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Uncovering hidden market opportunities for advanced nuclear reactors.

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SUMMARY

All the sectors need to be decarbonized to meet the energy transition goals. Particularly in the industrial sector, there is still a high share of processes that need to be decarbonized to reduce global emissions by 65–90% by 2050 to avert surpassing a 1.5°C temperature rise (Pörtner et al., 2022). Recent U.S. laws, including the Inflation Reduction Act (IRA), Bipartisan Infrastructure Law (BIL), Defense Production Act, Creating Helpful Incentives to Produce Semiconductors (or CHIPS), state programs, and other recent laws, have clean energy requirements and provide financial incentives to accelerate the use of clean energy technologies in the industrial sector. These new laws include supporting mechanisms with direct financial support for nuclear power (e.g., advanced reactor development and hydrogen production). However, advanced nuclear could also gain these financial benefits by coupling with low-carbon industrial projects. For example, microreactors could supply low-carbon energy to producers of critical metals that (1) are eligible to receive investment and production tax credits and favorable loans, and (2) the low-carbon product could gain preference in emerging markets for green products.

This analysis studies the maximum cost targets for microreactors (MRs) that the first price takers could tolerate with the new laws to understand the impacts on microreactor financial viability. The targets are analyzed considering possible matches of MR with market/industrial applications. Potential microreactor applications in U.S. markets are based on recent studies of niche markets in Alaska and Wyoming (Shropshire et al. 2023). High-interest applications for graphite mining in Alaska and Trona (a mineral used for sodium carbonate) processing in Wyoming were chosen for this initial study.

The study's objectives are to: (1) explore the maximum cost targets accepted by the first price takers when coupling microreactors with different industries for decarbonization; (2) assess the economic viability utilizing loans, grants, investment, and production credits, and identify any remaining financial gaps; (3) identify provisions in the law's implementation language to qualify these partnerships for financial support.

Key Findings

- Eligibility for IRA and BIL benefits is critical for the initial deployment of microreactors.
- Microreactors increase their competitiveness in relation to fossil fuel-based technologies when the combined benefits from the federal and state levels are included.
- All the benefits should be in place through 2040 to allow the learning curve to reach a competitive level against other technologies.
- The deployment of microreactors should start later in the 2020s and early 2030s to reach a competitive level in 2040 and help meet the economy-wide net-zero goals.

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The authors would like to recognize the contributions of David Shropshire and Andrew Foss that greatly enhanced the quality of the report.

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ACRONYMS

ACEEE	An Energy-Efficient Economy
AEA	Alaska Energy Authority
BIL	Bipartisan Infrastructure Law
BIL	Bipartisan Infrastructure Law
CHIPS	Creating Helpful Incentives to Produce Semiconductors
CO_2	Carbon Dioxide
CCUS	Carbon Capture, Utilization, and Storage
DOD	Department of Defense
DOE	Department of Energy
DPA	Defense Production Act
EIA	Energy Information Administration
FOAK	First of a Kind
GHG	Greenhouse gases
HALEU	High-assay low-enriched uranium
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
IRS	Internal Revenue Service
ITC	Investment Tax Credit
LCA	Life cycle analysis
LCOE	Levelized cost of electricity
LPO	Loan Program Office
LR	Learning Rate
MR	Microreactor
MW	Megawatt
NETL	National Energy Technology Laboratory
NRC	Nuclear Regulatory Commission
O&M	Operations and Maintenance
PE	Private Equity
PTC	Production Tax Credit
RD&D	Research, development, and demonstration

TELGP	Tribal Energy Loan Guarantee Program
TR	Tax rate
VC	Venture Capital
WACC	Weighted average cost of capital

1. REPORT BACKGROUND AND PURPOSE

About a dozen very small nuclear reactors called microreactors are under development in the United States; some of which are privately funded, and some also with support from the Department of Energy (DOE) and Department of Defense (DOD). These reactors may generate heat and electricity serving military operations, small public utilities, and industries that rely primarily on fossil fuels and electricity today.

As the social cost of greenhouse gas (GHG) emissions becomes increasingly salient to industries, there is a growing demand for low- or no-emission energy sources to power industrial processes. While some industries can utilize wind, solar, and carbon capture, utilization, and storage (CCUS) technologies, these options may not be feasible for all, especially remote operations like mines. Additionally, many emissions-intensive industries require significant amounts of process heat and electricity. Small nuclear reactors, specifically microreactors, could present a viable solution in such cases. With power capacities below 100 MW, these microreactors can cater to specific industrial load levels and provide a reliable and low-carbon energy source for various industries.

For this conversion to occur, the costs for the nuclear option must be competitive with carbon-based sources. Fortunately, recent laws in the United States are directing tax credits to climate-friendly energy technologies, including existing and future nuclear power plants. This paper focuses on a less obvious opportunity, where the industry may also tap these tax treatments by capitalizing on emerging opportunities for low-carbon products produced in clean energy factories powered by advanced nuclear technology. To understand these industrial opportunities, this study develops a methodology to select two specific industries, graphite and trona, in order to describe how capital and operations and maintenance (O&M) costs could be reduced through different supporting mechanisms.

In recent years, the United States has increased commitments toward mitigating climate change by reducing emissions from fossil fuels which currently supply 80% of U.S. energy (U.S. EIA, 2022a). Recent aggressive actions include the passage of the Inflation Reduction Act (IRA), Bipartisan Infrastructure Law (BIL), Defense Production Act (DPA), and Creating Helpful Incentives to Produce Semiconductors (CHIPS). Additionally, some states have their own low-carbon incentive programs. The intergovernmental panel on climate change (IPCC) set net zero targets by 2050 and they will require that industries in all sectors reduce their greenhouse emissions and carbon footprints by investing in clean energy technologies to decrease emissions by 65–90% to avert warming greater than 1.5°C (Pörtner et al., 2022). In this context, it seems to be an agreement that advanced nuclear energy is crucial to achieving a zero-carbon future (Clear Air Task Force, 2023). For instance, the DOE states that advanced nuclear technology is vital to achieving safe, clean, and affordable future power (DOE-NE, 2023a). U.S. nuclear capacity has the potential to scale from ~100 GW in 2023 to ~300 GW by 2050 (Kozeracki et al., 2023), and new federal and state legislation (IRA+ others) could incentivize the coupling of advanced reactors with industries that are key to this growth. Recent reports (Kozeracki et al., 2023; Shropshire et al. 2023) suggest that microreactors have high potential if they can be economical. This report contributes to this topic extending the analysis to assess options to create a market pull for a new generation of reactors to decarbonize industry.

It is important to note that in 2023, industries are reassessing their ambition and updating their plans for decarbonization, adapting their portfolios to the requirements of the new state and federal provisions (Aumeier et al., 2023). In this context, advanced nuclear technology are low-carbon systems that have the potential to completely alter the landscape of industrial energy sources by drastically reducing the carbon footprint tied to fossil fuels. Microreactors could provide high-temperature heat and hydrogen and reduce the need for transmission and distribution infrastructure (MIT, 2018; Forsberg et al., 2022). Industrial heat demands are an important market for microreactors to achieve high production levels of microreactors achieving high volume (Thiel and Stark, 2021; Rissman et al., 2020). For instance, in March 2023, Dow and X-energy announced a joint development agreement to install an SMR nuclear plant at an industrial site in Texas and the DOE named Dow a sub awardee under X-energy's Advanced Reactor Demonstration Program Cooperative Agreement (X-energy 2023).

Additionally, the U.S. Environmental Protection Agency's Greenhouse Gas Reporting Program (EPA, 2022) states that six thousand facilities have heat demands more significant than 1 MW.

Industry plans for decarbonization, including microreactors, are a win-win for industry and nuclear so long as carbon constrained mechanisms are in place. MRs become more attractive where the energy consumption includes heat, steam, and electricity. Furthermore, MRs makes sense when industries require electricity and significant process heat, especially in cases where renewable energy sources like wind and solar may not be feasible or sufficient to meet their energy needs (Buongiorno et al., 2021). Energy use by industry could involve directly converting primary energy sources to thermal and electrical energy at the point of consumption to produce hot gases and steam for process heating, process reactions, and process evaporation, concentration, and drying (McMillan et al., 2016). Microreactors with power levels from less than 1 MWe (megawatt electric) to 20 MWe are ideally sized to support industrial applications (Buongiorno et al., 2021). They could provide a resilient source of power and heat independent of power grids and weather conditions, high-temperature heat, and hydrogen and reduce the need for transmission and distribution infrastructure, offering a viable solution for industries with specific load profiles and high-energy demands. It is important to note that the peak temperature of the delivered heat from a nuclear reactor depends on the exact particular fuel technology and its intended application. Light-water reactors typically achieve peak temperatures around 300°C, while high-temperature reactors can deliver heat at temperatures up to 700°C. However, lower peak temperatures below 150°C may be enough for particular applications like district heating. This lower temperature requirement simplifies the system's design and reduces capital costs by eliminating the need for more complex and expensive components (Forsberg et al., 2022).

MRs' modular and scalable nature allows for incremental provisioning, meaning that industries can start with one or a few MRs and gradually expand their capacity size as needed. This approach reduces the upfront investment required and allows sectors to transition to zero emissions smoothly. New clean electricity generation, advanced reactors, and clean hydrogen are directly and indirectly benefited through IRA+. Coupling these energy sources with targeted activities could make them receive direct financial benefits in terms of loan guarantees, investment and production tax credits, and other support. Other applications could indirectly apply to advanced nuclear, including manufacturing and recycling clean energy equipment and components, critical minerals and strategic materials, and building or repurposing infrastructure to produce advanced energy products in Energy Communities. In this sense, this report states that microreactors could join these industries to produce clean energy products receiving supporting mechanisms that could potentially accrue from multiple funding sources (e.g., federal and State credits). In summary, MRs can couple with other zero-generating carbon energy sources to energize industries bearing a high-carbon footprint, suffering from pollution, and needing more diverse energy sources (Sepulveda et al., 2018).

While microreactors economics can become competitive in the long run through technology development, modularity and standardization, factory production, and use of industrial supply chains to maximize economies, the first stage of deployment will require delivering value to first-mover consumers who are able to cover higher, early production costs. Given this, the first price takers will depend on the competition in the industry, potential of new entrants into the industry, power of suppliers to transfer the cost of their inputs to consumer prices, power of customers to drive price lower, and threat of substitute products (Porter 1980). Also, it is critical to consider the competitive dynamics within the industry in order to select potential first price takers. For instance, Tirole (1988) stated that industries characterized by low barriers to entry and low product differentiation (e.g., commodities) had lower profit margins and a strong focus on cost-cutting. Conversely, industries with product differentiation and competitive advantages tend to have higher profit margins, potentially making them more interested in flexible, clean energy solutions. Following this criterion, some critical markets for MRs would be industrial, such as the commodity business and paper, microgrid, district heat, desalination, remote markets, and the military market (Forsberg et al., 2022).

To expand at the scales needed in the next 5–10 years, the federal incentives offered by IRA+ must clearly support new uses of advanced nuclear. This requires clarity in the implementing regulations of the new low-carbon laws to define advanced reactors, coupled with industries to produce low-carbon products as eligible recipients for credits. This eligibility also signals the financial world, enabling private equity financing and venture capital to help startups, early-stage funding, and emerging companies achieve their growth potential. Economic viability is vital for companies to move advanced reactors into commercial use in the United States and provide the catalyst for use in international markets. Not including advanced reactors in the future energy matrix could miss an opportunity for decarbonizing the industrial sector under favorable economic and financial conditions.

The opportunity afforded by using advanced reactors with industry lacks the depth needed to understand the possible value or limitations fully. National and international assessments of nuclear expansion by 2050 have not captured this potential evolution in our energy system and the unique role that advanced nuclear energy could contribute to meeting the industry's low-carbon needs for the future.

Integrating a microreactor into a new industry or remote location involves careful consideration of regulatory compliance, environmental impact, and the benefits and downsides associated with this decision. It requires adhering to the National Environmental Policy Act and state regulations, considering a comprehensive life cycle environmental impact assessment, and addressing factors such as safety, waste management, and public perception.
Given this the National Mining Association stated a comprehensive path for future mining: *"Actions to reduce global greenhouse gas emissions should support the continuing responsible production of the mined commodities necessary to build green and resilient infrastructure, maintain the affordability and reliability of U.S. electricity generation, and secure our economic recovery." (NMA 2023)*

On the other side, by integrating a microreactor, the industry can potentially achieve a cleaner supply chain, benefit from low-carbon emissions and a reliable energy supply, and experience cost savings through the leased heat and power business model. For instance, the X-energy Memorandum of Understanding with Dow Chemical for an industrial nuclear project is an excellent example of this (X-energy 2023). However, challenges include ensuring safety, managing radioactive waste, and addressing public concerns. Consulting experts and engaging with stakeholders are crucial for successful integration while supporting sustainable and efficient industrial operations.

The following section presents a description of the potential economically supported mechanisms from the main acts that could enable MRs coupling with industrial applications and reach profitable cost targets. The study describes loan guarantees programs, state-supported mechanisms, and fleet effects, which are critical sources that could, directly and indirectly, affect nuclear energy costs.

2. SUPPORTING MECHANISMS FOR INDUSTRIES AND MRS

Markets increasingly value low-carbon products (e.g., environmental, social, and governance standards) and international markets (EU Carbon Border Adjustment Mechanism) are considering taxes tariffs for high-carbon products. Products produced with MR energy have a low-carbon footprint, and a rising carbon price makes all low-carbon resources more attractive. This means that products made from carbon sources will increasingly become more expensive due to environmental levies (e.g., carbon taxes), and furthermore, the cost gap between renewable sources and MRs will be lower. While the costs for MRs are high now, the costs are expected to decrease due in part to a vast set of direct and indirect supported mechanisms (IRA+) and gains from mass production and standardization. At some point in the future, the supported mechanisms from low carbon (or avoidance of taxes) will match the added expense of the energy technology (MRs), increasing the competitiveness of those products that incorporate MRs in their production processes. Figure 1 shows the hypothetical production cost of a good that incorporates a

MR could follow through time (C0, C1, C2) if different supported mechanisms are introduced relative to the cost of the current energy sources that are based on fossil fuels (C w/fossil fuels).

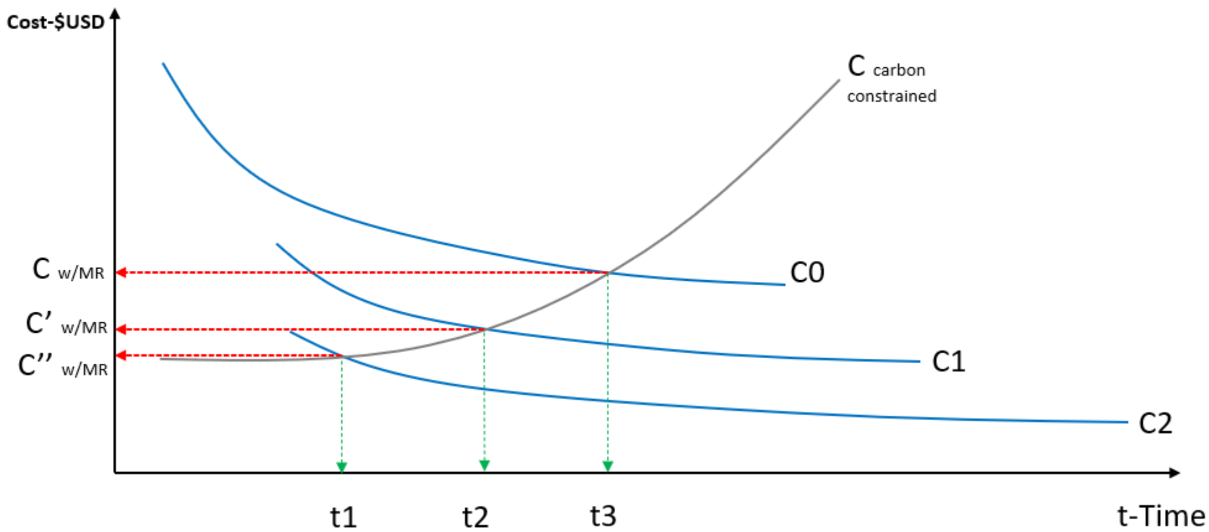

Figure 1. Supporting mechanisms generates different levels of production costs (e.g., trona and graphite) that incorporate a MR compared to fossil fuel energy sources subject to future carbon penalties.

In summary, the curves C0, C1, and C2 denote the production cost level that could be reached by an industry that incorporates a microreactor if different supporting mechanisms are activated in a carbon constrained market. It is important to note that some of the support mechanisms have fixed end dates, which could impact the deployment of microreactors if the support mechanisms end before the learning curve reaches a minimum level in which MRs are competitive relative to other energy sources. MRs could achieve a competitive level in 2040, and most of the supported mechanisms start to phase out in 2032 (Shropshire et al., 2021). The period of the supporting mechanisms is critical given the capacity they have to allow startups to avoid the valley of death, which happens when a new technology does not reach the market/commercialization stage. This situation occurs due to high technical and financial uncertainty resulting from null or inadequate funding (ARPA-E, 2023) that restrain the deployment of new technologies and put promising companies at risk (see Appendix A).

It is important to note that some support mechanisms will directly benefit the specific industry products where MRs provide energy. The other will benefit the MRs, and some mechanisms will affect advanced nuclear technology. In this latter case, the MR does not get the credit (e.g., DPA), but the industry partner does. This means that the industry partner could get the same credit no matter what their energy source is. That said, in the long run, advanced nuclear technologies will benefit. The following paragraphs describe the different supporting mechanisms, considering their effects on products, industry, or MRs, respectively.

The following support mechanisms might not directly support the deployment of microreactors. Some of them affect the current nuclear fleet, some the nuclear industry and others the research and development of advanced nuclear technologies. The purpose of describing them in this report is to emphasize the favorable financial and economic context for nuclear energy in general and in which microreactors could be couple with industrial applications.

IRA-Tax Credits

Most of the funding from the IRA in energy and climate is in the form of tax credits. MRs projects or electricity produced by MRs could be qualified to receive a production or investment tax credit. Specifically, the IRA introduced two technology-neutral clean energy tax credits: the clean energy, technology-neutral production tax credit (PTC) and the clean energy, technology-neutral, investment tax credit (ITC). The PTC provides an inflation-adjusted $27.5 per MWh in tax credits for every MWh of carbon-free power produced by a nuclear plant if the prevailing wage and apprenticeship requirements are met, while the ITC provides 30% of the capital cost for a nuclear plant in year 1 of operation if prevailing wage and apprenticeship requirements are met. Both incentives have two possible 10% bonuses for sitting in energy communities and for the use of domestic content. The PTC will add 10% of the base rate ($27.5/MWh) if the projects meet the domestic content requirement, plus an additional 10% of the base rate if the energy community requirement is met. This means that the final maximum amount received as a PTC could reach $33/MWh. On the contrary, the minimum rate for the PTC if no bonuses and requirements are met is $5.5/MWh.

Finally, vendors cannot receive the PTC (45Y) if others credit as 45, 45J, 45Q, 45U, 48, 48A, or 48E is allowed (U.S. Congress, 2021-2022d).

For the ITC, if a facility meets both requirements, the base rate (30%) increases by 10% points for each bonus. Furthermore, a facility eligible for both bonuses would have an effective 50% ITC total rate. On the contrary, the minimum rate for the ITC if no bonuses and requirements are met is %6.

Also, vendors cannot receive the ITC (48E) if others credit as the 45, 45J, 45Q, 45U, 45Y, 48, coal project under 48A, or 38 is allowed (U.S. Congress, 2021-2022d).

It is important to note that the IRA establishes that a qualified facility cannot receive both the PTC and ITC; the benefiter must choose one. This creates a trade-off because facilities should consider the ITC and PTC depending on their CAPEX, capacity factor, and a vast bundle of costs, which could be subjective and difficult to quantify. However, some preliminary results show that the CAPEX and capacity factor (i.e., production) is one of the most important variables affecting the trade-off (Bolinger and Wiser, 2009). This creates a decision problem or trade-off because facilities should consider the ITC and PTC depending on their capital expenditure (CAPEX), operating and maintenance cost (OPEX), and a vast bundle of costs, some of that could be subjective and difficult to quantify. However, some preliminary results of crossover points between the PTC and ITC show that the ITC could be more attractive in cases where capex exceeds ~$6,000 per kW, and the PTC could be preferred where CAPEX is lower than ~$6,000 per kW (U.S. DOE, 2023; Guaita and Hansen, 2023).

Finally, another factor affecting the selection of the ITC and PTC is the duration of the tax credits, as they will not be in place forever. The ITC and PTC end when the annual GHG emissions from electricity production are equal to or less than 25% of GHG emissions in 2022 or 2032. In 2033, the recipients could still receive a 75% of the base rate and 50% in 2034.

It is important to note that according to the IRA, after 2032, the PTC and ITC could stand in place if the emissions from electricity generation are more than 25% of 2022 levels. The tax credits (45Y) and (48E) will remain in effect until emission are reduced to 25% of 2022 levels:
“the term ‘applicable year’ means the later of— ‘‘(A) the calendar year in which the Secretary determines that the annual greenhouse gas emissions from the production of electricity in the United States are equal to or less than 25 percent of the annual greenhouse gas emissions from the production of electricity in the United States for calendar year 2022, or ‘‘(B) 2032.” (H.R.5376)

Advanced Energy Project Credit – 48C

The advanced energy project credit (48C), reinstated by IRA, is similar to an ITC as the 48C benefit is a credit percentage of the total cost of the investment, which means that accessing this credit could decrease the interest paid during the construction of a new investment project. MR investment projects could qualify and request this credit as the credit accepts advanced nuclear as a qualified energy technology. "Property designed to be used to produce energy from the sun, water, wind, geothermal deposits (within the meaning of § 613(e)(2)), or other renewable resources." (IRS 2023)

The current 48C credit provides $10 billion in credits for qualifying advanced energy projects, with $4 billion reserved for projects in energy communities:

- The credit provides a base rate of 6% of the total cost of the investment but up to 30% if wage and apprenticeship requirements are met
- Available for manufacturing or industrial facilities that produce specified renewable energy equipment, energy storage systems, electric vehicles, energy conservation technologies, and equipment designed to reduce greenhouse emissions.

Finally, notice that taxpayers who have received prior credits under sections 48B, 48E, 45Q, or 45V are not eligible for section 48C. Existing and modified industrial or manufacturing facilities may be eligible for the credit (U.S. Congress, 2021-2022d).

IRA-Loan Guarantees

The federal loan guarantee program can reduce the project's financing costs. Specifically, there are three main loan guarantees from Title 17: the "Innovative Energy and Supply Chain" (Title 1703), the "Energy Infrastructure Reinvestment" (Title 1706), and the Tribal Energy Loan Guarantee Program (TELGP). Title 1703 supports advanced nuclear energy projects. Title 1706 is oriented to avoid, reduce, utilize, or sequester air pollutants in any qualified equipment used to generate or transmit electric energy. Finally, TELGP is oriented to tribal communities and does not exclude advanced nuclear energy projects from their supporting mechanisms (LPO, 2023).

Title 17 Innovative Clean Energy Loan Guarantee Program (1703):

The program, known as Section 1703, includes advanced nuclear energy facilities and manufacturing of nuclear supply components and will be available through the end of fiscal year (FY) 2026.

- The program offers up to $62 billion in loan guarantees for nuclear projects using innovative technologies
- The loan guarantee could cover 80% of project costs and extend to domestic manufacturing of materials and components involved in the nuclear supply chain.

Title 17 Energy Infrastructure Reinvestment Program (1706):

The program can be used to retool, repower, repurpose, or replace energy infrastructure that has ceased operations or to reduce air pollutants and greenhouse gas emissions.

- The Loan Programs Office (LPO) has up to $250 billion in loan authority under this program, available through 2026
- Energy infrastructure includes electricity generation and transmission, fossil fuels, petroleum-derived fuels, or petrochemical feedstocks, and nuclear energy is not excluded from the qualified projects
- So far, there is no guidance on implementing this program.

TELGP:

- Federally recognized tribes and qualified tribal energy development organizations can receive up to $20 billion in loans or partial loan guarantees from LPO for nuclear projects (U.S. DOE, 2023c)
- The projects can use commercially available nuclear technologies and are not required to use innovative technologies (U.S. DOE, 2023c)
- No projects have received funding commitments under this program as of March 29, 2022 (U.S. Senate 2023).

The loan guarantee authority has no expiration date (LPO 2023). Also, it is critical to note that Title 17 supporting mechanisms can be stacked with the PTC/ITC tax credits from the IRA. Furthermore, a qualified facility/project could receive a benefit through lower interest rates and a tax return jointly (LPO, 2023).

Existing Loans from DOE

In addition to the Title 17 loan programs, recently, U.S. DOE announced its first advanced technology vehicle manufacturing loans to support supply chain manufacturing in 10 years in 2022. The loan will expand a graphite processing facility for graphite-based active anode material (U.S. DOE, 2022). This sets a precedent for future similar loans, for example, the project of Graphite One in Alaska. Furthermore, through these loans, the industry in which the MRs provides energy could benefit.

Loans or loan guarantee programs from the DOE can allow owners to finance a significant portion of their construction costs at interest rates well below market rates and to increase their debt fraction over their equity fraction, which significantly reduces overall financing costs since the cost of equity is much greater than the cost of borrowing, this can substantially reduce the levelized cost for the investment projects.

IRA-HALEU

IRA also provides funding for developing a domestic supply chain for high-assay low-enriched uranium (HALEU). This provision can benefit MRs indirectly through an impact on the fuel supply chain. For instance, this Act provides $100 million to support the availability of HALEU for research, development, demonstration, and commercial use; $100 million to design and license HALEU transportation systems; and $100 million to produce HALEU for the first advanced reactors and establish a consortium to support the availability of HALEU for commercial use.

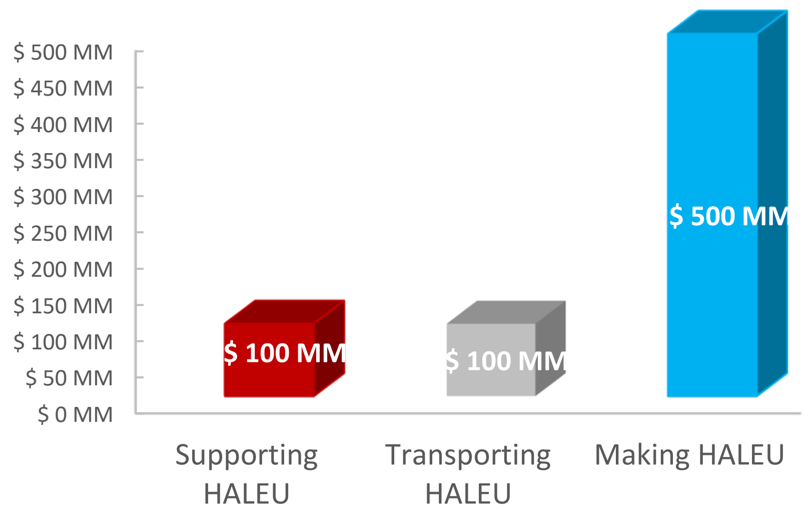

Figure 2. HALEU projected funding.

It is important to note that, so far, some funds for HALEU have been released, though there is no clarification on the annual limits of funding and/or if they are per application or total. Recently the DOE-NE office announced the intention to Acquire High-Assay Low-Enriched Uranium Material (DOE-NE, 2023b). Also, the NRC authorizes first US high-assay low-enriched uranium enrichment plant critical for advanced reactors (NRC, 2023)

BIL-Civil Nuclear Credit Program

BIL introduced a provision focused on the existent nuclear fleet. The Civil Nuclear Credit Program is a $6 billion investment to support the existing U.S. commercial reactor fleet so commercial reactor operators can seek certification to bid on credits to sustain their ongoing operations, and selected reactors will receive credits over 4 years. The program is designed to support selected certified reactors over 4 years until September 30, 2031, if funds remain available. The maximum 4-year total credit award value is up to $1 billion (U.S. Congress, 2021-2022a).

<u>Qualified Facilities:</u>

- An application must demonstrate that the reactor is projected to close for economic reasons, and that closure will lead to a rise in air pollutants.
- Award 1: eligibility to owners or operators of nuclear power reactors that had announced intentions to retire within the 4-year award period (before September 30, 2026).
- Award cycle 2: is open to owners or operators of nuclear reactors at risk of closure by the end of the 4-year award period (U.S. DOE, 2023b).

This supporting mechanism does not affect advanced nuclear energy deployment directly, but it indirectly affects those industries that use nuclear energy power, allowing them to buy cheap energy with low-carbon content.

CHIPS and Science Act

The CHIPS and Science Act is benefiting advanced nuclear energy indirectly. While there are no direct supporting mechanisms for MRs deployment projects, this Act has some sections that can affect industries that MRs can serve jointly with the research and development of advanced nuclear technologies funding.

The CHIPS and Science Act aims to enhance the semiconductor industry. In the first place, CHIPS allocates a budget of $52.7 billion to support various aspects such as research, development, manufacturing, and workforce development; $39 billion is designated for manufacturing incentives, with $2 billion specifically targeting legacy chips in automotive and defense systems. An additional $13.2 billion is allocated for research and workforce development, while $500 million is dedicated to international information communications technology security and semiconductor supply chain activities. Moreover, the Act introduces a 25% ITC to encourage capital expenses associated with semiconductor manufacturing and related equipment (U.S. Congress, 2021-2022b).

Second, directly related to energy, CHIPS provides an authorization of $11.2 billion to support research, development, and demonstration (RD&D) of the leading technology areas in the applied energy offices. This funding includes an allocation of $400 million from FY 2023 to FY 2026 for the Office of Nuclear Energy, enabling them to conduct advanced materials RD&D activities, which includes the nuclear field.

Other supported mechanisms could indirectly benefit advanced nuclear research and deployment. CHIPS established $1.2 billion from 2023 to 2026 to enhance the existing Advanced Research Projects Agency–Energy (ARPA-E) program, which does not exclude advanced nuclear energy. Finally, this Act also includes the National Nuclear University Research Infrastructure Reinvestment Act of 2021 (U.S. Congress, 2021-2022c), which boosts investment in both existing and new university nuclear science and engineering infrastructure:

> This section revises the program to support university nuclear science and engineering, including to allow support for revitalizing and upgrading existing nuclear science and engineering infrastructure that supports the development of advanced nuclear technologies and applications (U.S. Congress, 2021-2022b, Sec. 10743).
>
> Under the program to support university nuclear science and engineering, DOE shall carry out an Advanced Nuclear Research Infrastructure Enhancement Subprogram in order to (1) demonstrate various advanced nuclear reactor and nuclear microreactor concepts; (2) establish medical isotope production reactors or other specialized applications; and (3) advance other research infrastructure that is consistent with DOE's mission (U.S. Congress, 2021-2022b, Sec. 10744).
>
> Amounts made available under the University Nuclear Leadership Program may be used to assist with nontechnical nuclear research (U.S. Congress, 2021-2022b, Sec. 10745).

Finally, CHIPS allocates $390 million from 2023 to 2027 to create an Advanced Nuclear Research Infrastructure Enhancement Subprogram to advance the development of innovative nuclear technologies, including the demonstration of advanced and microreactor concepts, as well as the establishment of reactors for medical isotope production. Four research reactors and new nuclear science and engineering facilities are expected to be established to meet research demands and address infrastructure gaps (U.S. Congress, 2021-2022c).

Defense Production Act

The DPA allows the president to expedite and expand the supply of materials and services for national defense, including energy production and related activities. Nuclear could be benefited if some inputs in their supply chain receive financial support from the DPA. The DPA can indirectly affect MRs, as this Act provides funding for critical minerals that advanced nuclear technologies can use. The DPA

Title III was re-authorized in 2022 to enhance the U.S. industrial base for large-capacity batteries, allowing the Department of Defense (DOD) to augment domestic mining and processing of critical materials required to produce batteries.

The DPA is not specific to nuclear energy technologies, as evidenced by recent notice of intent and request for information regarding establishing a program to support electric heat pump manufacturing and deployment (U.S. DOE, 2022b). While the Act provides $250 million that will be used to support the manufacturing and deployment of electric heat pumps, it also supports materials, components, or facilities related to critical materials for the DOD. Given this, mining and processing of critical minerals as graphite, which is a potential industry that MRs can couple, could potentially receive funding from the DPA.

State Support Mechanisms

Currently, a bigger number of states have begun exploring and enacting policies to support the development of the next generation of nuclear reactors even when some of these are states that do not have commercial nuclear reactors such as Indiana, Montana, and Wyoming and on the contrary have deep economic ties to the coal industry. Also, zero emissions credits (ZECs) policies have been the most considered and enacted as they provide qualifying reactors with a supplemental payment for every megawatt hour (MWh) of carbon-free electricity sold (NCSL 2022).

State benefits are already in place in four states for existing reactors. These could be extended in the future; however, new buildings (e.g., MRs) are still unknown (Shropshire et al., 2023). Given this, other states could potentially offer future benefits for low-carbon tech.

The state support mechanisms considered in the present analysis directly affect the electricity production from MRs. Furthermore, the state support mechanisms can be considered similar to production tax credits, where carbon-free electricity production is incentivized through state tax credit rates from $10/MWh up to $20/MWh.

Additionally, in recent years, half of the U.S. states have some sort of decarbonization programs at the state level. This has created a diverse set of incentives across states, such as efficiency standards for buildings and equipment, tax credits for energy efficiency, alternative energy sources, rebates for industrial or commercial energy savings programs, and carbon offset programs such as clean energy standard, renewable portfolio standard or carbon target, which includes a range of technologies to reduce carbon emissions (Shropshire et al., 2023).

However, it is important to note two main changes at the state level:

- Policy changes are expanding definitions to incorporate nuclear technologies into zero-emission/carbon-free/clean energy definitions (CA, CT, ID, IL, IN, NJ, and VA)
- Policy adjustments to repeal nuclear development prohibitions or update siting authority to deploy advanced reactor technology (AK, CT, KY, MT, WI, and WV) (Shropshire et al., 2023).

Fleet Benefit – Learning Rates

Given the technical attributes of microreactors, the unit cost for MRs will likely, strongly depend on several factors, including technology development, supply chain, factory production, etc. (Shropshire, 2021; Abdalla et al., 2021). The combined impact of these factors is approximated through a learning rate. The manufacturing knowledge and unit costs will be intensely dependent on the market size that has to be attended to, which will determine the units that must be produced (Okun, 1962). A higher number of projected units could translate to decreasing production costs mainly for learning by doing and economies of scale (Kaldor, 1968). In addition, additional infrastructure investments are realized, and standardization, robust supply chains, novel materials, and advanced manufacturing could decrease even more the production and processes cost (Abdalla et al., 2021). This could enable entry into additional markets and manufacturing efficiencies (EPRI, 2018). For details about how the LRs were estimated, see Appendix A.

Finally, customers and investors are expected to have lower financial risks given the reduced dimensions and accelerated delivery schedules anticipated for MRs, which can contribute to decreased upfront investment requirements. Furthermore, MRs' compact size allows for greater adaptability in addressing incremental demand growth, strengthening their overall business feasibility in different industries (IEA, 2020).

As was described, the number of support mechanisms is vast, and some can be stacked. In the following section, a cost analysis for a microreactor is presented, considering stacking diverse supporting mechanisms that could make MRs more competitive.

Venture Capital

The federal and state supporting mechanisms converge with the market and could incentivize venture capital (VC) in the next decades. VC are flows of private funding that are generally provided to startups and companies at the nascent stage in which investors provide capital in exchange for taking partial ownership and offering expertise to help grow the startup/company with long-term growth potential. VC in the energy sector has been inspired by the success of Silicon Valley venture capitalists that fostered the development and adaptation of commercially viable technologies. Since the start of 2020, ~2,500 climate tech companies have raised $117 billion of venture funding across 3,332 deals, with cumulative industry growth averaging ~30% each quarter (CTVC, 2023). In this context, VC could begin after risk reduction from the successful deployment of initial reactors (late 2020s). Potentially, VC could take equity investments in small advanced nuclear technology firms and accelerate the development of these firms thanks to their network of private sector financing and private technology firms that allow to leverage the resources of private investors and use market mechanisms to promote technology development (Block and Keller, 2008).

It is important to note that VC will appear after the companies and startups cross the "valley of death," which happens when there is high technical and financial uncertainty that does not allow startups or small companies to move from the product development of technology into the market validation or commercialization stage. Given this, the way to overcome the valley and start the commercialization (i.e., deployment of MRs) of new technology is through adequate financial supporting mechanisms. The set of supporting mechanisms previously described could allow the scaleup of MRs, providing adequate funding that decreases risk and uncertainty. In the long run, VC will increase when the risk and uncertainty are low enough.

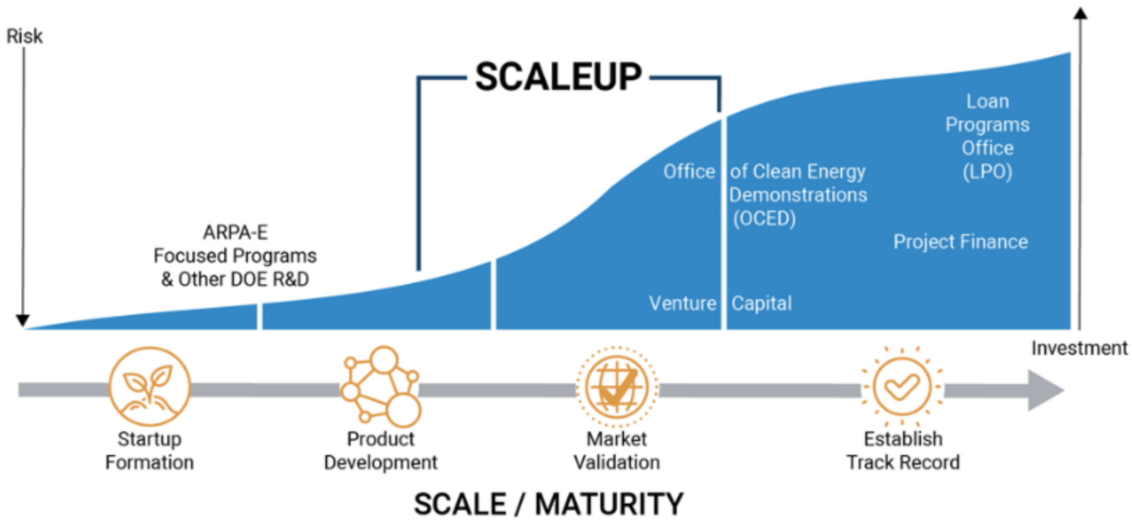

Figure 3. ARPA-e scaleup overview. Source: ARPA-e, 2023. Taken from: https://arpa-e.energy.gov/news-and-media/blog-posts/arpa-e-continues-work-scale-high-risk-high-potential-transformational.

An excellent example of how VC could boost MRs deployment can be seen in the hydrogen electrolyze industries where VC started to pour into startups and established companies. Through most of 2022, private equity firms spent $3.1 billion on hydrogen-related companies across 37 deals, while venture firms invested $2.6 billion, in 192 startups. Since 2014, the number of annual VC hydrogen deals has more than tripled as private equity deal count quadrupled (PitchBook, 2023).

So far, a set of actual and potential supporting mechanisms has been described. They could provide potential financial benefits for a diverse set of investors. Figure 4 shows the supporting mechanisms that could be available by year till 2050. The bars represent the different mechanisms that could be received by year.

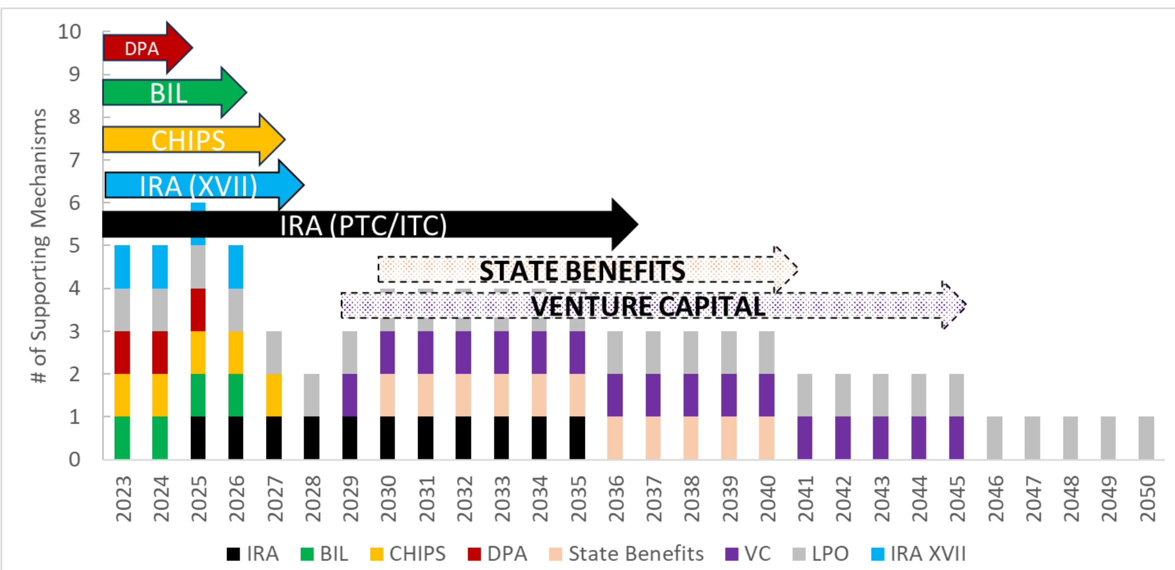

Figure 4. Potential supporting mechanisms to scaleup MRs.

3. METHODS AND DATA

This analysis builds on the previous projects uncovering indirect benefits for MRs in diverse, representative industrial projects considering a bundle of supported mechanisms from different laws, acts, and bills. Evaluations were initially conducted by the INL-led Emerging Energy Markets Analysis initiative on the use of microreactors in Alaska (AK) and Wyoming (WY) energy markets focused on serving location-specific energy needs and the potential for electricity and heat.

An additional novelty of this report comes from a new methodology for study cases selection, which is based on the following criteria:

- High-energy uses include processing heat and electricity
- Highly dependent on high-carbon fossil energy sources providing for potential reductions in CO_2 emissions and other greenhouse gases (GHG)
- The global market potential for low-carbon products, avoiding potential tariffs in export markets (e.g., green steel)
- Value-added supply chain, providing access to different industries in producing mid-stream and final-end products.

Industrial project characteristics closer to each of these dimensions are preferred over others. Our industry selection criterion is represented in the following figure.

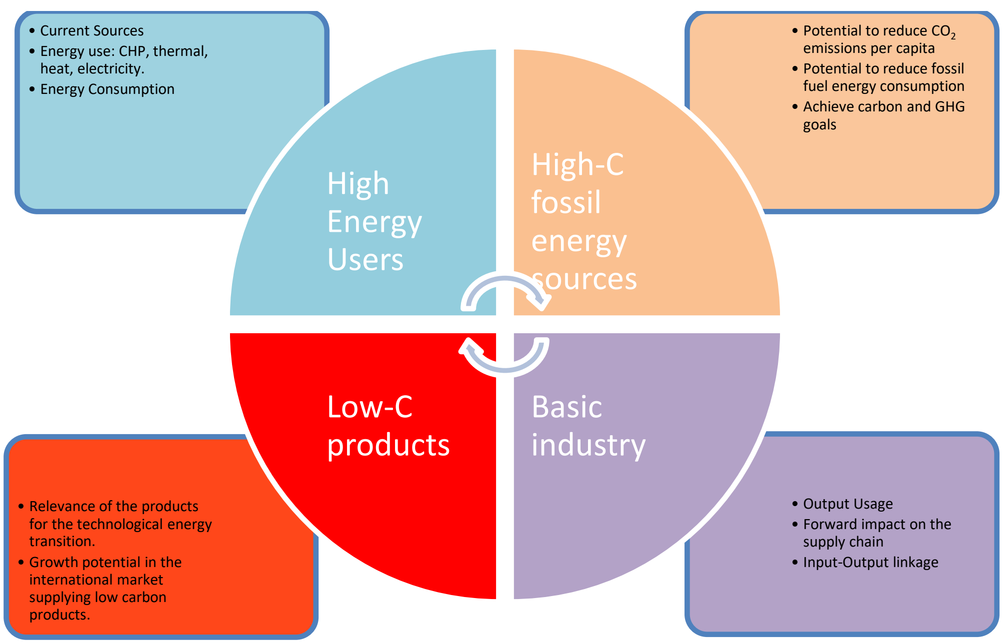

Figure 5. Case study selection criterion.

The four dimensions cross each other and are not exhaustive. On the contrary, those four dimensions represent some of the most influential trends affecting the economy's competitiveness and environmental and economic results of diverse industrial projects where MRs could couple. Each dimension has a series of attributes that need to be considered, as described in each rectangular box in Figure 5. Those attributes will define what industrial study cases will be selected. For instance, a current industrial user that utilizes fossil fuels-based technologies, he wants to reduce its CO2 emissions, and his production is a critical input for other industries and for the energy transition would be preferred over others that have no such attributes.

It is important to note that those dimensions are dynamic and change slowly over time. For instance, a high-energy user in the present could be a medium- or low-energy user in the future, thanks to the introduction of innovations, as a requirement to access IRA benefits, that creates a demand for cleaner and more efficient technologies. This does not mean that the four dimensions are predictive variables of future scenarios, but they act as centers of gravitation around which different industries could approach if they want to meet the environmental requirements and regulations.

In the first place, the data of high energy users were taken from the 2018 MECS Survey Data. Sectors with an energy demand of heat and electricity or high-energy demand are preferred to those with fewer energy requirements. Since heat is mainly produced with fossil fuels, and oil and gas prices are unstable due to geopolitical conditions, energy savings and reducing fossil fuel consumption are critical to maintaining industrial competitiveness. According to the Energy Information Administration (EIA), pulp and paper manufacturing, chemical production, petroleum refining, iron and steel manufacturing, and iron ore production are representative industries in energy-intensive manufacturing (U.S. EIA, 2016).

The second dimension, representing high-C fossil energy users, was selected given that industries are heavily fossil fuel dependent, and a business-as-usual scenario would not reach the net zero goals by 2050 (Pörtner et al., 2022). This means that in a business-as-usual scenario, we could expect higher flows of CO_2 and GHG into the atmosphere. Given this, newer and cleaner technologies such as MRs could play a more significant role in reaching negative carbon dioxide, and GHG flows into the atmosphere, putting the industry on a cleaner path.

The third one, the future global market potential for low-C products, was considered by combining three attributes: (1) products critical for the technological energy transition are preferred over others, (2) the number of potential benefits are coming from IRA, BIL, and other benefits, and (3) the global low-C markets for different industries were compared by the compound annual growth rate in the next decade. This allows us to distinguish these industries with low expected growth rates that will be less attractive for new investments in relation to the higher growth rate sectors that will attract more capital. Also, products that can reach a reduced carbon footprint or are carbon neutral are expected to play a more significant role in the global market, driven by increasing environmental awareness, government initiatives, and regulations.

The last dimension of basic industry was considered looking at the sectors that provide a diverse supply of inputs to other industries. IRA requests that goods and intermediate inputs should be produced with cleaner technologies and production processes. Furthermore, a cheaper, more competitive, and cleaner basic industry will benefit all the production processes across all the industries and sectors, given the input-output relationships of the economic system. In this sense, this final dimension is critical for net zero. Cleaner energy technology coupled with strategic industries can have a more significant impact and a multiplier effect on the economic system than the non-basic industries. It is important to note a critical difference between this approach and the life cycle analysis (LCA). In the input-output approach, we also look at the carbon footprint of the inputs with which we manufacture the inputs of the final goods. While in LCA, we only look at the inputs of the final product under analysis. For instance, it is not only essential to produce lithium batteries with a smaller carbon footprint, but also it is vital to produce the inputs of lithium batteries with cleaner energy sources. Otherwise, it could be possible that the production of lithium batteries could generate more CO_2 and not less.

Following this qualitative methodology, the specific industries selected for this study are a trona facility in Wyoming and a graphite mine in Alaska.

3.1. Assumptions and Data

To simulate the deployment of a microreactor in the graphite mine in Alaska and a Trona facility in Wyoming, the following assumptions in Table 1 were stated.

Table 1. Parameter assumptions.

Parameter	Value	Source
Investment Tax Credit	[6%, 30%, 40%, 50%]	IRA, 2022
Production Tax Credit	[$5.5/MWh, $27.5/MWh, $30.25/MWh, $33/MWh]	IRA, 2022
State Benefits	[$10/MWh; $20MWh]	D. Shropshire et al., 2023
Learning Rates	[5%-10%-15%]	Abdala et al., 2021
Construction Period	[1-2] years	D. Shropshire et al., 2023
Units Built	[1-9, 10, 100, 1000, 100000]	D. Shropshire et al., 2021
Reactor Size	[5 MWe - 50MWe]	NREL, 2016
Capacity Factor	[93%-100%]	D. Shropshire et al., 2021
Discount Rate	10%	US EIA, 2023
CAPEX	[$0.15/kWh - $0.6/kWh]	D. Shropshire et al., 2021
OPEX	[$0.05/kWh - $0.19/kWh]	D. Shropshire et al., 2021

The assumptions will be specific to each industrial project; furthermore, the tax credits, reactor size, capacity factor, and discount rate will be different depending on the investment project under analysis.

Table 2 shows the full range of capital expenditure and the number of units, presented in Table 1, that need to be produced if the cost target is to be reached to enter specific markets. The FOAK, remote operations, distributed energy, and resilient cities give the market threshold. It is critical to note that the capital expenditure will depend on the number of units built and the green cells do not represent a FOAK estimate but the maximum cost target that a private investor would be able to accept to enter the market. All values are in 2021 US dollars.

Table 2. Cost target for MRs. Source: Adapted from: D. Shropshire et al., "Global Market Analysis of Microreactors," INL/EXT-21-63214, Idaho National Laboratory/DOE Microreactor Program (2021).

Time Frame		**Cost Targets at Cumulative Number of Builds**				
1st Units	**Profile Markets**	**1 to 9**	**10**	**100**	**1000**	**10000**
2020-2030	**FOAK units/ DOD Units**	**<$0.60/ kWh**				
2030-2035	**Remote Operations**		**<$0.50/ kWh**	**<$0.35/ kWh**	**<$0.20/ kWh**	**<$0.15/ kWh**
2035-2040	**Distributed Energy**			**<$0.35/ kWh**	**<$0.20/ kWh**	**<$0.15/ kWh**
2040-2050	**Resilient Cities**				**<$0.20/ kWh**	**<$0.15/ kWh**

For instance, $0.50/kWh is the threshold or cost target that should be reached if deployment in remote operations wants to be profitable. For our study cases this means that for example, for the graphite mine in Alaska, the Microreactors start to be profitable when their costs in under $0.5/kWh. Following a learning curve as expressed in Table 2, the supported mechanisms will decrease the cost of the projects, and furthermore, the entry cost of microreactors in terms of capital expenditures could be higher than $0.5/kWh. In addition, spreading the supported mechanisms over time will be critical to maintaining a decreasing cost trend in capital expenditures and operating and maintenance costs. This would allow MRs to reach higher learning rates, and furthermore, the capital cost will decrease even faster as the effects arising from the learning by doing, economies of multiples, etc., start to affect production costs and decrease capital expenditures.

Although the MRs cost structure is unknown, and there is high uncertainty for their final market outlook, there is a consensus (IEA, 2020) on three potential applications besides providing baseload electricity: (1) extending nuclear markets for off-grid/remote locations, (2) fostering decarbonization through the replacement of coal plants and non-electric applications such as industrial and district heating, and (3) distributed energy. In the following sections, the estimated curve cost for capital expenditures is presented with a qualitative analysis of two study cases where MRs could be deployed, considering specific supported mechanisms that could push costs downward.

4. RESULTS

Maximum Tolerated CAPEX if ITC Is Allowed

The present section provides the CAPEX ($/kWe) needed to meet the levelized ($/kWh) cost target in four scenarios: FOAK/DOD units, remote operations, distributed energy, and resilient cities.

Figure 6 shows the CAPEX levels that would be consistent with the target costs presented before if the ITC is active. An ITC with a 6% base rate means that no adders or bonusses are active; an 30% ITC means that the labor requirements were met; 40% ITC rate is available is labor requirements plus domestic content bonuses are met, and a 50% ITC rate is available when labor requirements, plus domestic content bonus, plus energy community bonus is met.

If the capital expenditure is on or below the dashed line, it means that the MR cost of capital is competitive to enter the market. Furthermore, given a higher ITC, the tolerated capital expenditure to enter different markets (dashed lines) can be higher.

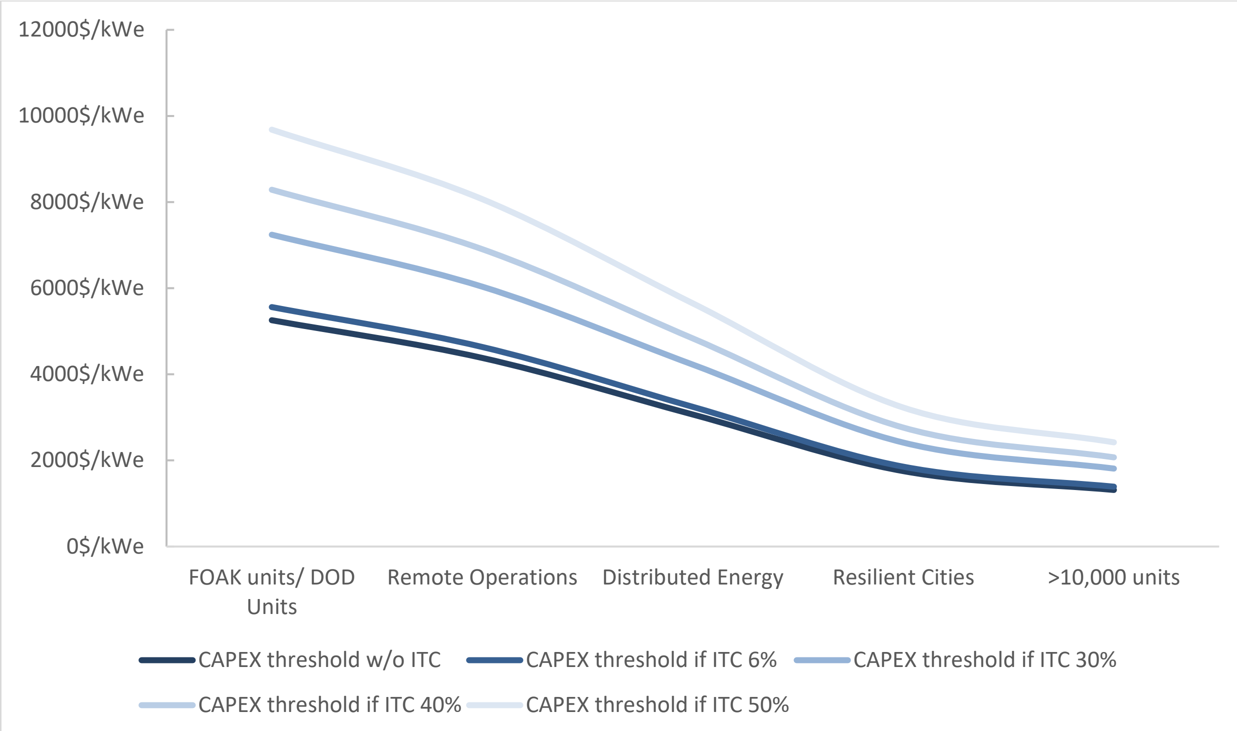

Figure 6. Maximum tolerated CAPEX for a cumulative number of units with different levels of ITC.

FOAK/DOD units: The minimum threshold level of the FOAK units will be reached between 1 to 9 units deployed with a capital expenditure of $5,256/kWe.

Remote Operations: A capital expenditure consistent with remote operations can be reached when there are around 10 units deployed. This means the capital expenditure without benefit is around $4,380/kWe.

Distributed Energy: A lower level of CAPEX, around $3,066/kWe, will allow MRs to be competitive in the distributed energy markets. This would require 100 units deployed.

Resilient Cities: When deployed units reach 1,000 units, the cost of capital would be around $1,314/kWe. MRs would be competitive to enter the market of resilient cities.

It is important to note that the previously listed levels of CAPEX are not adjusted by the IRA, BIL, etc. benefits. Suppose we adjust this minimum level by those benefits that are a proportion of the capital expenditures. In that case, the minimum cost curve starts to move upward, which means that the capital expenditure before receiving supported mechanisms can be higher than the minimum threshold from each market scenario. For instance, in the case of the remote operations market, the range of CAPEX goes between $4,380/kWe to $8,068/kWe depending on the level of the ITC (6%, 30%, 40%, 50%), respectively.

Maximum Tolerated CAPEX with State-Supported Mechanisms

Figure 7 shows the CAPEX levels that would be consistent with the target costs presented before if the state benefit is active. This means that the capital expenditure tolerated to enter different markets can be slightly higher under different levels of state benefits.

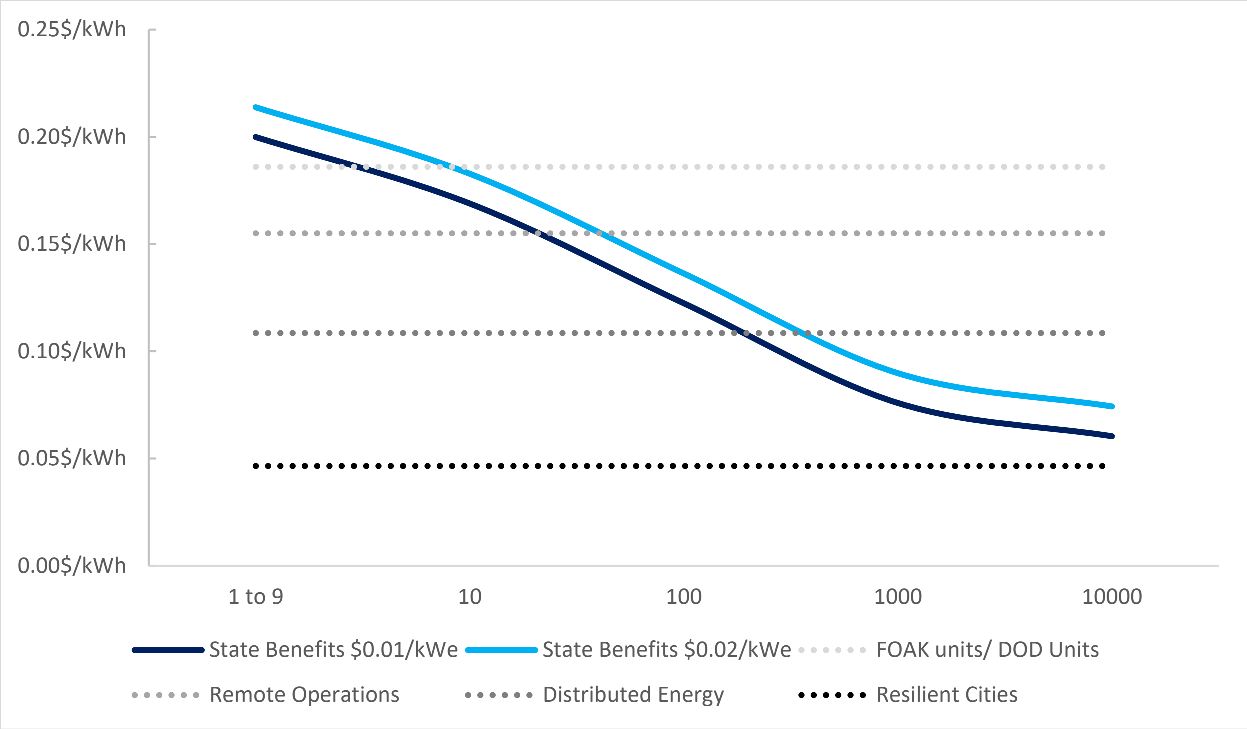

Figure 7. Maximum tolerated OPEX with State supporting mechanisms to meet cost targets.

State and federal-supported mechanisms could be stacked if they are present in the same period of time. As we described before, the IRA benefits go from 2025 to 2034. Furthermore, state-supported mechanisms should be enacted in that decade to obtain a double benefit.

Maximum Tolerated CAPEX under Different Interest Rates

The interest rate during construction will be higher depending on if the weighted average cost of capital (WACC) is 10% or 5%. This means that for a 2-year construction period, the CAPEX will be higher by an amount equal to the interest rate paid during the construction years as follows:

$$CAPEX_{total} = CAPEX_{overnight} * (1 + WACC)^{years\ of\ construction}.$$

In Figure 8 the maximum tolerated CAPEX under different interest rates is presented. A lower cost of capital would allow private investors to compensate for the higher cost of capital expenditure. Furthermore, with a lower WACC, the maximum tolerated CAPEX is higher.

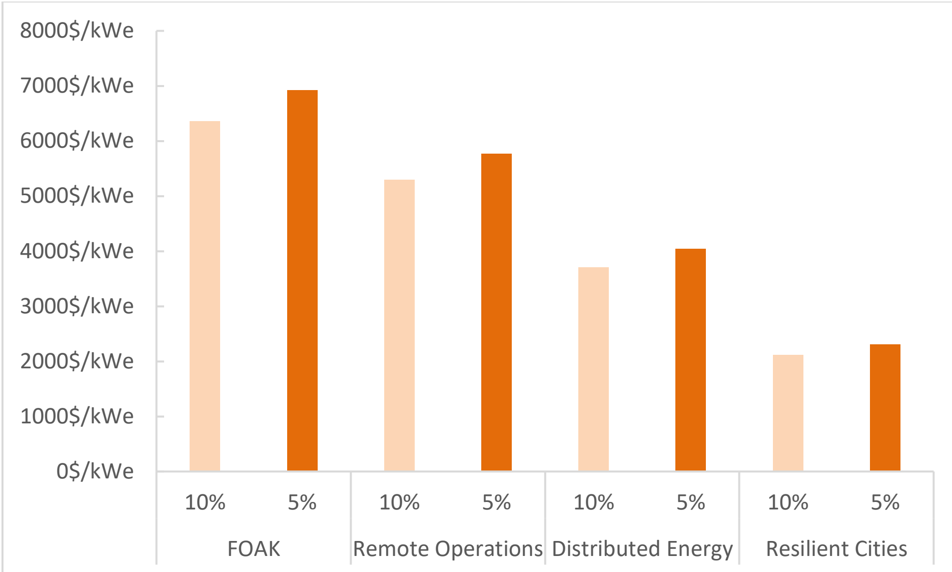

Figure 8. Maximum tolerated CAPEX in 2 years of construction period with a 5% and 10% WACC.

In Figure 9 the maximum operating and maintenance (O&M) cost needed to reach cost targets is presented under different levels of PTC. The O&M includes the annualized O&M costs and the annualized fuel costs. The proportions were taken from Abdalla et al. (2021).

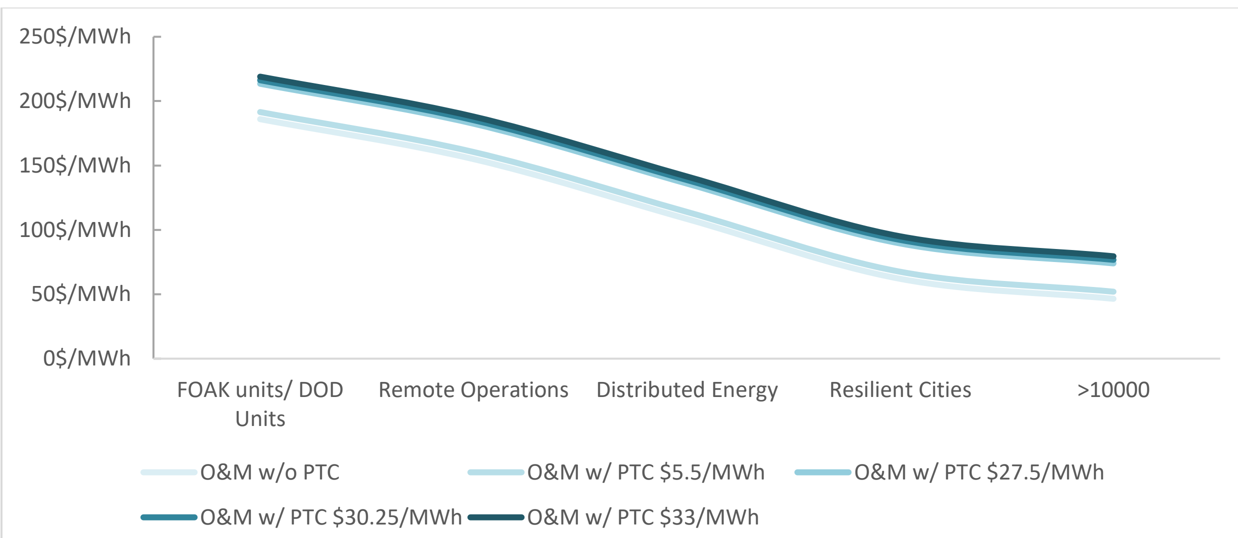

Figure 9. Maximum tolerated O&M costs ($/MWh) to reach cost targets.

FOAK/DOD units: The minimum threshold level of the FOAK units will be reached between 1 to 9 units deployed with an O&M cost of $186/MWh without the PTC.

Remote Operations: A capital expenditure consistent with remote operations can be reached when there are around 10 units deployed. This means that the O&M without benefit is around $155/MWh.

Distributed Energy: A lower level of O&M costs without PTC, around $109/MWh, will allow MRs to be competitive in the distributed energy markets. This would require around 100 units to be deployed.

Resilient Cities: When the units deployed reach 1,000 units, the O&M cost would be around $62/MWh. MRs would be competitive to enter the market of resilient cities.

Given the guidance by The Department of Treasury and DOE, the most critical supported mechanisms so far are the investment and production tax credits, loans, and loan guarantee programs. As described before, those supported mechanisms reduce investment costs when they are provided as a percentage of the project's investment cost and reduce operating costs when provided as a sum of the electricity produced.

The supported mechanisms cannot be stacked all at the same moment but at different periods, which can give the investment owners certainty on the future schedule of supported mechanisms throughout the project life. It is critical to remember that these acts have specific conditions and requirements to access the credits and the different bonuses, and furthermore, the potential investment projects that can be qualified will depend on many factors that have to be considered by the owners in each case. However, in the following section, two study cases are presented to describe how those supported mechanisms could decrease the cost of microreactors deployment when coupled with the industry.

5. INDICATIVE CASE STUDIES

5.1. Case Study #1: Graphite One Project in Alaska

It is critical to note that graphite has not been produced in the United States since the 1950s, and graphite is one of 50 mineral commodities included in the whole-of-government list of critical minerals published by the USGS (2022). Only two companies are developing graphite mining projects in the United States—one in Alabama and one in Alaska. Recently, the U.S. Geological Survey (USGS) and the DOE confirmed that the most significant graphite deposit is located in the Kigluaik Mountains 60 km north of Nome on the Seward Peninsula, Alaska (USGS, 2022), and it is among the largest in the world (King et al., 2019). The supply constraint combined with a high-demand scenario of graphite in the future could push up graphite prices and delay clean energy transitions.

Graphite One, the company developing the graphite mine in Alaska, is envisioning a vertically integrated supply chain to extract, process, and produce graphite. The graphite would be extracted in Alaska and then sent to the purification and processing plant adjacent to the mine. The manufacturing plant is expected to be in Washington State.

According to the Graphite One (2019) report, the mining plan outlined above proposes the mining of graphite mineralized material at an ultimate rate of 3,090 tons per day, or the equivalent of 1,018,00 tons per year (tpy), to transform it into 60,000 tpy concentrate grading 95% graphite (Cg). Based on the modeled portion of the graphite mineralization at 7% Cg, the inferred resources could conceivably sustain the proposed mining rate for 20 years and up to 40 years. Three diesel generators, of two-MW each, will conform the power plant to produce electricity at the site, operating at 80% of nameplate capacity. The annual diesel fuel consumption was estimated at 9,000 m^3 when production at the Mineral Processing Plant reaches the total capacity of 60,000 tpy concentrate (Graphite One, 2019). Diesel fuel would be imported from Washington State and stored at leased facilities with a 3-month inventory of fuel maintained at the plant site.

It is important to note that many rural communities in Alaska rely primarily on diesel-fueled electric generators for power, and Alaska ranks second only to Hawaii in the share of its total electricity—14% in 2022—generated from petroleum (U.S. EIA, 2022b). Diesel generators are the primary source of electrical generation in remote Alaska communities (EPA, 2020). Alaska's per capita energy consumption is the second highest in the nation, explained mainly by the state's small population, harsh winters, and energy-intensive industries; in this context, this is where the Graphite Creek Project site will be developed. Assuming 10 years mine operations, a diesel efficiency of 12.69kWh/gal (U.S. EIA, 2021) and the cost of a 1-gallon remote of $3.02 (Alaska Energy Authority, 2022), the present value of diesel is $0.16/kWh (see Appendix A). It is not close to any established electrical infrastructure (ADEC, 2023), making installing additional capacity at an existing plant and running transmission lines to the site costly.

Given this, an alternative scenario could be the deployment of a small modular reactor of 6MW to supply the requirement of electricity. An advanced microreactor could satisfy the annual electricity consumption, making the U.S. graphite more competitive in the existing markets, and reaching low emissions industrial products processes. The technology's ability to operate independently from the commercial grid and reduce CO_2 emissions makes microreactors a competitive power source for remote locations critical to the industry's supply chain. Coupling MR in the graphite production process would provide a cleaner and cheaper energy source.

Furthermore, some of the expected funds from the DPA could also be directed to graphite projects to strengthen its supply chain. Potential supported mechanisms that could support this project include the ITC/PTC, Advanced Energy Project Credit (48C), loan guarantee programs from section 1703/1706/TELGP, and the DPA. Given this, the final value of electricity could reach lower competitive levels against the current fossil fuel energy sources.

Finally, another advantage of deploying advanced microreactors for the graphite mine industrial process is that the regulations are being supported due to an existent program of the Air Force, which issued a request for proposals to construct a 2.5-MW microreactor at Eielson Air Force Base to supplement its current 20-MW coal-fired heat and power plant. In support of Governor Dunleavy's Office of Energy Innovation and in response to the U.S. Air Force Microreactor Pilot Program, the Alaska Department of Environmental Conservation is developing draft microreactor siting permit regulations authorized under Alaska Statute (AS) 18.45. (ADEC, 2023).

Table 3 shows the maximum tolerated CAPEX for the FOAK unit in a graphite mine in Alaska considering different set of benefits.

Table 3. MRs FOAK CAPEX tolerated before and after benefits.

	Min CapEx	**Max CapEx**
Overnight Capital Costs (OCC) - No Benefits	5256$/kWe	5256$/kWe
OCC w/ITC	5561$/kWe	8286$/kWe*
OCC w/WACC [5%-10%]	5795$/kWe	6925$/kWe
Stacking Benefits	6113$/kWe***	9457$/kWe***

*Includes domestic content + labor requirements bonuses.

***Includes Interest during construction.

Table 4 shows the maximum tolerated OPEX considering different sets of benefits.

Table 4. MRs FOAK OPEX tolerated before and after benefits.

	Min OpEx	**Max OpEx**
OPEX - No Benefits	0.186$/kWh	0.186$/kWh
OPEX w/PTC	0.192$/kWh	0.219$/kWh
OPEX w/State Benefits	0.200$/kWh	0.214$/kWh
Stacking Benefits	0.205$/kWh	0.247$/kWh

MR could receive significant benefits from different supporting mechanisms, becoming the maximum CAPEX and OPEX tolerated significatively higher than the scenario with no benefits for the FOAK units.

5.2. Case Study #2: Trona Processing Plant in Wyoming

Wyoming is a net energy producer and a leading producer of fuel resources, including coal, oil, and natural gas. However, the portfolio of sustainable and renewable energy is growing due to market and energy policies in the neighboring states and favorable policy and regulatory frameworks for carbon capture utilization and storage, hydrogen, and mineral extraction. This context, in conjunction with the state's high-energy literacy, demographics and the relative remoteness of many communities within the state, makes it a potentially attractive market for the introduction of MRs in different industries (Gerace et al., 2023).

Mainly, Wyoming contains a major deposit that produces a significant amount of the total world supply of trona and supplies about 90% of the nation's soda ash (WMA, 2019). The infrastructure in the area is well developed as the trona facilities have been in operation for 35 to 70 years (Stantec, 2022). Also, trona is found at Owens Lake and Searles Lake, California and in the Green River Formation of Wyoming and Utah. Trona is a common source of soda ash, an essential economic commodity because of its applications in manufacturing glass, chemicals, paper, detergents, and textiles. It is used to condition water and remove sulfur from both flue gases and lignite coals, and it is also used as a food additive. The total value of domestic natural soda ash (i.e., sodium carbonate) produced in 2021 was estimated to be about $1.8 billion, and the quantity produced was 12 million tons, about 20% more than that of the previous year. The U.S. soda ash industry comprised four companies in Wyoming operating five plants and one company in California operating one plant. The five producing companies have a combined annual nameplate capacity of 13.9 million tons (15.3 million short tons). In addition, chemical caustic soda, sodium bicarbonate, and sodium sulfite were manufactured as coproducts at several Wyoming soda ash plants. Finally, sodium bicarbonate was produced at an operation in Colorado using soda ash feedstock shipped from the company's Wyoming facility (USGS, 2022).

Trona processing to make soda ash (i.e., sodium carbonate) entails converting the sodium bicarbonate into carbonate, then removing the clay and iron contaminants by recrystallizing the sodium carbonate. After mining and crushing, the trona ore is calcined at about 250ºC to drive off the water that hydrates the sesquicarbonate crystal and to drive a chemical reaction. The sodium carbonate is dissolved in water, leaving behind insoluble clays and iron compounds to be physically separated from the sodium carbonate solution. A facility producing 2,740 tons/day of soda ash—the scale of each one of the four plants near Green River, Wyoming—uses an estimated total of 13.5 TJ/day (12,800 TBtu/day) and 5 MWe for a total CHP thermal energy load of about 161 MWt of heat (McMillan et al., 2016).

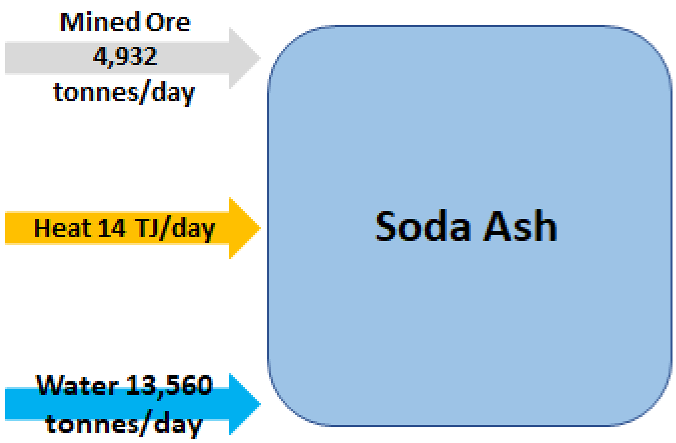

Figure 10. Material and energy requirements for a soda ash production plant. Source: Adapted from McMillan et al. (2016).

The total demand, heat quality (mostly steam), and proximity of the four plants in Wyoming could provide a favorable opportunity to replace fossil-fired steam boilers with a nuclear-based heat source. Other stand-alone plants of this variety may be candidates if economies of scale are favorable—that is when the cost of building and operating an MR is comparable to the costs of fossil-fuel-based technologies.

Some trona companies are currently considering alternative supply sources for heat and power to reduce their carbon footprint and provide power supply flexibility (Gerace et al., 2023). In this context, it is vital to note that new projects in Wyoming are highly likely to receive the energy community bonus, as seen in the Figure 11 map released by the DOE (see also Appendix A). The blue area represents areas labeled as "energy communities" according to the definition of the DOE. An investment project in this area as a MRs means that the ITC available for the project could reach a level of 50% if the labor and domestic content requirements are met.

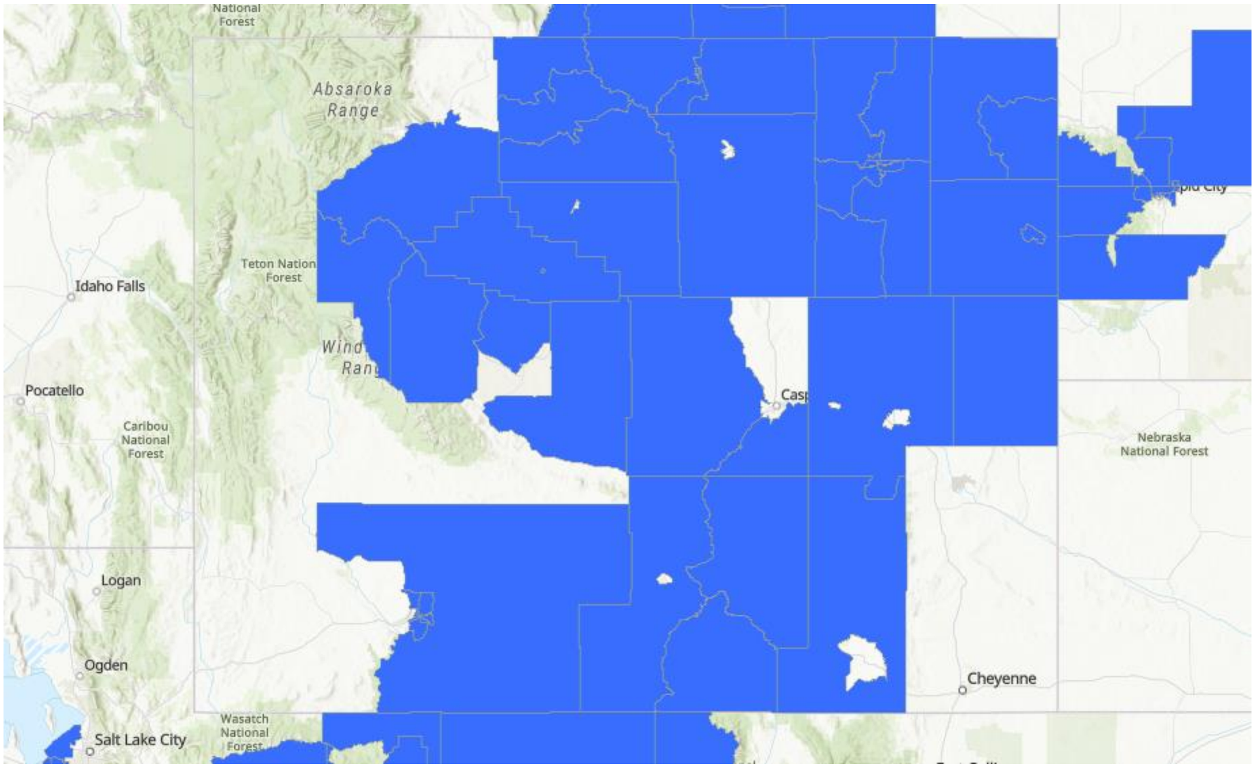

Figure 11. Section 48C tax credits - designated Energy Communities. Source: U.S. DOE, NETL 2023.

Some supported mechanisms that could be available are the ITC/PTC, 48C, and loan guarantee programs from Title XVII. VC funding could also complement the total benefits as the units start to be deployed.

Table 5 shows the maximum tolerated CAPEX for the first of a kind unit in a trona facility in Wyoming considering different set of benefits that could be available for the facility. It is important to note that the trona facility includes the energy community bonus because almost all the state is considered an energy community (see Appendix A).

Table 5. MRs FOAK CAPEX tolerated before and after benefits for trona case study.

	Min CapEx	**Max CapEx**
Overnight Capital Costs (OCC) - No Benefits	5256$/kWe	5256$/kWe
OCC w/ITC	5561$/kWe	9681$/kWe**
OCC w/WACC [5%-10%]	5795$/kWe	6925$/kWe
Stacking Benefits	6113$/kWe***	10090$/kWe***

**Includes domestic content + labor requirements bonuses + energy community bonuses.

***Includes Interest during construction.

Table 6 shows the maximum tolerated OPEX considering different sets of benefits.

Table 6. MRs FOAK OPEX tolerated before and after benefits for trona case study.

	Min OpEx	Max OpEx
OPEX - No Benefits	0.186$/kWh	0.186$/kWh
OPEX w/PTC	0.192$/kWh	0.219$/kWh
OPEX w/State Benefits	0.200$/kWh	0.214$/kWh
Stacking Benefits	0.205$/kWh	0.247$/kWh

Like the graphite project in Alaska, a MR for trona in Wyoming could receive significant benefits from different supporting mechanisms, becoming the maximum CAPEX and OPEX tolerated significatively higher than the scenario with no benefits for the FOAK units.

6. DISCUSSION AND FINDINGS

The industrial sector is recognized as a challenging sector to decarbonize within the energy economy. This is primarily due to the wide range of energy sources used in various industrial processes and operations. In 2020, the industrial sector accounted for 33% of the country's total primary energy consumption, contributing to 30% of energy-related CO_2 emissions (U.S. DOE, 2022). MRs are a reliable and suitable energy source with the potential to satisfy electric and heating demands; however, in order to decarbonize the industrial sector and increase low-carbon production, it will be necessary to find first adopters of MRs in different industries able to tolerate the costs for the FOAK units. First adopters, such as the graphite and trona producers described in this study, can benefit from different federal supported mechanisms, State-support mechanisms, and VC benefits. This study analyzed the economic and financial suitability of MRs deployment to meet a broad range of market applications, producing products that are cost competitive and low carbon, and thanks to different benefits, it could present lower risk to investors.

In the first place, from the legislation reviewed, the most significant direct impact in terms of money flows on nuclear costs will come in the form of tax credits and loan guarantee programs as soon as their implementation is defined. The tolerated capital expenditure that could be considered competitive in order to introduce MRs into new markets is higher if federal, State, and VC benefits are considered. This means that investors can face investment projects with higher overnight capital costs, given that federal-, State- and private-supported mechanisms would compensate a portion of these costs. The challenge is maintaining the mechanisms for MRs through time to reach different learning rates and decrease the costs of the MRs. As the supported mechanisms are not supposed to be active in similar periods, it is essential to maintain the flow of mechanisms incentivizing the continuous deployment of MRs. The purpose of this is to trigger economies of scale, allowing lower production costs of MRs because of a more considerable quantity of units deployed and, at the same time, increasing the market size for MRs as new customers start to adopt the new technologies.

VC is an option for investors when secure funding is needed to expand and grow the business. This supporting mechanism could be developed after the first units are deployed, and potential market growth is envisioned for the industry as a whole. Venture money is not long-term money as the main idea is to invest in a highly profitable, acceptable risks company's balance sheet and infrastructure until it reaches a sufficient size and credibility so that it can be sold to a corporation or so that the institutional public-equity markets can step in and provide liquidity (Harvard Business Review, 1998).

Sometimes, stacking benefits also could add an extra push for MR competitiveness. As was described, Alaska and Wyoming are attractive markets for MRs as their political, economic, and environmental context present incentives for deploying advanced nuclear technologies into industrial projects. Stacking benefits could give enormous incentives for investments whenever possible as the tolerated CAPEX or OPEX would be higher than the case with a single benefit. While MRs are generally less expensive than larger nuclear reactors, they still require significant upfront investment and ongoing maintenance costs. This could be particularly challenging for specific industrial segments with limited resources or funding. However, the new IRA and BIL provide significant options for funding, such as grants, loans, and tax credits that can reduce the project's financial constraints.

7. SUMMARY

Recent legislation has created a variety of technologically neutral supporting mechanisms to advance all clean energy technologies. This study provides information for the private sector and research community on expectations for advanced nuclear cost data for the effects of recent legislation, State supporting mechanisms, and VC.

The report provided a review of a set of supporting mechanisms and estimations of the CAPEX and OPEX under different incentives, describing and differentiating which policies will impact directly and indirectly microreactor deployment in industrial applications. Stacking federal benefits in the next decade, additional state benefits and potential VC flows mean that the expected tolerated CAPEX and OPEX to be competitive in remote operations, such as trona and graphite production processes, can be higher than projected.

8. REFERENCES

Abou-Jaoude, A., Y. Arafat, A. W. Foss, & B. W. Dixon. (2021). An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept. INL/EXT-21-63067-Rev000, Idaho National Laboratory, United States. https://doi.org/10.2172/1811894.

ADEC. (2023). Sitting of Microreactors Regulations. Alaska Department of Environmental Conservation. https://dec.alaska.gov/eh/siting-of-microreactors-regulation-development/.

Akers, P. G. (2022). Technical Report Summary - Trona Property. *Stantec Consulting Services Inc*., Salt Lake City, UT: https://www.sec.gov/Archives/edgar/data/1022321/000102232122000018/ex961_genesisalkalitrsum.htm.

Alaska Energy Authority. (2022). Power Cost Equalization Program Statistical Report. https://www.akenergyauthority.org/Portals/0/Power%20Cost%20Equalization/FY22%20PCE%20Community%20Report.pdf.

ARPA-E. (2023). ARPA-E Continues Work to Scale High-Risk, High-Potential Transformational Energy Technologies by Unveiling Third SCALEUP Program. Advanced Research Projects Agency – Energy. https://arpa-e.energy.gov/news-and-media/blog-posts/arpa-e-continues-work-scale-high-risk-high-potential-transformational.

Aumeier, S. E., D. E. Shropshire, K. Araujo, C. Koerner, C. Bell, R. Johnson, J. Parsons, S. Gerace, E. Holubynak, & T. Righetti. (2023). Microreactor Applications in U.S. Markets: Evaluation of State-Level Legal, Regulatory, Economic and Technology Implications. INL/RPT-23-71733-Rev000, United States. https://doi.org/10.2172/1964093.

Buongiorno, J.; B. Carmichael, B. Dunkin, J. Parsons, & D. Smit. (2021). Can Nuclear Batteries Be Economically Competitive in Large Markets? *Energies*, *14*(14), 4385. https://doi.org/10.3390/en14144385.

Burleson, E. (2023). Private investment in hydrogen breaks record. *PitchBook.* https://pitchbook.com/news/articles/hydrogen-energy-transition-deals-record-pe-vc-2022.

Clean Air Task Force. (2023). Nuclear energy's role in global decarbonization efforts. https://www.catf.us/2023/01/nuclear-energys-role-in-global-decarbonization-efforts/.

CNBC. (2022). Why Silicon Valley is so hot on nuclear energy and what it means for the industry. [Updated: Dec. 02, 2022]. https://www.cnbc.com/2022/12/02/why-silicon-valley-is-so-hot-on-nuclear-energy.html.

CTVC. (2023). Macro market freeze chills climate tech: Venture funding down 40% in H1 2023. *Climate Tech VC*. https://www.ctvc.co/climate-tech-h1-2023-venture-funding/.

EPRI. (2018). *Full-Power Microreactor Demonstration Expands Horizons for Nuclear Energy* [Brochure]. Energy Technologies Brief, Electric Power Research Institute, Inc. https://www.epri.com/research/products/000000003002014871.

Forsberg, C., A. Foss, & A. Abou-Jaoude. (2022). Fission battery economics-by-design. United Kingdom. *Progress in Nuclear Energy*, *152*, 104366. https://doi.org/10.1016/j.pnucene.2022.104366.

Gerace, S., E. Holubynak, & T. Righetti. (2023). Wyoming Carbon Policy Sensitivity Analysis. In Microreactor Applications in U.S. Markets. Emerging Energy Analysis Initiative (EMA), Report, INL/RPT-23-71733, Appendix B, 87-110, University of Wyoming, Feb. 2023. https://gain.inl.gov/MicroreactorProgramTechnicalReports/Document_INL-RPT-23-71733.pdf#page=89. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_65488.pdf.

Hoffmeister, A., & N. Elliott. (2022). Notice of Intent and Request for Information regarding establishment of a Program to Use Defense Production Act to Support Electric Heat Pump Manufacturing and Deployment. American Council for an Energy-Efficient Economy (ACEEE), Washington, DC: 1-12. https://www.aceee.org/sites/default/files/pdfs/aceee_dpa_electricheatpump_rfi_final_0.pdf.

LPO. (2023). Title 17 Clean Energy Financing. U. S. Department of Energy, *Loan program Office* (webinar), Accessed Jul. 11, 2023. https://www.energy.gov/lpo/title-17-clean-energy-financing.

Kaldor, N. (1968). Productivity and Growth in Manufacturing Industry: a Reply. *Economica*, *35*(140), 385–391. Wiley & Sons. https://doi.org/10.2307/2552347.

Kozeracki, J., C. Vlahoplus, K. Scott, M. Bates, B. Valderrama, E. Bickford, T. Stuhldreher, A. Foss, & T. Fanning. (2023). Pathways to Commercial Liftoff: *Advanced Nuclea*r. https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf.

Lo, A.W. (2019). Bridging the Valley of Death Through Financial Innovation; Written Testimony of Andrew, W. Lo Prepared for the US House of Representatives Financial Services Committee. Lo Prepared for the US House of Representatives Financial Services Co; U.S. House of Representatives Financial Services Committee: Washington, DC, USA.

McMillan, C. A., R. Boardman, M. McKellar, P. Sabharwall, M. Ruth, & S. Bragg-Sitton. (2016). Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions. INL/EXT-16-39680; NREL/TP-6A50-66763, United States. https://doi.org/10.2172/1334495.

Merrifield, J. S., C. J. Saperstein, S. L. Fowler, & N. Steinberg. (2022). The CHIPS and Science Act Offers Support to Advanced Nuclear and Fusion Industries. *Pillsbury Insights,* Aug. 24, 2022. https://www.pillsburylaw.com/en/news-and-insights/chips-science-act-supports-nuclear-fusionindustries.html.

NCSL. (2022). Nuclear Power and the Clean Energy Transition | The State Role (main text) National Conference of State Legislature. [Updated: Apr. 06, 2023]. https://www.ncsl.org/energy/nuclear-power-and-the-clean-energy-transition.

NMA. (2023). NMA Climate Change Position. https://nma.org/esg/nma-climate-change-position/

Okun, A. M. (1962). Potential GNP: Its Measurement and Significance. In *Proceedings of the Business and Economic Section of the American Statistical Association*, Alexandria, VA. American Statistical Association, 89-104.

Porter, Michael E., Competitive Strategy: Techniques for Analyzing Industries and Competitors (1980). University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship, Available at SSRN: https://ssrn.com/abstract=1496175.

Pörtner, H.-O, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama**.** (2022). Climate Change. 2022. Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change *Cambridge University Press*. Cambridge, UK and New York, NY, USA: 3056. https://doi.org/10.1017/9781009325844.

Rissman, J., C. Bataille, E. Masanet, N. Aden, W. R. Morrow, N. Zhou, N. Elliott, R. Dell, N. Heeren, B. Huckestein, J. Cresko, S. A. Miller, J. Roy, P. Fennell, B. Cremmins, T. K. Blank, D. Hone, E. D. Williams, S. de la Rue du Can, B. Sisson, M. Williams, J. Katzenberger, D. Burtraw, G. Sethi, H. Ping, D. Danielson, H. Lu, T. Lorber, J. Dinkel, & J. Helseth. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. ISSN 0306-2619 *Applied Energy*, *266*, 114848. https://doi.org/10.1016/j.apenergy.2020.114848.

Sepulveda N. A., J. D. Jenkins, F. J. Sisternes, & R. K. Lester. (2018). The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. ISSN 2542-4351, *Joule*, *2*(11), 2403-2420. https://doi.org/10.1016/j.joule.2018.08.006.

Short, S. M., & B. E. Schmitt. (2018). Deployability of Small Modular Nuclear Reactors for Alberta Applications – Phase II. PNNL-27270, Pacific Northwest National Laboratory. United States. https://albertainnovates.ca/wp-content/uploads/2020/07/Pacific-Northwest-National-Laboratory-Deployability-of-Small-Modular-Nuclear-Reactors-for-Alberta-Applications-Phase-2.pdf.

Shropshire, D. E. (2021). Microreactors Electrify the Future of Mining. United States. https://www.osti.gov/biblio/1975280

Shropshire, D. E., G. Black, & K. Araujo. (2023). Global Market Analysis of Microreactors. INL/EXT-21-63214-Rev000, United States. https://doi.org/10.2172/1806274.

Thiel G. P., A. K. Stark. & K. Addison. (2021). To decarbonize industry, we must decarbonize heat. *Joule, 5*(3), 531-550. https://doi.org/10.1016/j.joule.2020.12.007.

Tirole, J. (1988). *The Theory of Industrial Organization*. ISBN: 9780262200714, (Aug. 26, 1988) MIT Press, Cambridge, MA. https://mitpress.mit.edu/9780262200714/the-theory-of-industrial-organization/.

U.S. Congress. (2021-2022a). H.R.3684 - Infrastructure Investment and Jobs Act. United States Congress (Nov. 15 2021). https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

U.S. Congress. (2021-2022b). H.R.4346 - Chips and Science Act. United States Congress (Aug. 9, 2022). https://www.congress.gov/bill/117th-congress/house-bill/4346.

U.S. Congress. (2021-2022c). H.R.4819 - National Nuclear University Research Infrastructure Reinvestment Act of 2021. United States Congress (Sep. 14 2022). https://www.congress.gov/bill/117th-congress/house-bill/4819.

U.S. Congress. (2021-2022d). H.R.5376 - Inflation Reduction Act of 2022. United States Congress (Aug. 16, 2022). https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

U.S. DOE. (2018). Manufacturing Energy and Carbon Footprints (2018 MECS). <Manufacturing Energy and Carbon Footprint: Sector: All Manufacturing (NAICS 31 33)>. United States Department of Energy, Industrial Efficiency & Decarbonization Office. https://www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.

U.S. DOE. (2022). DOE Announces First Advanced Technology Vehicles Manufacturing Loan in More than a Decade. United States Department of Energy. https://www.energy.gov/articles/doe-announces-first-advanced-technology-vehicles-manufacturing-loan-more-decade.

U.S. DOE. (2023b). Civil Nuclear Credit Program. U. S. Department of Energy, *Grid Deployment Office*. Accessed Jun. 26 2023. https://www.energy.gov/gdo/civil-nuclear-credit-program.

U.S. DOE. (2023c). Tribal Energy Loan Guarantee Program. U. S. Department of Energy, *Loan Programs Office*. Accessed Jun. 26 2023. https://www.energy.gov/lpo/tribal-energy-loan-guarantee-program.

U.S. DOE-NE. (2023a). Commercializing Advanced Nuclear Reactors Explained in Five Charts. United States Department of Energy, Office of Nuclear Energy. https://www.energy.gov/ne/articles/commercializing-advanced-nuclear-reactors-explained-five-charts.

U.S. DOE-NE. (2023b). U.S. Department of Energy to Acquire High-Assay Low-Enriched Uranium Material. United States Department of Energy, Office of Nuclear Energy. https://www.energy.gov/ne/articles/us-department-energy-acquire-high-assay-low-enriched-uranium-material

U.S. DOE & NTEL. (2023). IRA Energy Community Tax Credit Bonus. United States Department of Energy & National Energy Technology Laboratory. https://arcgis.netl.doe.gov/portal/apps/experiencebuilder/experience/?id=a2ce47d4721a477a8701bd0e08495e1d.

U.S. DOE & NTEL. (2023). Section 48C Tax Credits - Designated Energy Communities. United States Department of Energy & National Energy Technology Laboratory. https://arcgis.netl.doe.gov/portal/apps/experiencebuilder/experience/?id=a44704679a4f44a5aac122324eb00914&page=home.

U.S. EIA. (2016). International Energy Outlook. United States Energy Information Administration, Independent Statistics & Analysis. https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf.

U.S. EIA. (2021). How much coal, natural gas, or petroleum is used to generate a kilowatt hour of electricity? Energy Information Administration, Independent Statistics & Analysis. [Last updated Nov. 8, 2022]. https://www.eia.gov/tools/faqs/faq.php?id=667&t=6.

U.S. EIA.(2022a). US energy facts explained. United States Energy Information Administration, Independent Statistics & Analysis. [Last updated May 3, 2023]. https://www.eia.gov/energyexplained/us-energy-facts/data-and-statistics.php.

U.S. EIA. (2022b). Alaska State Energy Profile. United States Energy Information Administration, Independent Statistics & Analysis. [Last updated Mar. 16, 2023]. https://www.eia.gov/state/print.php?sid=AK.

U.S. EIA. (2023). Assumptions to the Annual Energy Outlook 2023: Electricity Market Module. United States Energy Information Administration, Independent Statistics & Analysis. https://www.eia.gov/outlooks/aeo/assumptions/pdf/EMM_Assumptions.pdf.

U.S. EPA. (2020). Remote Areas of Alaska Affordable and Reliable Options for Meeting Energy Needs and Reducing Emissions. A Report to Congress as Directed by the Alaska Remote Generator Reliability and Protection Act. United States Environmental Protection Agency. https://19january2021snapshot.epa.gov/sites/static/files/2020-09/documents/2020_argrpa_report_to_congresssept2020.pdf.

U.S. EPA. (2022). Inventory of U.S. Greenhouse Gas Emissions and Sinks | US EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 (main text) United States Environmental Protection Agency. [Updated: Apr. 19, 2023]. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks#:~:text=Key%20findings%20from%20the%201990,sequestration%20from%20the%20land%20sector

USGS. (2022). Mineral Commodity Summaries. 2022. United States Geological Survey. https://doi.org/10.3133/mcs2022.

U.S. IRS. (2022). Publication 946 (2022), How to Depreciate Property. The United States Internal Revenue Service, Washington, DC.

https://www.irs.gov/publications/p946#:~:text=To%20claim%20depreciation%20on%20property,Partial%20business%20or%20investment%20use.

U.S. IRS. (2023). Additional Guidance for the Qualifying Advanced Energy Project Credit Allocation Program under Section 48C(e). Taken from: https://www.irs.gov/pub/irs-drop/n-23-44.pdf

U.S. Senate. (2023). Statement of Dr. Kathleen Hogan, Principal Deputy Under Secretary and Acting Under Secretary for Infrastructure U.S. Department of Energy Before the Committee on Indian Affairs United States Senate Regarding Implementation of the Bipartisan Infrastructure Law and Inflation Reduction Act in Indian country. Mar. 29, 2023.

Utilitydive. (2023). NRC authorizes first US high-assay low-enriched uranium enrichment plant critical for advanced reactors. https://www.utilitydive.com/news/nrc-HALEU-doe-advanced-nuclear-plants/653629/

Vanatta, M., D. Patel, T. Allen, D. Cooper, & M. T. Craig. (2023). Technoeconomic analysis of small modular reactors decarbonizing industrial process heat. *Joule, 7*(4), 713-737. https://doi.org/10.1016/j.joule.2023.03.009.

Wisevoter. (2023). Corporate Tax Rate by State. Online media. *Wisevoter*. https://wisevoter.com/state-rankings/corporate-tax-rate-by-state/.

WMA. (2019). Trona. https://www.wyomingmining.org/minerals/trona/.

X-energy. (2023). Dow’s Seadrift, Texas location selected for X-energy advanced SMR nuclear project to deliver safe, reliable, zero carbon emissions power and steam production. https://x-energy.com/media/news-releases/dows-seadrift-texas-location-selected-for-x-energy-advanced-smr-nuclear-project-to-deliver-safe-reliable-zero-carbon-emissions-power-and-steam-production

Zider, B. (Nov./Dec 1998). How Venture Capital Works. *Harvard Business Review*. https://hbr.org/1998/11/how-venture-capital-works.

Appendix A

It is possible to estimate the capital expenditure adjusted by the learning rate following the formula below:

(1) $Cost\_adj = Cost * (1 - LR)^{\wedge}log_2 N$

where:

- LR is the learning rate,
- N is the number of reactors built,
- Cost is the FOAK capital expenditure,
- Cost_adj is the CAPEX adjusted.

For example, Table A-1 shows the cost target assuming that the deployed units are deployed with a schedule where 1,000 units are built in 2040–2050.

Table A-1. Target cost given a learning rate of X%.

Year	Cost Target	# Unit Deployed
2020–2030	<$0.60/kWh	1 to 9
2030–2035	<$0.50/kWh	10
2035–2040	<$0.35/kWh	100
2040–2050	<$0.20/kWh	1000
2050–	<$0.15/kWh	10000

Following Equation (1), the capital expenditure for different learning rates can be estimated. The results are shown in Figure 10 below.

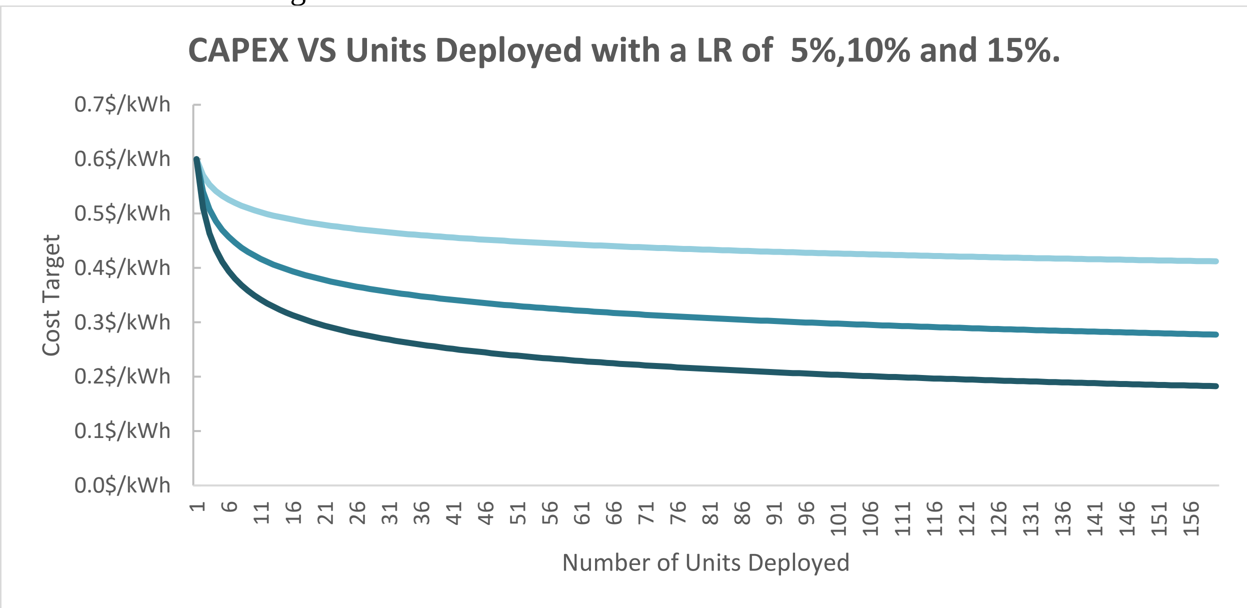

Figure A-1. CAPEX for different learning rates of MRs.

Present Value Estimations of a Microreactor Versus a Diesel Power Plant in Alaska

Dollars cost per kilowatt hour for the microreactor and diesel were estimated assuming the following assumptions:

Table A-2. Techno-economic Assumptions.

Economics	Assumption	Reference
Inflation Adjustment Factor 2016	0.223	CPI-U from BLS (2022)
Inflation Adjustment Factor 2021	0.131	CPI-U from BLS (2022)
State Tax Rate	7%	Wisevoter (2023)
Federal Corporate Tax Rate	21%	US EIA (2023)
Depreciation Schedule	MACRS (half-year convention); Recovery period: 17 years; 200% declining balance method	U.S. IRS (2022)
ITC	50%	IRA (2022)
WACC	10.20%	U.S. EIA (2023)
Diesel Power Plant	**Assumption**	**Reference**
Disel Power Plant	6MW	Graphite One (2019)
Disel Cost/Year at Full Capacity	$ 9,900,000.00	Graphite One (2019)
Capital Cost	$ 12,000,000.00	Graphite One (2019)
1 Year Generation	52560000 kW/year	Calculated
Diesel Consumption	4074419 gal	Calculated
1 Gallon Remote	$3.02	AEA (2022)
Small Modular Reactor	**Assumption**	**Reference**
CAPEX	$5256/kWe	Shropshire et al. (2021)
OPEX	$186/MWh	Shropshire et al. (2021)
Capacity kW	6000	Calculated
Hours/Day	24	Calculated
Days/Year	365	Calculated
Capacity Factor	97%	Average from Shropshire et al. (2021)
1 Year Generation kWe	52,560,000.00	Calculated
Electricity Cost/Year	$214,151,441,860.47	Calculated

All the monetary values were escalated to 2022 values using the inflation adjustment factor, which was calculated using the consumer price index from the Bureau of Labor Statistics.

The total capital cost for a microreactor was calculated assuming the construction of a 6 MW microreactor with a CAPEX of $5256/kWe. Also, for a period of 10 years, the present value of operating cost (OPEX), which includes O&M and fuel costs, was estimated assuming an OPEX of $186/MWh and a WACC of 10.2%.

The total capital cost for the diesel plant was taken from the Graphite One (2019) report, which provides specific data for the diesel plant in the future graphite mine. The OPEX for the diesel plant was calculated over a period of 10 years assuming diesel cost and efficiency rates from the AEA (2022) and EIA (2023).

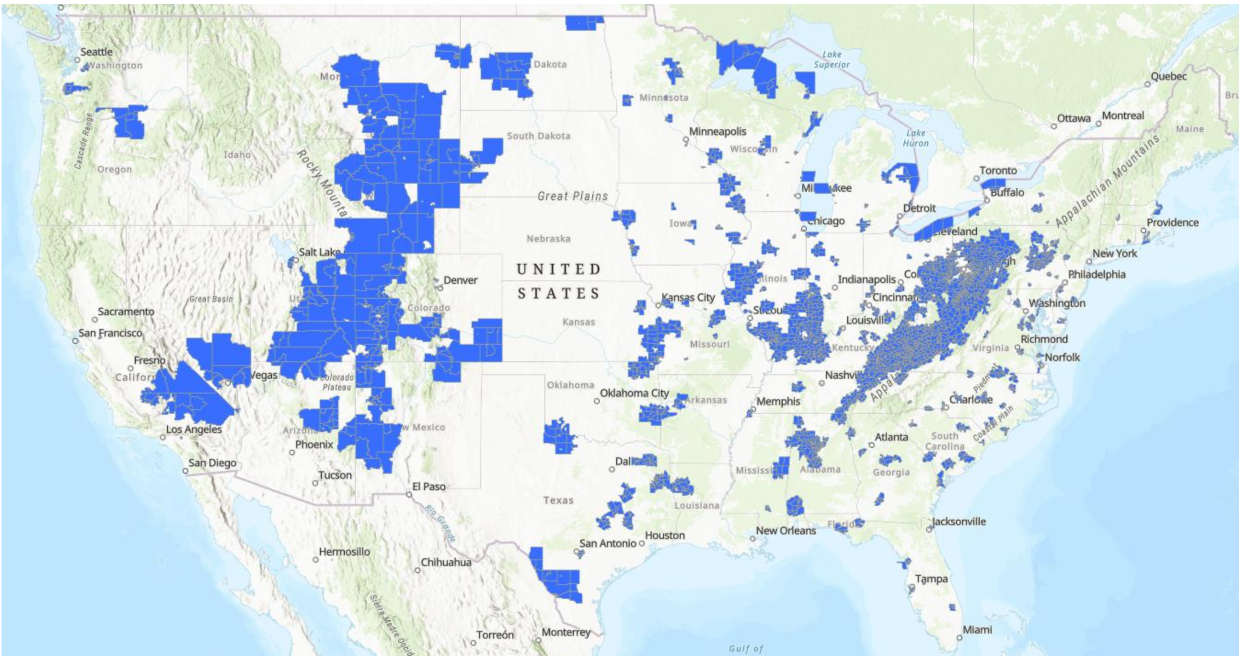

Figure A-2. Section 48C tax credits - designated energy communities. Source: U.S. DOE and NTEL (2023).

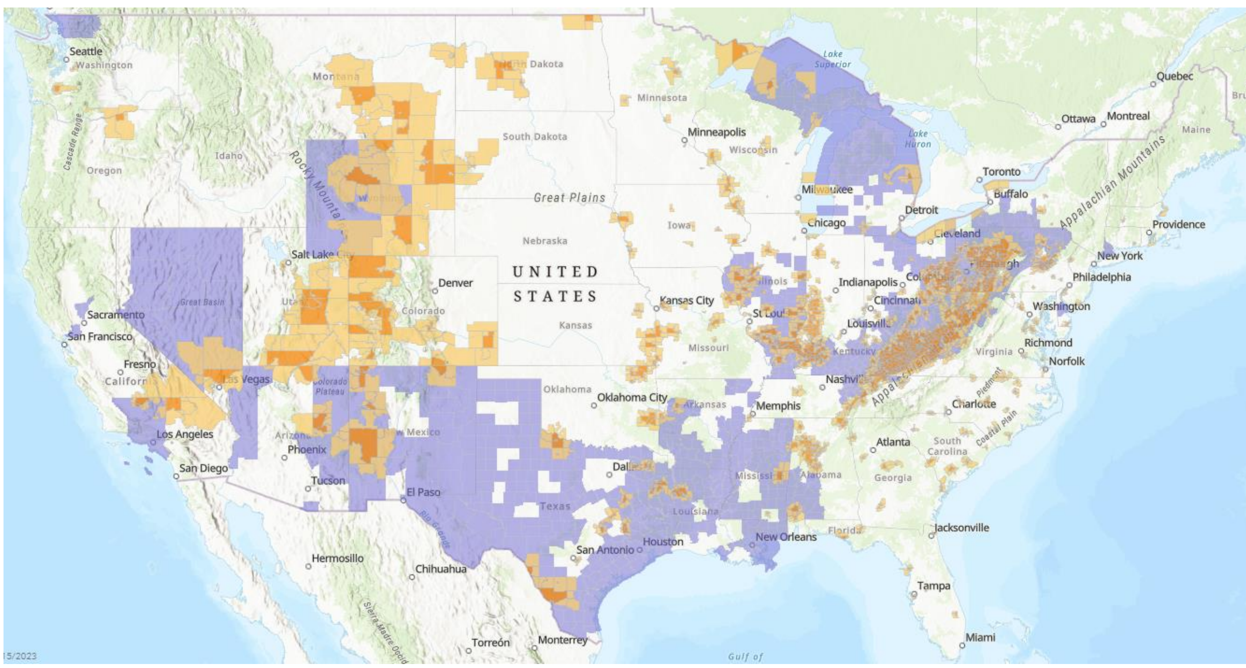

Figure A-3. Energy community tax credit bonus. U.S. DOE and NTEL (2023).