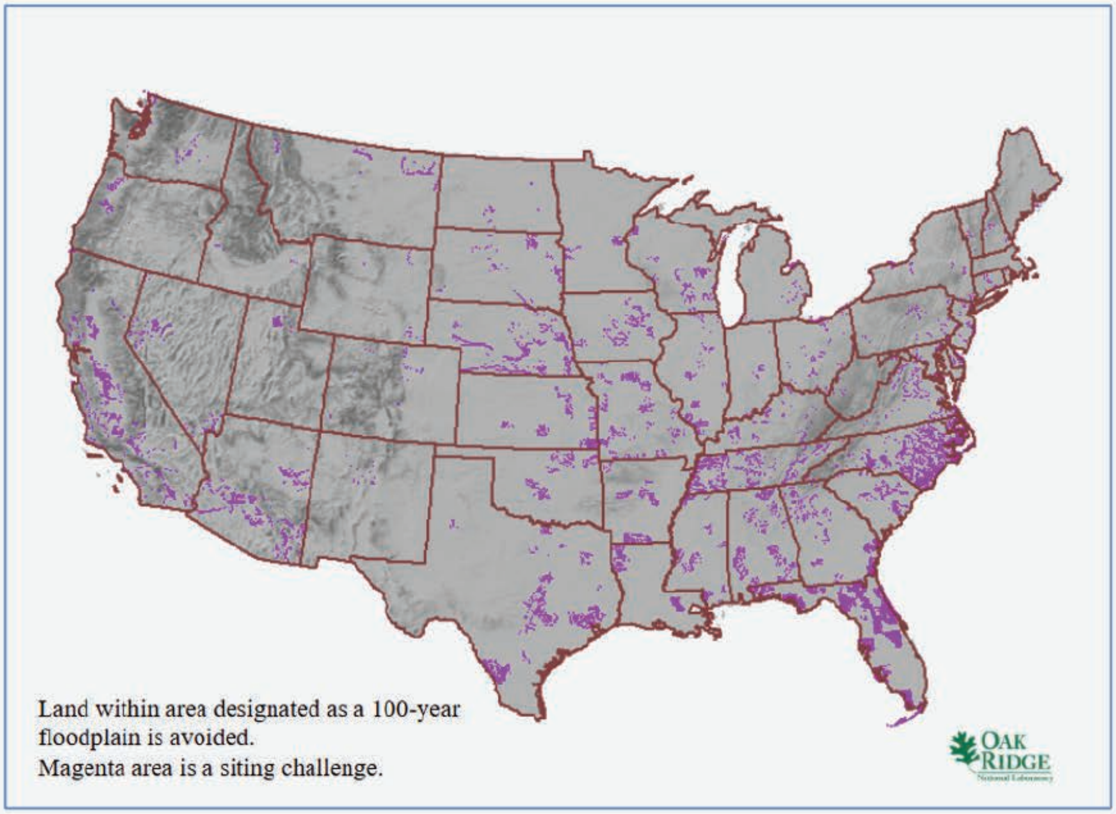
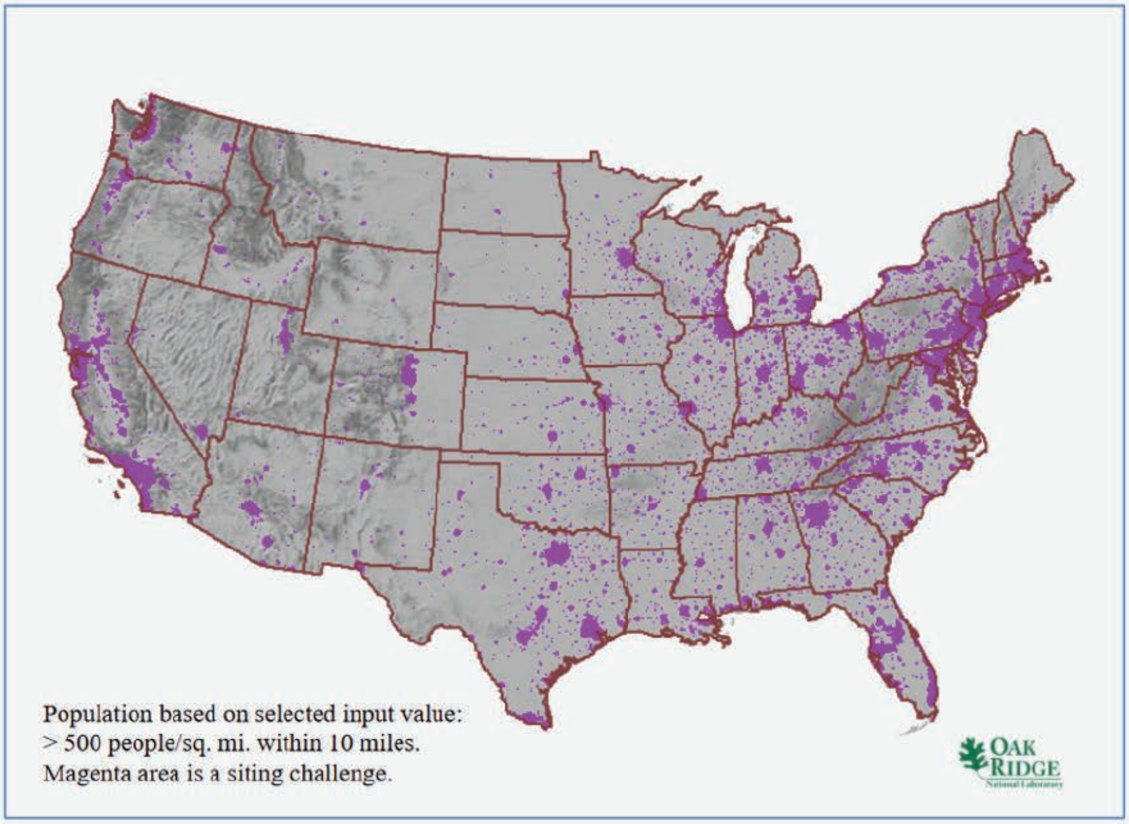
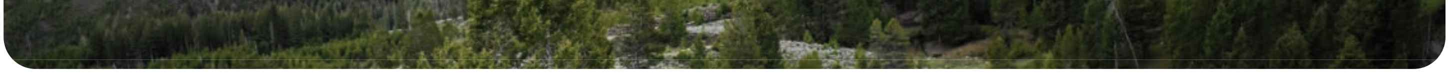


Figure 7: Nominal, bounding SMR high-population SSEC layer.





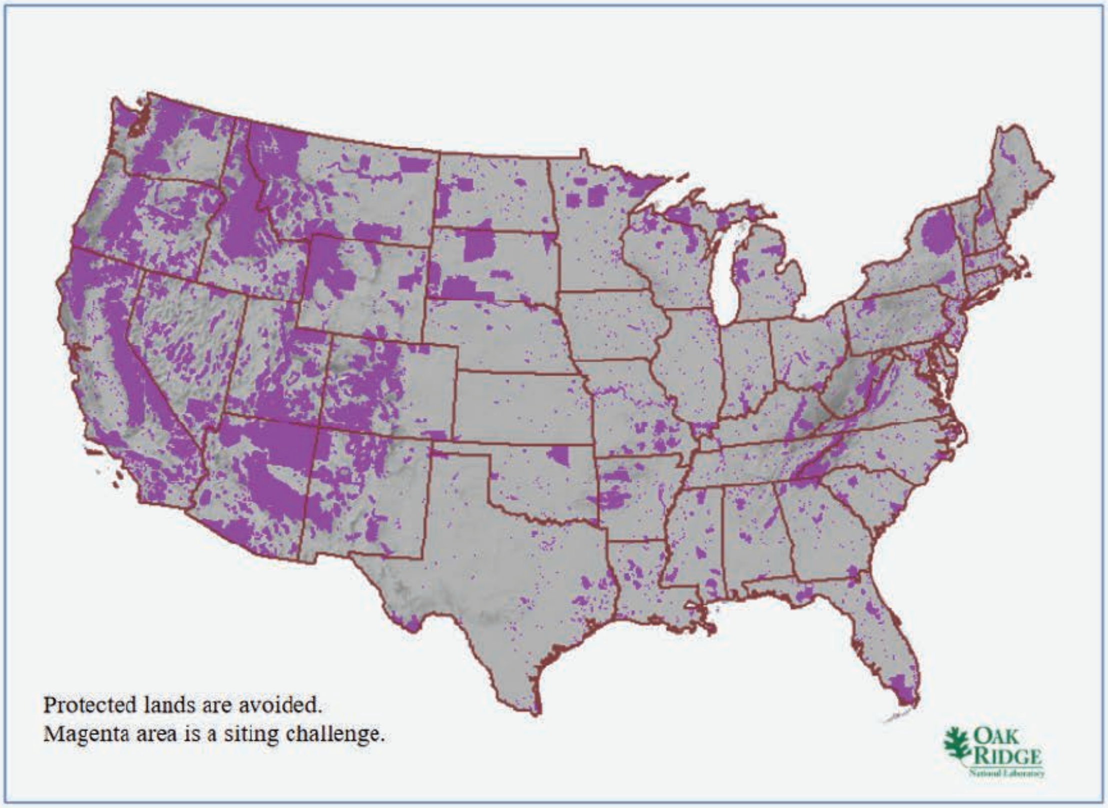


Figure 9: Nominal, bounding SMR protected-lands SSEC layer.

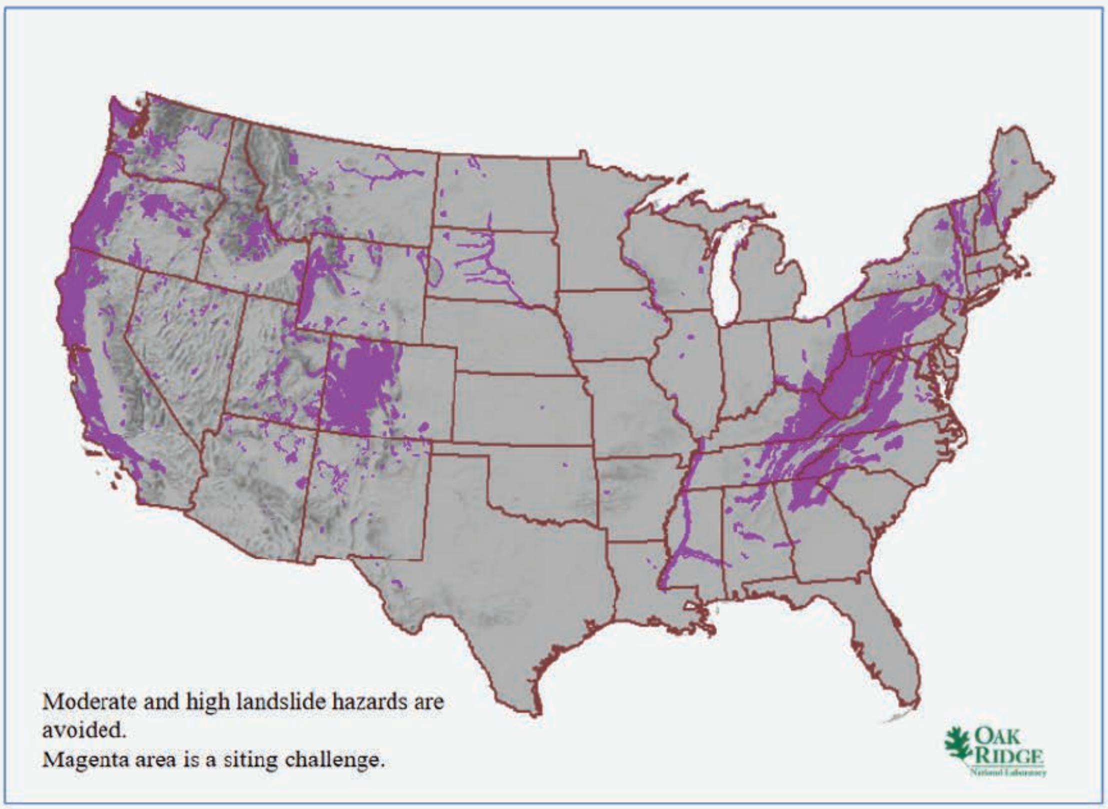


Figure 10: Nominal, bounding SMR landslide-hazards SSEC layer.

Figure 12: Nominal, bounding SMR high-slope SSEC layer.

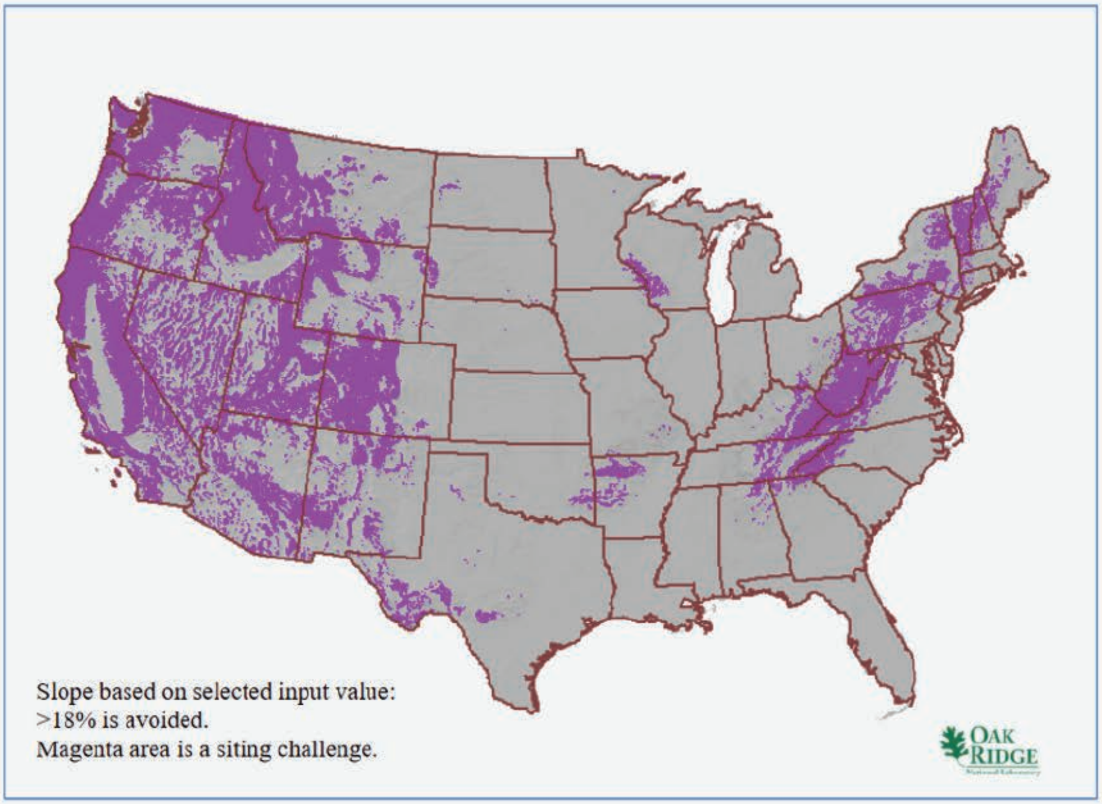
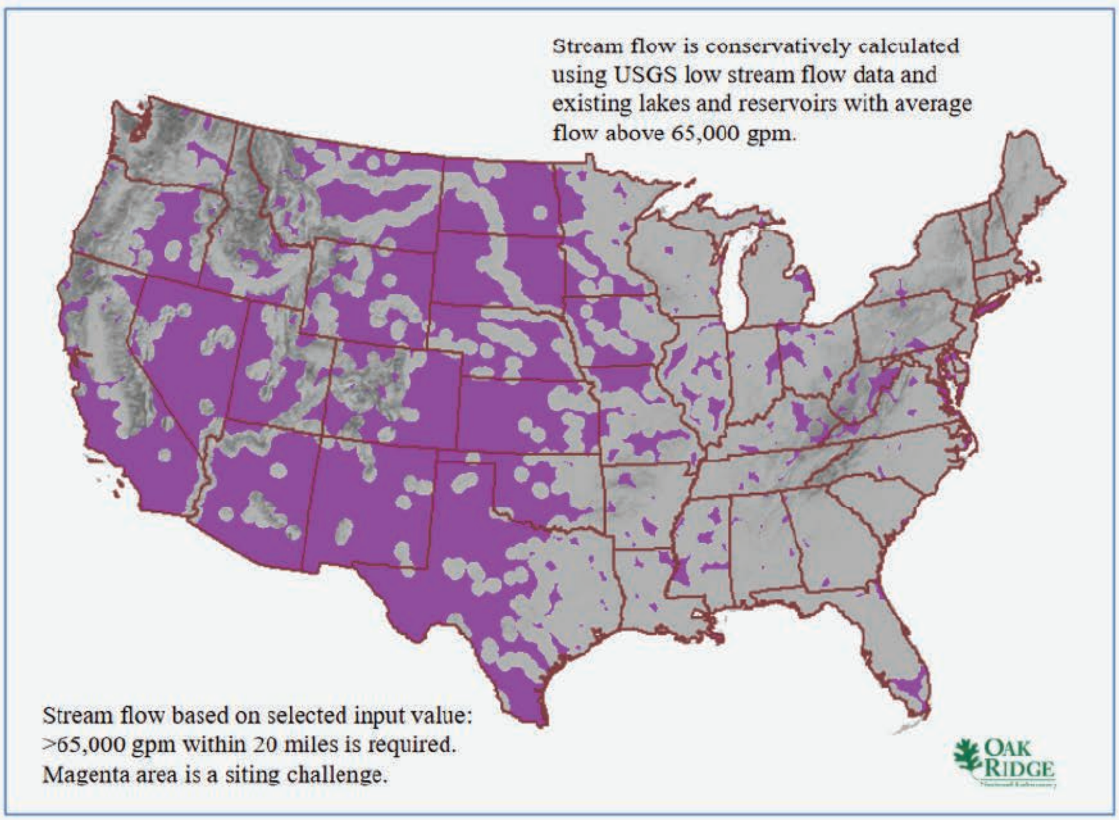


Figure 13: Nominal, bounding SMR minimum low-stream-flow SSEC layer.



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