NBER
Energy and the Environment
The 32nd NBER-TCER-CEPR TRIO Conference

Few areas of economics are more relevant to current policy than energy and environmental economics. Climate change and other environmental issues are top priorities for national governments and multilateral organizations. And since energy use is the primary source of carbon emissions, addressing climate change requires a detailed understanding of often complex energy markets.

The organizers welcome submissions in all areas of energy and environmental economics and on related topics. Both theoretical and empirical work will be considered, and the research need not be related to Japan. Topics of particular interest include:

- Climate change
- The economics of nuclear and renewable energy
- Research that intersects with finance, corporate governance, public finance (e.g. financing of decarbonization investments) and international economics (e.g. carbon border adjustments).

Papers presented at the conference may be submitted to a special issue of the *Journal of the Japanese and International Economies* (*JJIE*), and authors are encouraged to consider this outlet for their work. If a paper is published in the *JJIE*, the author(s) will receive a total honorarium of JPY200,000, which can be divided among multiple authors. Papers submitted to the *JJIE* will undergo the normal journal reviewing process.

The deadline for submitting papers is **11:59pm, Boston time, on January 9th, 2025**. **Upload Papers**

Preference will be given to completed papers and to detailed drafts. Selected authors will be notified by January 24th, 2025. The NBER will cover travel and hotel expenses for one North America-based author of each paper to attend the conference.

The Economics of SMRs in Energy Production, Security, and Innovation: What Role Can They Play?

Ultimately, I want to talk about SMRs, the current energy landscape, and if and where SMRs can fit into it.

- What is a desirable energy mix? Where do SMRs come into play?
- What are the optimal use cases for this case? What is the risk (meltdown, disposal of nuclear waste)?
- Desire for renewables and carbon net zero initiatives
- Reports about large expected increases in energy consumption and need (data centers, AI, heating homes, etc.)
- Cost of SMRs
    - Estimations and actual
    - Technology is still in the early stages so costs are ballooning past expectations and projects are being delayed as the actual implementation faces setbacks
- Potential power capacity of SMRs and historical actual capacity
- Planned SMR projects, setbacks, partnerships
- SMR companies
- Types of SMRs

Use demand forecasting models to predict future demand for energy, whether renewables will meet that demand, and if SMRs can bridge the gap in estimated demand. Will analyze the life cycle cost of SMRs and other sources of energy production (renewable, gas, etc.). Determine probability of meltdown and effect of nuclear waste disposal (what kind of infrastructure is there for that?). Analyze the least amount of dead space around SMRs necessary and compare that to other sources of energy such as renewables. Key: determine the capability of SMR technology to speed up or slow down innovations in AI (think data centers). If SMRs are not produced quickly enough and running, what will this cost AI development? Can they turn to other sources of energy? Will that overwhelm the grid?

The term SMR (Small Modular Reactor) has been thrown about in recent years. In the last 2-3, however, the relevance of these miniaturized nuclear reactors has seen quite the uptick. An uptick that can be attributed to a large extent from such events as the development of energy security issues in Europe and the announcements several of the largest companies in the world have made in looking toward SMRs as solutions for the energy demand brought upon by data centers. This paper investigates whether SMRs have a role in the energy landscape, what role that would be, how such a role could be realized, and which entities would see the most benefit of SMR utilization.

What is an SMR exactly and how does it fit into the landscape of energy production and energy security? SMRs can be described as a small form of fission reactors, small and modular in size and design, allowing for offsite manufacturing and shipment to onsite locations. Commercial SMRs have been designed to deliver power output in the range of 5 MW_e and 300MW_e per module. First designed and utilized in the 1950s for military use in powering nuclear submarines and aircraft carriers, SMRs have since entered the limelight due to the interest of tech companies in utilizing them to power data centers. Such tech companies include the likes of ____ and ____, among others (add citation). The true cost of SMRs is a topic that is obfuscated by the variety of SMR designs, the lack of information, and the nascent nature of the technology. And while some critics believe that costs can be brought down if some sort of economies of scale is reached by firms, the threshold to do so and necessary market share continues to fail to be met. As such, many (who?) believe that SMRs are of a cost comparable to conventional large reactors (a lot of the last few sentences are paraphrased from https://en.wikipedia.org/wiki/Small_modular_reactor).

Only two SMRs are currently operational in the world, with none of them in the US. The first is a pair of KLT-40S deployed in Akademic Lokomosov (a floating nuclear power plant) and fully commissioned in May 2022, 2020. The other is a pair of HTR-PM reactors (both power one turbine) commissioned by the China National Nuclear Corp. on Dec. 6, 2023 (GRID CONNECTED ON DEC. 20, 2021 ?). Each KLT currently provides "heat to the town of Pevek and supplies electricity to the regional Chaun-Bilibino power system." (https://www.powermag.com/a-closer-look-at-two-operational-small-modular-reactor-designs/). Each KLT-40S has a capacity of 35 MWe (megawatt electric), making for a combined capacity of 70 MWe for both modules. The HTR-PM has a capacity of 210 MWe.

"Concerning the Chinese HTR-PM, the WNISR says, "Between January and December 2022, the reactors operated for only 27 hours out of a possible maximum of 8,760 hours. In the subsequent three months, they seem to have operated at a load factor of around 10 percent." The Russian units' performance has been nearly as dismal. "The operating records of the two KLT-40S reactors have been quite poor. According to the IAEA's PRIS [Power Reactor Information System] database, the two reactors had load factors of just 26.4 and 30.5 percent respectively in 2022, and lifetime load factors of just 34 and 22.4 percent. The reasons for the mediocre power-generation performance remain unclear," the report says."

- The World Nuclear Industry Status Report 2023 (WNISR)
    - https://www.worldnuclearreport.org/IMG/pdf/wnisr2023-v5.pdf
- https://www.powermag.com/a-closer-look-at-two-operational-small-modular-reactor-designs/

FIND ALL THREE, WHERE THEY ARE LOCATED, THEIR POWER OUTPUT, THEIR BUILD COST, THEIR MAINTENANCE COST, ETC.

In this paper, several SMR companies including NuScale[1], Energy Northwest[2], X-Energy, Dominion Energy, Kairos Energy[3], and ____ will be used as models for pricing, land use, time from ideation to build, power output, and more (if different types make a difference). *Information for current operational SMRs will also be used to estimate pricing and manufacturing timelines*.

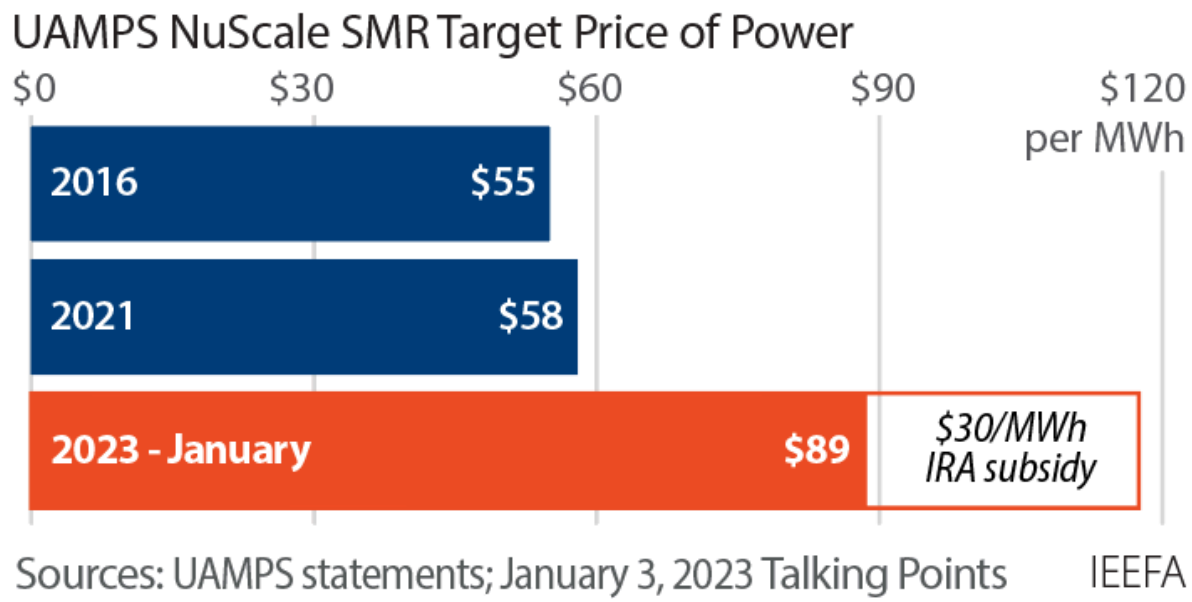
How much would the price of manufacturing SMRs need to go down to make them monetarily viable alternatives to renewables? How much would the per unit/module price need to go down? By how much do SMR companies underestimate the cost to production for their projects? What is a realistic estimation?

- Make a graph with horizontal bars representing the price of different renewables per unit of MWe, the price of specific fossil fuels per unit of MWe, the price of nuclear energy per unit of MWe, and the price of SMRs per unit of MWe
- Have graph of potential energy capacity (MWe) of each of the above sources of energy
- Have a graph of the amount of space (square feet and square meters) each source of energy takes up per 100 MWe of capacity (include uninhabitable zones around renewables, nuclear reactors, and SMRs)
- Have a graph of projected costs for various projects as well as estimated actual costs (based on a variety of factors; find the factors that could contribute to it; look at research related to this; maybe there is a model that can decently predict ballooning costs of major technology and infrastructure new projects; or maybe as an infrastructure project, the ballooning of its cost is expected to some extent (sources in HS2 rail in UK and California High Speed Rail projects))

Estimations for SMR projects, like any newer technology, are often uncertain at best. Take the NuScale and Utah Associated Municipal Power Systems (UAMPS) Carbon Free Power project for example. In 2020, the Department of Energy approved $1.35 billion over the course of 10 years for the planned multi-reactor 462 megawatt project (fact check what the project was when they got this funding). (https://www.reuters.com/business/energy/nuscale-power-uamps-agree-terminate-nuclear-project-2023-11-08/). The project fell through due to new estimates for the target price for power, largely driven by a substantial increase in construction cost (https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor). From 2016-2020, the target price of power was stated to be $55/MWh. This increased in 2021 to $58/MWh as the project was downsized from 12 reactors to six. In 2023, the target

[1] NuScale Power has partnered with Oregon State University (the developers of the first commercial SMR prototypes in the late 1990s and early 2000s) since 2006 to apply an economies-of-unit-mass-production manufacturing strategy.
[2] AWS announced an agreement to invest in the development of four SMRs from Energy Northwest
[3] On Oct. 14, 2024, Google revealed a power purchase agreement with SMR developer Kairos Energy

price drastically increased by 53% to $89/MWh when including a $30/MWh IRA subsidy. The construction price for the six reactors jumped significantly as well, from $5.3 billion to $9.3 billion, representing a 75% increase. At 6 reactors, the project was slated to cost $1.55 billion per reactor. That is, if the project's price hadn't further increased leading up to the 2030 launch date.



(https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor)

Looking back further, we see a similar situation of costs ballooning in that of the Akademic Lokomosov project (two SMRs). The cost of building Russia's floating nuclear power plant "spiked from an original estimate of 9 billion rubles ($140 million) in 2006 to a current 37 billion rubles ($740 million) official Russian sources report, citing government documents." (https://bellona.org/news/nuclear-issues/2015-05-new-documents-show-cost-russian-nuclear-power-plant-skyrockets). That aligns with $370 million a pop for each SMR. Compared with the estimated costs of the Carbon Free Power project ($1.55 billion per), it is about 23.87% of the cost. Looking at power, CFP, being a 462 megawatt project, was slated to have a per unit output of 77 megawatts. The Lokomosov project, on the other hand, reported that each plant would have a power output of 35 megawatts, 45% of the power the CFP reactors were supposed to display. If the report by the IAEA's PRIS (Power Reactor Information System) database mentioned earlier is taken into account where each reactor had lifetime load factors of just 34

and 22.4 percent, the average power output of each reactor is calculated to be (11.9 + 7.84) / 2 = 9.87 megawatts, just shy of 13% of what each CFP reactor was expected to produce.

Moving on to the HTR-PM reactors from China, it was estimated that "the specific cost for HTR-PM modules has been projected to be around 2000 $/KWe." (https://nucleus.iaea.org/sites/htgr-kb/HTR2014/Paper%20list/Track2/HTR2014-21416.pdf). With the estimated capacity of 210 MWe, this would amount to an estimated cost of $420 million. According to the 2023 World Nuclear Industry Status Report (WNISR), "Between January and December 2022, the reactors operated for only 27 hours out of a possible maximum of 8,760 hours. In the subsequent three months, they seem to have operated at a load factor of around 10 percent."

https://nucleus.iaea.org/sites/htgr-kb/HTR2014/Paper%20list/Track2/HTR2014-21416.pdf

Some might say it's impossible to compare nuclear energy to renewable energy. We'll attempt to do so anyway.

Energy Source	SMRs		
Project/type	CFP	Lokomosov	HTR-PM
Units	6	2	Pair that drive 1 turbine
Power output per unit	77 megawatts	35 megawatts	210 megawatts
IAEA power adjustment	N/A	9.87 megawatts	N/A
WNISR power adjustment	N/A	N/A	21 megawatts
Cost per unit	$1.55 billion	$0.370 billion	$210 million
Cost per MWe; (adjustments as applicable)	$20.13 million	$10.57 million; $37.49 million (IAEA adjusted)	$2 million; $20 million (WNISR)
Est. lifetime (yrs)			

https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/#:~:text=%241%2C300%2C000%20USD%20per%20megawatt.,on%20wind%20turbine%20operational%20cost.

https://www.solar.com/learn/solar-panel-cost/

It remains to be seen if another company or country for that matter can produce and go live with an SMR, hopefully with better efficiency than what has been reported for the only two operational projects. Companies like NuScale have promised…, however, as can be seen from the CFP, …

"Project Description

We are working with RoPower, owned by Nuclearelectrica and Nova Power & Gas S.A., to deploy a VOYGR-6 SMR power plant in Doicesti, Romania by the end of the decade. The plant will generate 462 MWe of carbon-free electricity, and is estimated to create 193 permanent power plant jobs, 1,500 construction jobs, and 2,300 manufacturing jobs.
The project's focus is on repurposing retired coal plant sites. This supports the Government of Romania's National Recovery and Resilience Plan to phase out 4.59 GWe of coal fired energy production by 2032.
"The Nuclearelectrica team, based on its track record of operating at nuclear safety as one of the safest performing nuclear plants in the world, has the experience, knowledge and professional skills to embark alongside NuScale for the first deployment of a small modular reactor in Europe. " - Cosmin Ghita, CEO Nuclearelectrica"

https://www.nuscalepower.com/en/projects

Energy Source	SMRs			Wind	Solar
Project/type	CFP	Lokomosov	HTR-PM	Turbine	Panel
Units	6	2	Pair that drive 1 turbine	1	1
Power output per unit	77 megawatts	35 megawatts	210 megawatts	2-3 MW (onshore); 16-18 MW (offshore)	Monocrystalline panel avg. 400 watts
IAEA power adjustment	N/A	9.87 megawatts	N/A	N/A	N/A
WNISR power adjustment	N/A	N/A	21 megawatts	N//A	N/A

Cost per unit	$1.55 billion	$0.370 billion	$210 million	~$3.25 million; ~$22.1 million	$400-500
Cost per MWe; (adjustments as applicable)	$20.13 million	$10.57 million; $37.49 million (IAEA adjusted)	$2 million; $20 million (WNISR)	$1.3 million	$1.13 million
Lifetime (yrs)					

AI Overview:

The amount of power a data center requires depends on its size, purpose, and the efficiency of its equipment:

Small data centers
These are typically 5,000–20,000 sq ft and have 500–2,000 servers, consuming 1–5 megawatts (MW) of power.
Large data centers
These can be 100,000 sq ft to several million sq ft and have tens of thousands of servers, consuming 20–100 MW of power.
AI data centers
These can consume tens to hundreds of MW of power, depending on their size, scale, and the AI tasks they support.

Links:

- https://www.datacenterknowledge.com/energy-power-supply/data-center-power-fueling-the-digital-revolution
- https://www.integrityenergy.com/blog/is-data-center-energy-usage-driving-up-my-energy-bills/#:~:text=How%20much%20power%20does%20a,to%20power%20200%20American%20households.
- https://www.middletowndatacenter.com/resources/blog/post/data-center-power-consumption-in-the-us#:~:text=to%20681%20megawatts.-,How%20Much%20Energy%20Do%20AI%20Data%20Centers%20Use?,responsible%20growth%20of%20AI%20technologies.

In 2022, worldwide data center energy consumption was 260–360 TWh (terra watt hour). However, data center power demand is expected to grow:

- **Goldman Sachs Research**: Estimates that data center power demand will grow 160% by 2030.
- **Newmark**: Reports that US data center power consumption is expected to double by 2030.

Links:

- https://www.goldmansachs.com/insights/articles/AI-poised-to-drive-160-increase-in-power-demand
- https://www.datacenterdynamics.com/en/news/us-data-center-power-consumption/#:~:text=Existing%20markets%20are%20already%20struggling,the%20first%20half%20of%202025.

It is important to note that current SMRs and proposed designs thereof, use nuclear fission reactions, the action of splitting atoms (usually uranium atoms). This splitting of atoms releases energy, including nuclear radiation, and introduces the problem of finding a way to reliably and sustainable dispose of the released nuclear waste.

France

- How are they used here?
- How else could they be used?
- Saturation point of SMRs?

USA

- Any current use?
- Proposed uses
    - Data centers (Microsoft and other companies)

Romania

- NuScale SMRs

Japan

China

SMRs

- How much power do they generate?
    - Is it enough?
- Cost?
- How difficult is it to connect to the power grid?

- From preliminary research, all current SMRs use fission reactions, releasing nuclear waste. The disposal of such waste is a topic of contention
- https://en.wikipedia.org/wiki/Small_modular_reactor
- Land use
    - Local jurisdictions and regulations
    - Size

- Look into how many SMRs would have to be implemented in certain scenarios, if there are companies that can even provide that many in a realistic timeframe, if and where renewables could play a part (supplementing), and whether fossil fuels would need to be turned to in certain scenarios until other energy sources catch up to the necessary demand
    - E.g. data centers take a lot of energy and the amount that companies desire to create and spin up would require atrocious amounts of energy, something which the current SMR landscape would likely not be able to handle and a gap which the supplementation of renewables may not be able to bridge. Enter fossil fuels potentially

Model for likelihood of implementing SMR project.

- Country? Company?
- Energy makeup of location proposed and for which entity (country, region, company, etc.)
- Location
- Cost
- Extent of land use
- Regulations

Model for likelihood and the extent of benefit with implemented SMR project.

- Which SMRs? Types? Models?
- Where will the SMRs be?
- Energy needed in the area?
- How much energy can the SMR supply?
- Cost associated with building the SMR in the area. Opportunity cost for not building renewables such as wind or solar. Need to add that certain areas are not very viable for wind or solar.
- Net Benefit of SMR unit = marginal Benefit of SMR unit - (marginal cost of SMR unit + (marginal benefit of renewable alternative - marginal cost of renewable alternative))
- $NB_{SMR} = MB_{SMR} - (MC_{SMR} + (MB_{Re} - MC_{Re}))$
- NB of SMR = MB of SMR - (MC of SMR + opportunity cost of not implementing renewable)

- Marginal benefit in being able to meet energy demand and ensure energy security and stability

Marginal benefit is a small but measurable benefit to a consumer if they use an additional unit of a good or service. It usually declines as a consumer decides to consume more of a single good. Marginal benefit is often expressed as the dollar amount the consumer is willing to pay for each purchase. The formula for marginal benefit is:

Marginal Benefit = Change in Benefit ÷ Unit Change

Resources:

https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors

https://www.powermag.com/a-closer-look-at-two-operational-small-modular-reactor-designs/

https://en.wikipedia.org/wiki/Small_modular_reactor

- Used to find other resources and to gain understanding on the topic

https://www.goldmansachs.com/insights/articles/AI-poised-to-drive-160-increase-in-power-demand

https://www.datacenterdynamics.com/en/news/us-data-center-power-consumption/#:~:text=Existing%20markets%20are%20already%20struggling,the%20first%20half%20of%202025.

https://www.datacenterknowledge.com/energy-power-supply/data-center-power-fueling-the-digital-revolution

https://www.integrityenergy.com/blog/is-data-center-energy-usage-driving-up-my-energy-bills/#:~:text=How%20much%20power%20does%20a,to%20power%20200%20American%20households.

https://www.middletowndatacenter.com/resources/blog/post/data-center-power-consumption-in-the-us#:~:text=to%20681%20megawatts.-,How%20Much%20Energy%20Do%20AI%20Data%20Centers%20Use?,responsible%20growth%20of%20AI%20technologies.

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https://bellona.org/news/nuclear-issues/2015-05-new-documents-show-cost-russian-nuclear-power-plant-skyrockets

https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor

https://www.reuters.com/business/energy/nuscale-power-uamps-agree-terminate-nuclear-project-2023-11-08/

https://www.worldnuclearreport.org/IMG/pdf/wnisr2023-v5.pdf