The State and Outlook for Nuclear Generation

Charging Ahead Webinar

November 18, 2025

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Agenda and Housekeeping

Agenda

- Housekeeping and Introductions
- Nuclear Policy
- Key Technologies and Performance Indicators
- Competitiveness
- Review Charging Ahead Webinars

Housekeeping

This webinar is being recorded and distributed to all registrants along with this presentation

Add your questions to the chat. My colleague, Sara Gonzales, is monitoring the chat for the Q&A session

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Ezra Beeman

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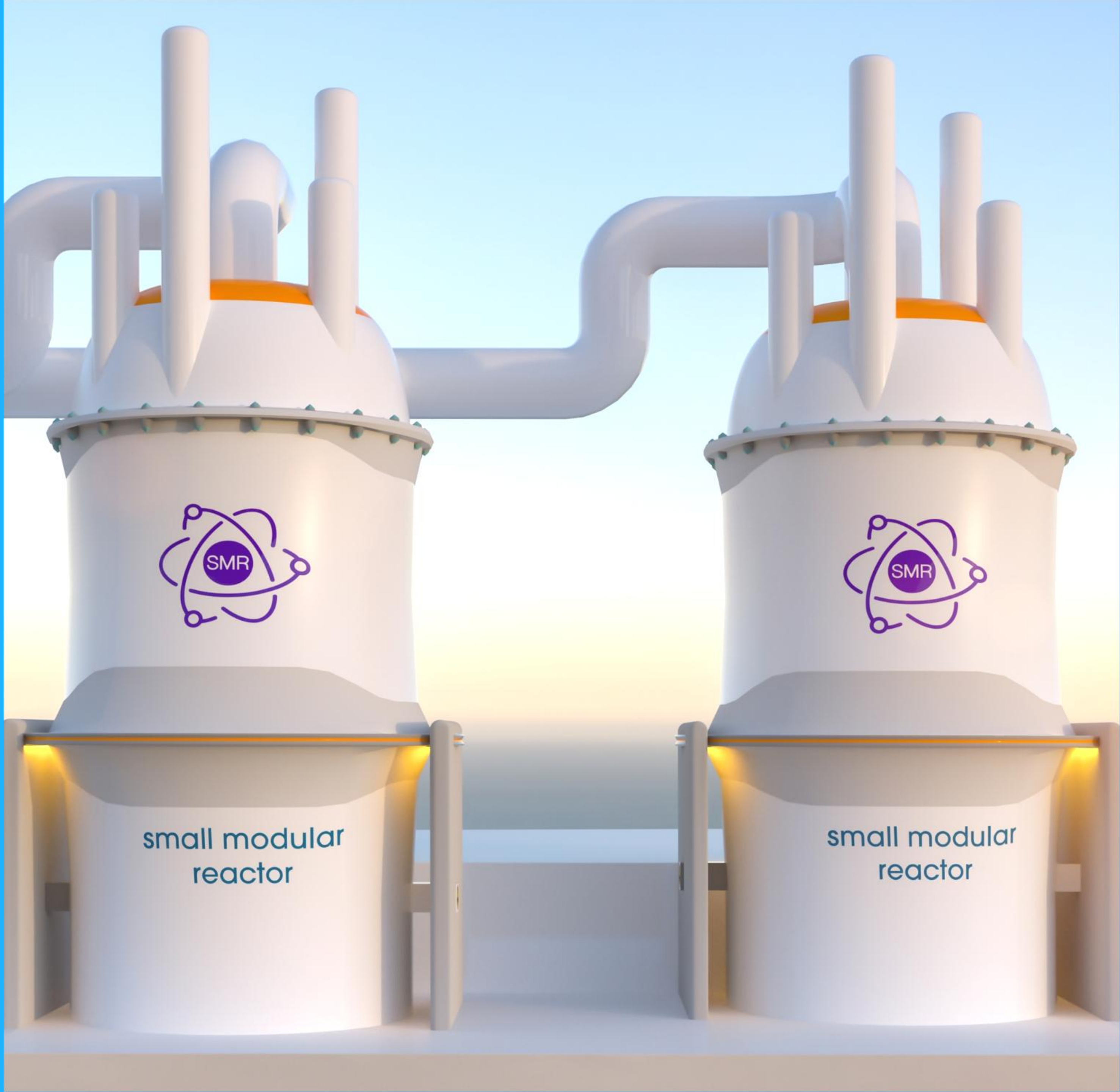
Nuclear Policy

United States

Targets

Incentives



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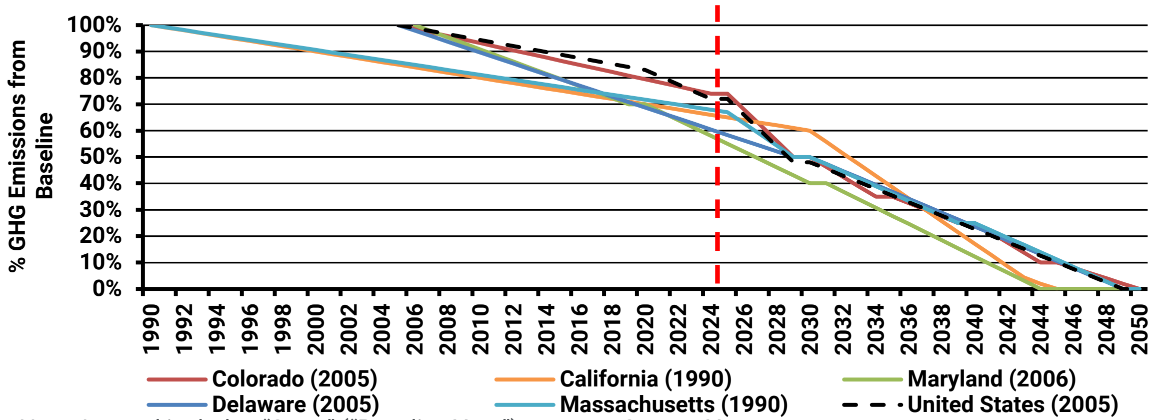
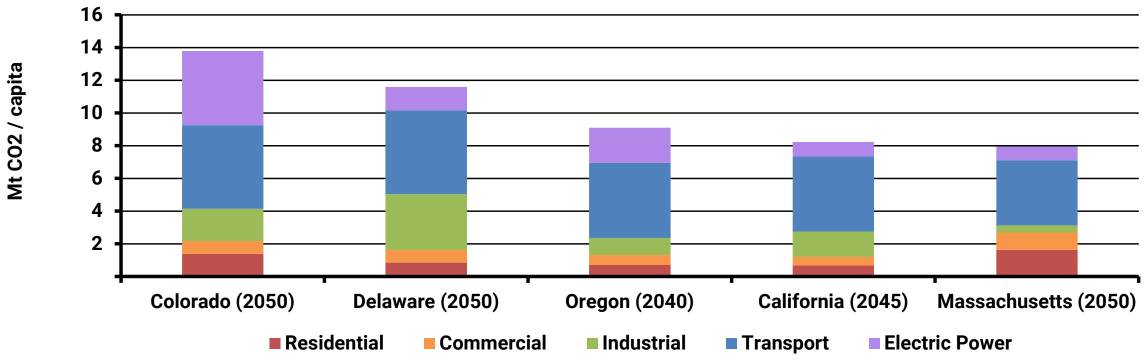
CO2 Targets and Sources by Key State

Leading State and Federal CO2 Targets



Note: Legend includes "State" ("Baseline Year")
Source: Energeia Research, US EIA (2023)

Leading States Emissions per Capita by Sector



Note: labeling includes "State" ("Target Year")
Source: Energeia research and analysis, US EIA (2025)

- The United States had adopted a trajectory to reduce emissions by 50-52% of 2005 baseline levels by 2030 under its NDC to the Paris Agreement, but is expected to alter or scrap the targets per the withdrawal from the Paris Agreement
- State CO2 targets vary substantially in terms of:
  - Baseline year
  - Target sectors
  - Trajectory
- California (CA), Colorado (CO), Massachusetts (MA), and Maryland (MD) are undertaking some of the most comprehensive climate action plans, driven by state policy
  - Note: States with the most comprehensive CO2 roadmaps have been included, but may not represent the states with the most stringent targets

A key question is would nuclear generation reduce the cost of these state's power system transition to zero carbon?

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Global Nuclear Policy – Targets

Summary of Worldwide Nuclear Targets											
Target Type	**USA**	**EU**	**UK**	**France**	**Russia**	**China**	**Japan**	**South Korea**	**India**	**Canada**	**Finland**
Total Target Installed Capacity	400 GW by 2050	109 GW by 2050	24 GW by 2050			200 GW by 2035			100 GW by 2047		
New Capacity	~300 GW by 2050	~10 GW by 2050	~18 GW by 2050	6 New Reactors		~145 GW by 2035			~90-95 GW by 2047		2 New Reactors
Share of Genera-tion					23.5% by 2042	15% by 2050		34.6% by 2036			
Exports						Targetin g BRI Nations		Export 10 Nuclear Plants by 2030			
Other					Full Recyclin g of Fuel						

- The US has the largest total and new nuclear capacity targets internationally
- Canada is a current world leader in nuclear energy, but notably has no explicit targets
- France reversed their 2014 policy to lower nuclear penetration from 70% to 50% in 2022, now plans to install 6 new reactors
- A notable exception to this nuclear renaissance is Japan, who are expected to reduce their overall dependence on nuclear going into the future
- Global targets represent potential markets for US nuclear generation technology, with the US targets providing platform for their development and showcasing

Source: Energeia Research

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Global Nuclear Policy – Incentives

Summary of Worldwide Nuclear Incentives

Funding Type	USA	EU	UK	France	Russia	China	Japan	South Korea	India	Canada	Finland
Loans	Federal loans and loan guarantees			Gov. discounted loan for half the build costs (estimated to be over 50 billion euros)		State-backed loans cover around 70% of the cost of Chinese reactors (27.5 billion USD in 2025)		Low-interest loans up to $7.5 million ($USD)		Financing available under the Green Bond Framework	
Subsidies	Civil Nuclear Credit Program ($6 billion Total Investment)		Use a CfD and RAB model to ensure nuclear investors secure a return on investment (GBP 4-19 billion)	Use a CfD model to ensure nuclear investors a guaranteed energy sell price		Gov. providing financing and subsidies, including feed-in tariffs			$3 billion ($USD) budget for the Department of Atomic Energy	$55 million ($CAD) grant for three small modular reactor projects	
Tax Incentive	Tax credit of 0.3c/kWh ($USD) for gross generation									30% tax credit for small modular reactors	

- Countries are commonly funding the nuclear energy development through federal subsidies and loans
- South Korea’s incentive is almost zero

Source: Energeia Research; Note: CfD = Contract-for-Difference, RAB = Regulatory Asset Base

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Key Nuclear Technologies – Definitions

Nuclear Reactor Technologies

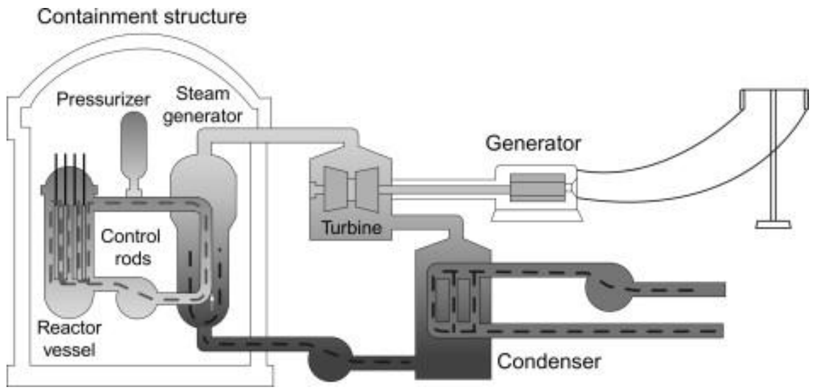
Type	Definition
Pressurized Water Reactor	Pressurized Water Reactors (PWR) are the most common type of nuclear reactor present today and uses either pressurized light or heavy water to both moderate and cool the reactor core. The heat is transferring from the reactor core into a secondary steam circuit to drive turbines
Boiling Water Reactor	Boiling Water Reactors (BWR) are the next most common type of nuclear reactor present today, where light water that's used to cool and moderate the reactor core is directly boiled in the reactor vessel into steam. This steam is then sent straight from the reactor to the generator turbines to produce electricity
Molten Salt Reactor	Molten Salt Reactors (MSR) use molten fluoride or chloride salts as the reactor coolant and in some designs, the fuel carrier. The fission energy that is absorbed by the molten salt is transferred to a secondary fluid circuit which is used to drive turbine generators
Fast Neutron Reactor Sodium Fast Reactor Lead Fast Reactor Gas Fast Reactor	Fast Neutron/Breeder Reactors (FNR/FBR) use fast neutrons, no neutron moderator, to sustain the reaction. Sodium, Lead, and Gas Fast Reactors (SFR, LFR, GFR) use liquid Sodium, Lead, or Helium Gas as the coolant, transferring fission energy into a secondary fluid circuit to generate electricity
High Temperature Gas Reactor	High Temperature Gas Reactors (HTGR) use Helium gas as a coolant, with the reactor running at very high temperatures (1,000°C), and relatively low pressure. HTGR's can be used for process heat generation as well as electricity generation
Supercritical Water Reactor	Supercritical Water Reactors (SCWR) operate similar to BWR's, except rather than allowing the coolant to boil into steam, the coolant is kept supercritical and transferred directly to the generating turbines. SCWR's are designed to operate in a very similar manner to traditional fossil-fuel plants
Small Modular Reactor	Small Modular Reactor (SMR) is an umbrella term for compact nuclear reactors designed to be mass-produced in factories and transported to site, typically producing 30-300 MWe of electricity
Microreactor	Microreactors are small nuclear reactors under 20 MWe that are factory-built, easily transportable, and self-regulating. Their compact, safe design allows quick deployment with minimal staffing needs. They can operate for up to 10 years without refueling, integrate smoothly with renewables, and provide power and/or heat, including black start.

Source: Energeia Research

- Generation IV nuclear reactors indicated in light green aim to be the next step in reactor designs, promising improvements to nuclear sustainability, economics, safety and reliability, and proliferation resistance
- They are still novel, with limited to-date grid deployment
- However, with nuclear becoming increasingly prospective for generating flat (data centers), clean electricity, as well as the slated construction of Gen IV nuclear reactors, they're expected to capture a greater worldwide generation market share
- Small modular reactors are indicated in light blue, as this approach can be applied to the other reactor technologies
    - It is mainly a design philosophy around standardization, modularity, etc.

Conventional Technology - Installations by Type

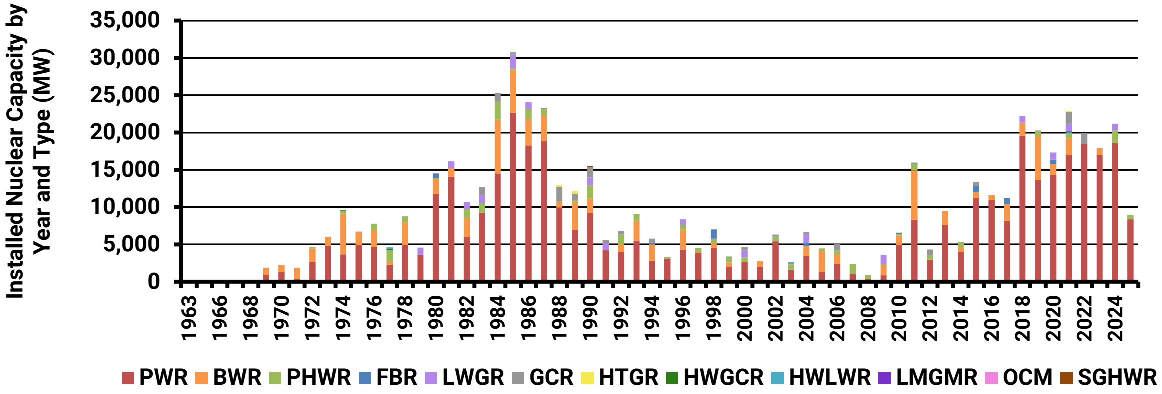
Pressurized Water Reactor



Source: United States Nuclear Regulatory Commission

- The most common nuclear reactor technology that is used today is the Light Water Reactor (LWR)
  - The two most common types of LWR's are the PWR and the BWR, which have a global market share of 71% and 14% respectively
  - Their operation mechanism is similar, except that a PWR transfers heat through two fluid circuits, compared to a BWR, that only uses a single fluid circuit
- There are variants of these designs that use Heavy Water (D2O) in the reactor vessel, such as the Pressurized Heavy Water Reactor (PHWR - 11% of market share), but the method of operation is still the same

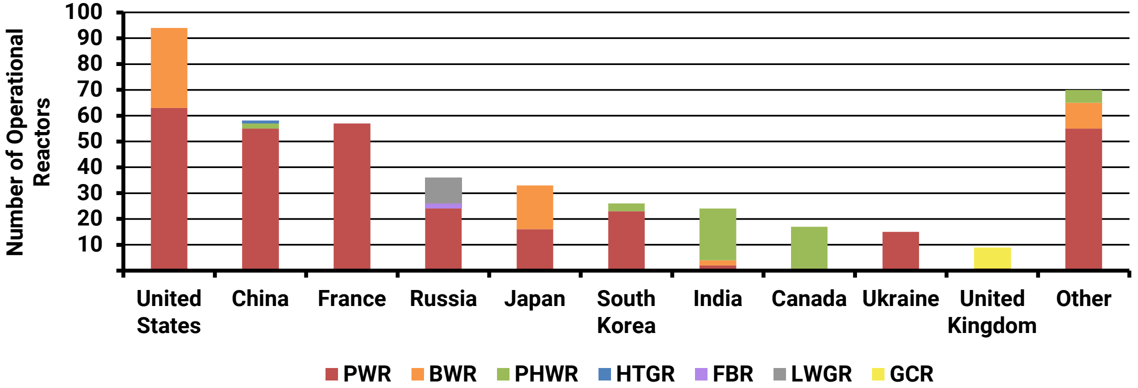
Historical and Future Installed Nuclear MW by Year and Type



Source: World Nuclear Association

Note: PHWR – Pressurized Heavy Water Reactor, FBR – Fast Breeder Reactor, LWGR – Light Water Graphite Reactor, GCR – Gas Cooled Reactor, HTGR – High Temperature Gas Reactor, HWGCR – Heavy Water Gas Cooled Reactor, HWLWR – Heavy Water Light Water Reactor, LMGMR – Liquid Metal Graphite Moderated Reactor, OCM – Organically Cooled and Moderated Reactor, SGHWR – Steam Generating Heavy Water Reactor

Nuclear Reactor Counts by Country and Type



Source: World Nuclear Association. Note: PHWR – Pressurized Heavy Water Reactor, HTGR – High Temperature Gas Reactor, FBR – Fast Breeder Reactor, LWGR – Light Water Gas Reactor, GCR – Gas Cooled Reactor

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Nuclear Retirements and New Technology Developers

New Nuclear Technology by Company

Proposer	High Temperature Gas Reactors	Light Water Reactors	Molten Salt Reactors / Molten Chloride Fast Reactors	Sodium Cooled Reactors	Microreactor Design	Other Designs
Count	**8**	**8**	**5**	**5**	**9**	**7**
Energy Northwest	✓					
General Atomics	✓					
General Atomics Electromagnetic Systems	✓					
Radiant Industries, INC.	✓				✓	
Terra Innovatum (SOLO)	✓				✓	
University of Illinois at Urbana-Champaign - NANO Nuclear Energy Inc.	✓				✓	
X-Energy, LLC (XE-100)	✓					
X-Energy, LLC (XENITH)	✓					
Deep Fission		✓				
GE-Hitachi BWRX-300		✓				
Hadron Energy, Inc.		✓				
Last Energy		✓			✓	
REPLOY Power, Inc.		✓				
Rolls-Royce SMR Limited		✓				
SMR, LLC (Holtec)		✓				
Westinghouse AP300		✓				
Abilene Christian University			✓			
Kairos Power, LLC			✓			
Natura Resources			✓			
TerraPower, LLC			✓			
Terrestrial Energy USA, INC.			✓			
Aalo Atomics				✓	✓	
Antares Nuclear, Inc.				✓	✓	
ARC Clean Technology				✓	✓	
Oklo Inc.				✓		
TerraPower & GE - Hitachi Natrium				✓		
Appalachian Power Company						✓
Blue Energy, Inc.						✓
Duke Energy - Belews Creek, NC						✓
Japan Atomic Energy Agency						✓
Shepherd Power, LLC					✓	✓
Texas A&M University - RELLIS Campus						✓
Westinghouse eVinci					✓	✓

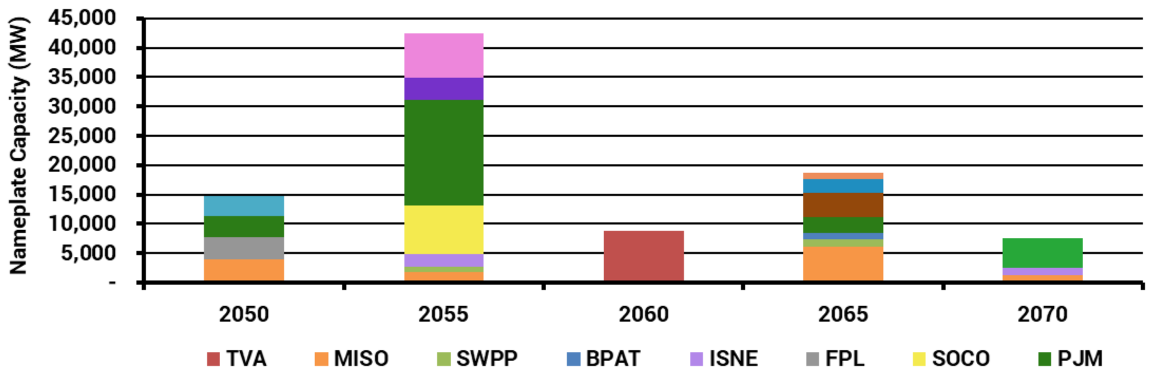
Source: United States Nuclear Regulatory Commission

= Microreactor Design

= Early Stages of Design or Research

- Nuclear power stations have 80-year design lifetimes, meaning that very few are scheduled to retire anytime soon
- The market for nuclear power is therefore not replacement, though there may be an opportunity for early repowering
- Most demand is expected to come from replacement of coal and gas fired generation, as well as data center load growth
- The potential market is driving investment in a significant number of new players across a wide range of technology

Nuclear Retirements by Year and Market



Source: EIA, Energeia Research

Small Modular Reactors – Current Projects

Proposed Reactors in the US

Vendor	Utility	Site	Type	Siting		CPA		Nuclear Construction	
				Start Year	End Year	Start Year	End Year	Start Year	End Year
TerraPower	Pacificorp	Kemmerer, WY	Advanced Nuclear Reactor	2021	2024	2024	2026	2026	2031
GEHitachi	(TVA)	Clinch River, TN	Advanced Nuclear Reactor	2016	2019	2025	2027	2027	2033
Holtec International	Holtec International	Palisades, MI	Pressurized Water Reactor	2023	2027	2026	2027	2028	2030s
xEnergy	Dow Chemical	Seadrift, TX	Advanced Nuclear Reactor	2023	2024	2025	2027	2028	2030s
xEnergy	Energy Northwest	Washington State	SMR	2023	2026	2026	2028	2029	2030s

Source: Energeia Research; Note: TVA = Tennessee Valley Authority, OPG = Ontario Power Group

- SMRs have seen limited grid-connection deployment worldwide to date, with Russia and China leading SMR deployment to date
- The US has plans to catch-up, with two projects aiming to come online before the end of the decade
- SMR projects are not limited to conventional PWR designs, there are reactors in operation and being constructed that use advanced reactor technologies, such as:
  - High Temperature Reactors
  - Fast Breeder Reactors, and
  - Molten Salt Reactors
- SMR pilots are currently targeting
  - ~3-5 year deployment times
  - ~$5-10m ($/M) unit rates
- However, actual delivery times and costs for the planned projects is TBC

Small Modular Reactors Under Construction

Country	SMR Name	Completion Year	Build Years	Capacity (MW)	Budget ($USD/MW)	Technology
China	ACP100	2026	5.4	125	$6.3 Million	Pressurized Water Reactor
Russia	BREST-OD-300	2026	5	300	$6 Million	Sodium Fast Reactor
Russia	RITM-200S	2027	5	300	$6 Million	Pressurized Water Reactor
Argentina	CAREM-25	2027	3	32	$3.6 Million	Pressurized Water Reactor
USA	Hermes	2027	2.5	70	$6 Million	Molten Salt Reactor
Canada	BWRX-300	2030	5	300	$18.5 Million	Boiling Water Reactor

Grid-Connected Small Reactors Operating

Country	SMR Name	Completion Year	Build Years	Capacity (MWe)	Budget ($USD/MW)	Technology
Russia	KLT-40S	2020	11.5	70	$10.5 Million	Pressurized Water Reactor
China	HTR-PM	2023	9	210	$5 Million	High Temperature Gas Reactor

Source: World Nuclear Association, Energeia Research

Summary of Key Nuclear Reactor Technologies

Comparison of Key Nuclear Reactor Technologies

Name	Cost ($/MW)	Lead Time (Years)	Sizing (Min MWs)	Ramping (% MW / Min)	Maintain Time (%/Year)	Min Load (%)	Water (kL/MWh)	Restart Costs ($/MW)	Maturity (Total MWs)	Availability (Years)
Conventional Nuclear Reactor Technologies										
Light Water	$3.8 Million	7.5	1,000	5%	5%	20-50%	2	-	511,807	80 Years
Small Modular – Pressurized Water	$20.1 Million	2.5	10	10%	2%	20%	1.2	-	70	60 Years
Generation IV Nuclear Reactor Technologies										
Molten Salt Reactor	$7 Million	2.3	10	12%	-	-	-	-	0	12 Years
Sodium Fast Reactor	$4.2 Million	4.5	50	8%	18%	30%	-	-	5,001	60 Years
Lead Fast Reactor	$13.2 Million	3.0	50	-	12%	-	-	-	300	60 Years
Gas Fast Reactor	-	3.5	40	20%	-	-	-	-	0	60 Years
High Temperature Gas Reactor	$6.8 Million	8.5	24	-	-	25%	-	-	296	60 Years
Supercritical Water Reactor	$3.8 Million	-	-	-	-	-	-	-	0	60 Years

Source: Energeia Research

- Key issues with nuclear technology in the past has included cost overruns, minimum sizing, flexibility, leaks and waste disposal
- A new generation of technology is promising to address these concerns, the question is, will they be competitive?
- Competitiveness is defined by the cost of generation to meet load, which is driven by:
  - Capex ($/MW)
  - Fixed Opex ($/MW/year)
  - Variable Opex ($/MWh)
  - Planned and Unplanned Outages
  - Ramp Rates (% MW/min)
  - Minimum Load (% MW)
  - Restart Costs ($/MW/Cycle)
  - Water Requirements
- Our research suggests that data is difficult to find on some of the key metrics

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Conventional vs. Small Modular Reactors

Conventional vs Small Modular Reactors (PWR)		
Parameter	**Conventional Nuclear Reactors**	**Small Modular Reactors**
Levelized Cost of Energy ($USD/MWh) in 2030	$84 (NREL)	$96 (NREL)
CAPEX ($/kW) in 2030	$7,616 (NREL)	$9,650 (NREL)
Construction Time (Years)	7	3-5
Minimum Sizing (MW)	1,000	300
Safety / Leaks	Significant Measures in Place	Significant Measures in Place
Ramp Rate (/min)	5%	Control Rods: 3.3% down, 0.8% up[1] Turbine Bypass: 10% down, 3.0% up[1]
Capacity Fator (%)	93%	93%
Minimum Run (%)	20%-50%	20%[1]
Planned Outages	1 Month every 18-24 Months	10 days every 18-20 months[1]
Waste Management	Significant waste management required	Significant waste management required
Water Requirements (L/MWh)	1,500-2,700	950-1,500[1]

Source: Energeia Research, NREL (2024), IAEA
[1]based on current NuScale SMR estimates
[2]https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

- The table compares a conventional PWR to a small modular reactor
- Small Modular Reactor (SMR) is an umbrella term for reactors with the following features determined by the International Atomic Energy Agency (IAEA)[2] and World Nuclear Association (WNA)
  - Reactors and other major components are designed to be standardized
  - Smaller physical footprint
  - Designed with inherent passive cooling, in the case of a power failure
  - Minimum capacity 30-300 MWe, which can be daisy-chained
- Estimates for the SMR are based on NuScale, which is not yet fully commercialized, but is the only SMR to be certified by the US nuclear regulatory commission

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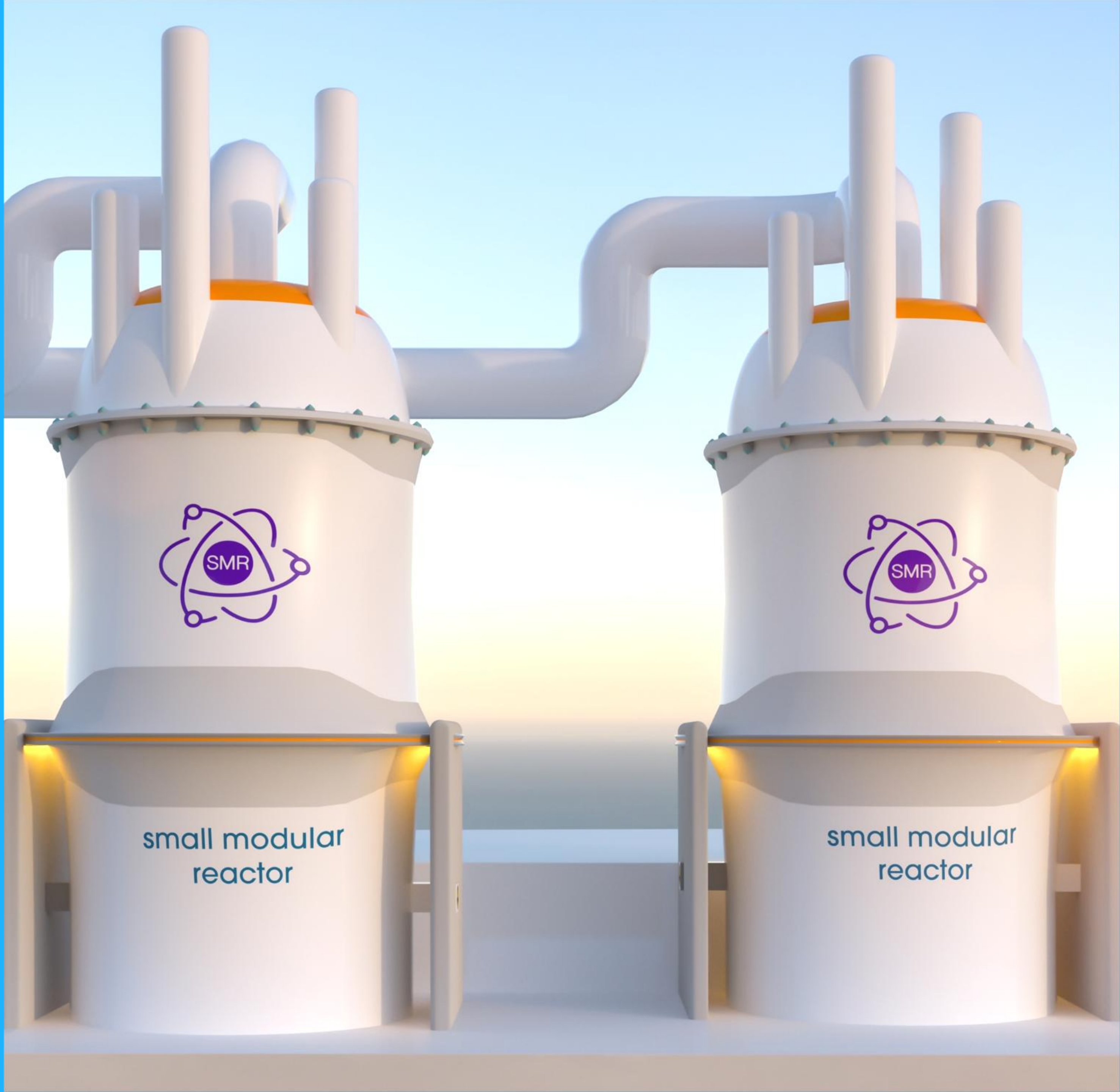
Cost Competitiveness

CAISO Case Study

Data Center Case Study



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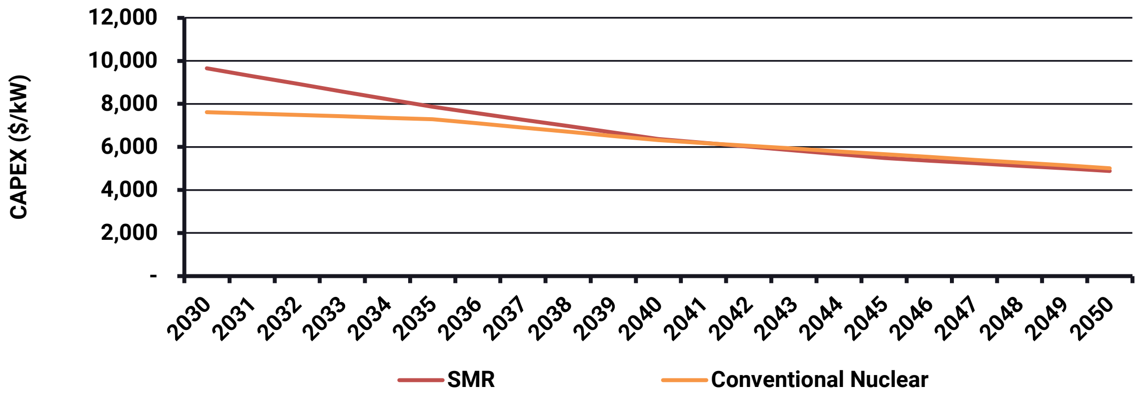
US Nuclear Generating Cost Outlook

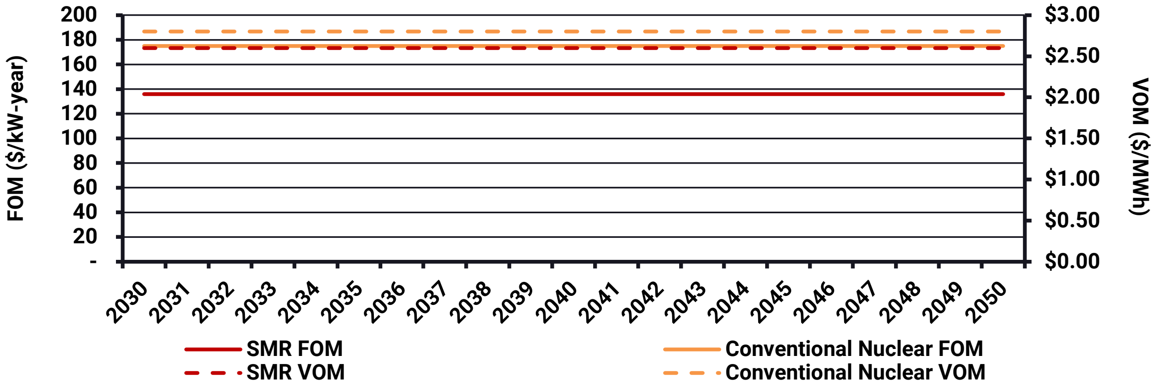
NREL Nuclear Capex Outlook



Source: NREL Annual Technology Baseline (ATB) (2024)

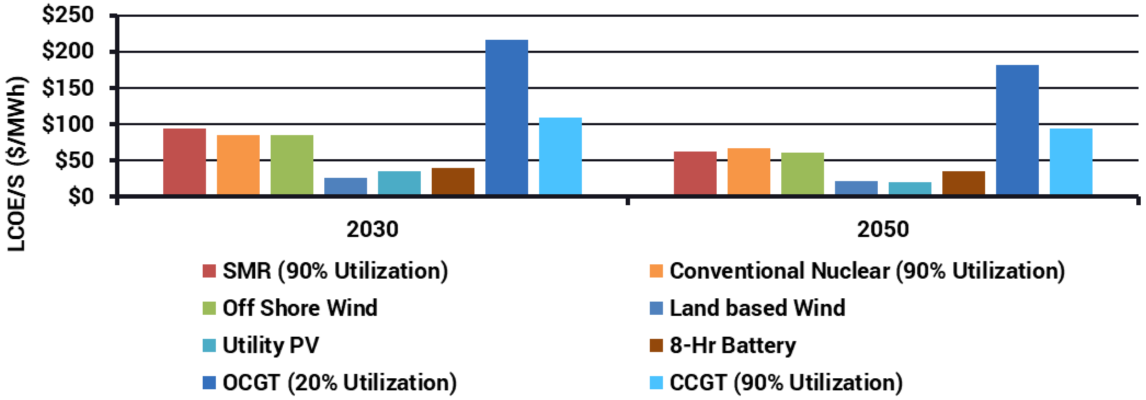
- NREL is currently forecasting a 50% reduction in SMR capex to 2050
- No reduction seen in fixed or variable operating expenditure over the period
- SMR fixed operating costs are shown as substantially lower than conventional operating costs
- On a levelized, $/kWh basis, which is a very simplified view, 90% utilized SMRs are comparable to
  - Intermittent offshore wind
  - Combined cycle gas turbines (CCGT)s at 90% utilization
  - Open cycle gas turbines (OCGT) at 20% utilization

NREL Nuclear FOM + VOM Outlook



Source: NREL ATB (2024)

Wind, Solar, 8-Hr Battery, Nuclear, OCGT, and CCGT LCOE/S



Source: NREL ATB (2024), Energeia Research
Note: Assumes 30 MW, 8-Hr Battery

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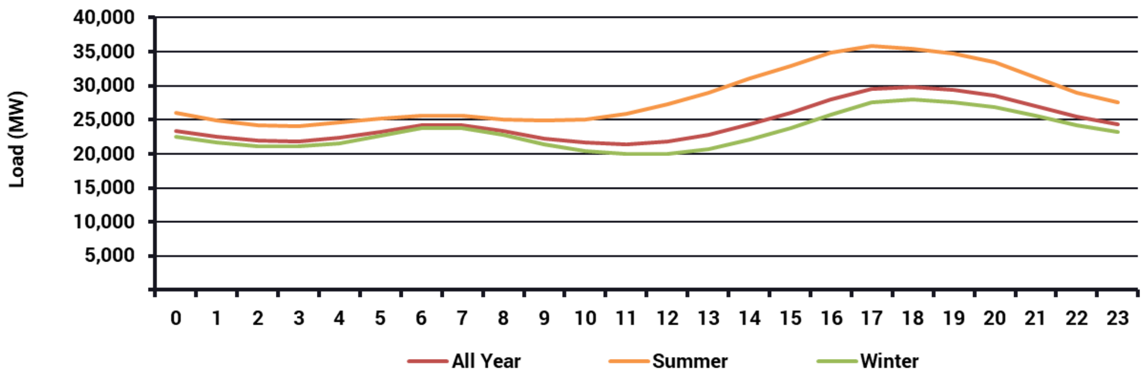
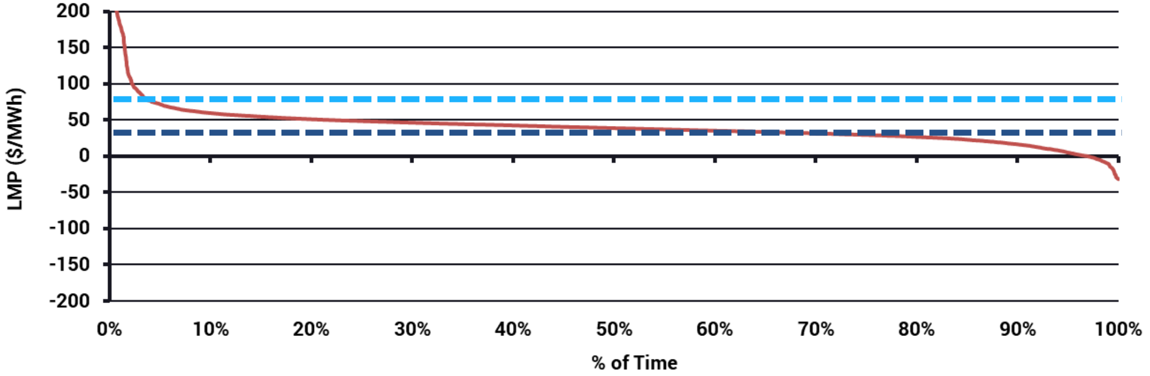
Bulk System Load and Price Duration in CAISO in FY24

CAISO Average All, Summer and Winter Days (2024)



Source: CAISO, Energeia Analysis

CAISO NP15 Price Duration Curve (2024)



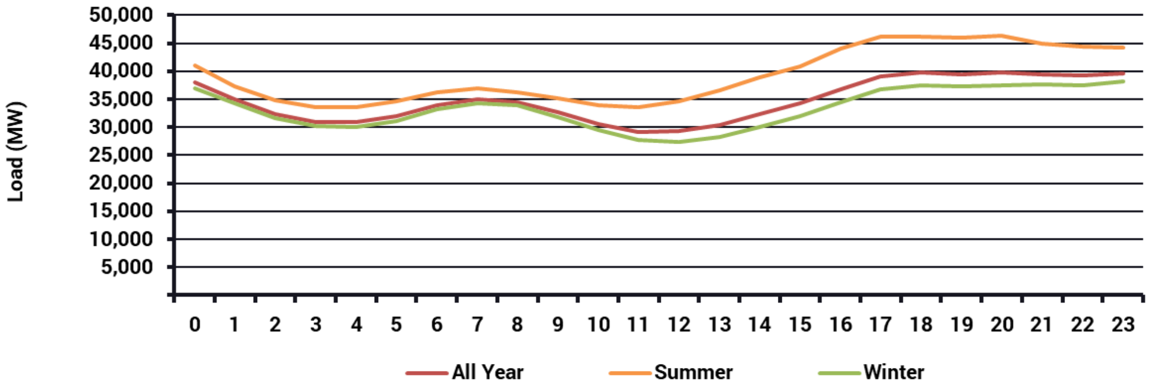
Note: = SMR Cost; = Time-Weighted Average (TWA) Market Price

Source: CAISO, Energeia Analysis

- Energeia has analyzed the California Independent System Operator (CAISO) electricity energy market for insight into potential strengths and weaknesses of new nuclear projects
- We found that at 2024 prices, an SMR plant with an adjusted levelized cost (LCOE) of $78/MWh would expect to earn around $41/MWh
  - Energeia's adjustment for Resource Adequacy (RA) payments of around $156,000/MW/year using current prices
- This implies that a new nuclear power station would be uncompetitive in today's CAISO, given the assumptions made

Bulk System Load in CAISO in 2040

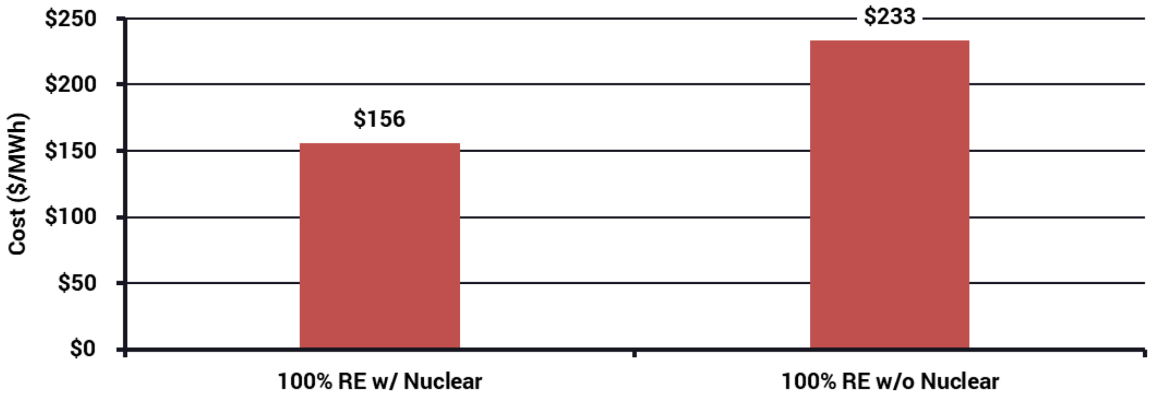
CAISO Average All, Summer and Winter Days (2040)



Source: CAISO, Energeia Analysis

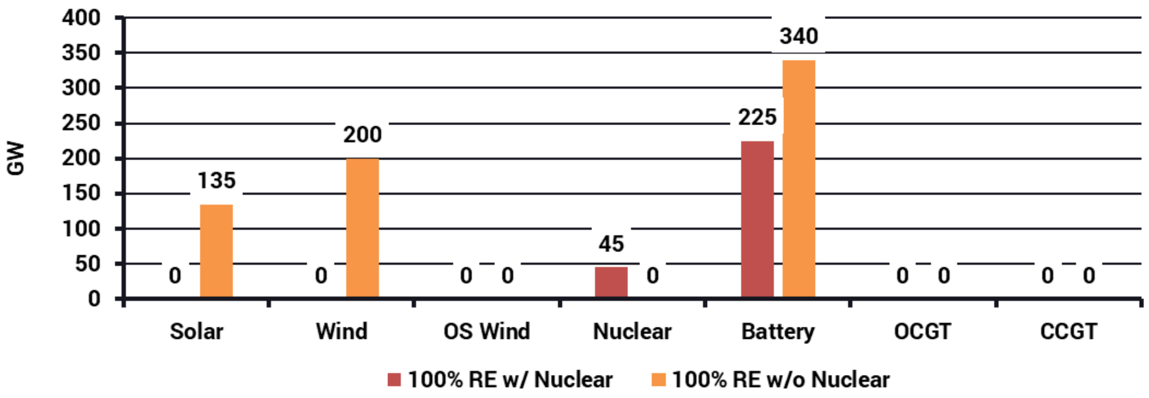
- In 2040, load is expected to evolve due to electrification and behind the meter resources
- Our indicative analysis of the cost to serve these load is reported below left
- Analysis uses resource capex and opex costs from NREL's ATB, identifying the least cost combination that serves 100% of load
- The analysis is simplified in that it does not account for forced outages or maintenance, or inter-state trade
- However, we think these would not change the overall finding – that a nuclear future could be a lower cost under the assumed conditions

CAISO Cost in 2040 – With and Without Nuclear



Source: Energeia Analysis, CAISO (2024), IEPR 2024 California Energy Demand 2024-2040

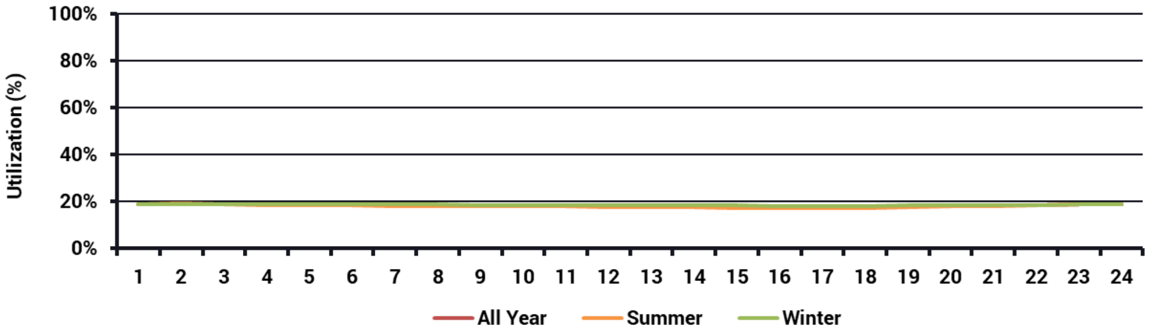
Assumed CAISO Capacity in 2040 – With and Without Nuclear



Source: Energeia Analysis, CAISO (2024), IEPR 2024 California Energy Demand 2024-2040

Data Centre Load and Price to Beat in FY25 ($/MWh)

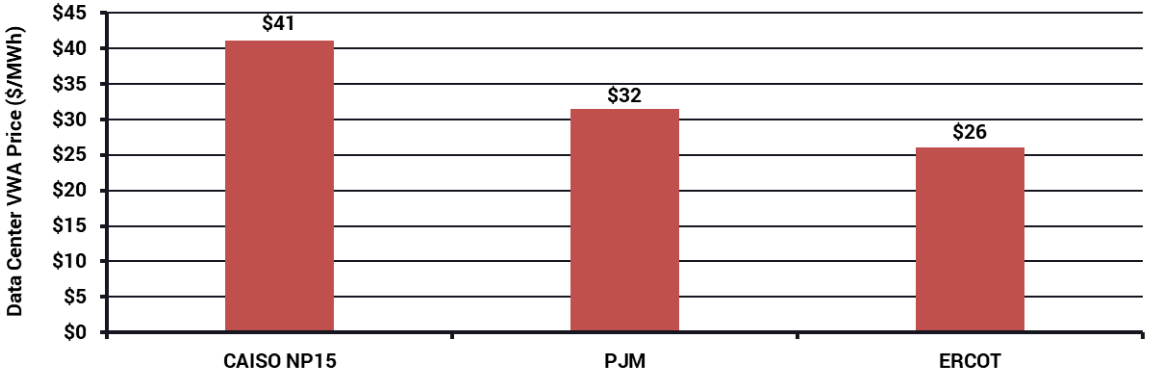
Estimated Data Center Load (2024 UK Data Center Example)



Source: UK Power Networks Data Center Demand Profile (2024)

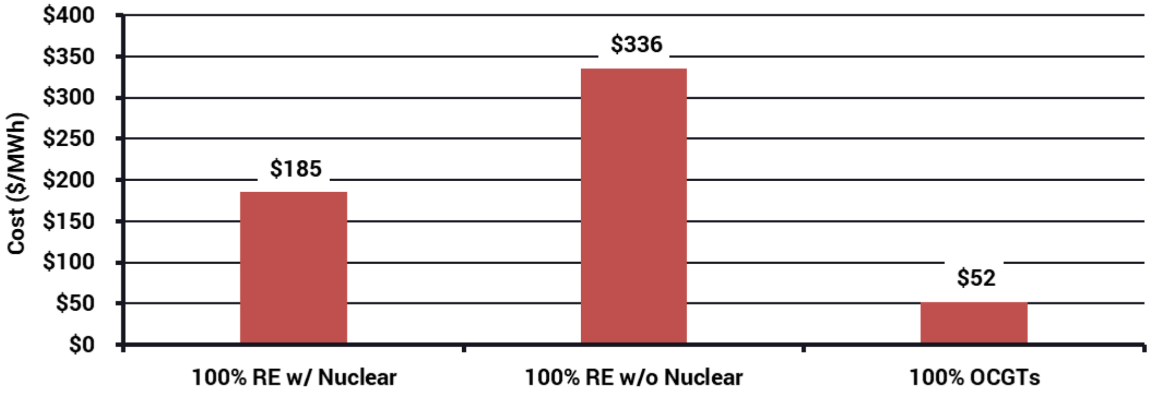
- Data centers typically run a flat load because the majority of their power consumption comes from non-time dependent processing
  - The example load profile shown at left highlights the typical build out profile of these projects, much like any major development
- Selected markets have an avg. data center load weighted average (VWA) Day-Ahead Energy Market Locational Marginal Pricing of $32.90/MWh
- The analysis shows that a data center would pay less buying from these spot markets than the best priced nuclear station in 2024
  - A key issue is that data center loads are increasing wholesale market prices
  - Another key issue is being able to connect
- Where a data center cannot connect, the key question is which stand alone electricity solution delivers the lowest cost power solution?

Data Center ($/MWh) by Balancing Authority in 2024



Source: CAISO OASIS (2024), PJM LMPs (2024), ERCOT Market Prices (2024)

Data Center Cost of Service by Solution (2024, $/MWh)



Source: Energeia Analysis, CAISO (2024), IEPR 2024 California Energy Demand 2024-2040

Takeaways and Recommendations

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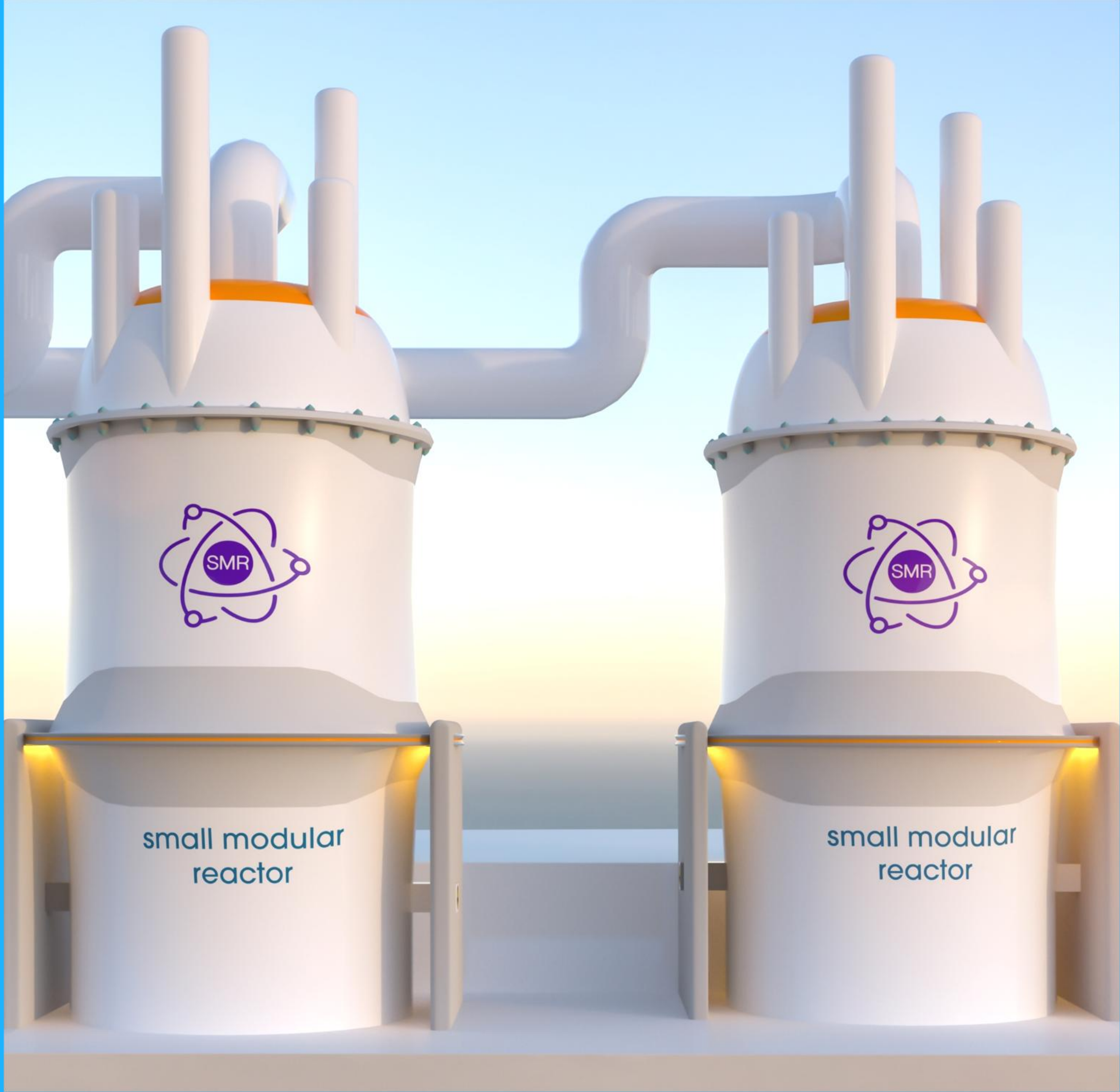
Takeaways and Recommendations

- **Takeaways**
  - There is a great deal of nuclear capacity around the world, which will need to be replaced at some point
  - Most countries with nuclear capabilities are aiming to invest in next generation technology, or at least keep their options open
  - Small modular reactors promise smaller form factors, faster construction times, without too much of a cost impact from the smaller scale
  - There are very few small modular reactor designs in the world that have been certified
  - Key limitations of the technology still include nuclear waste management, water consumption, ramping rates, and restart costs
  - A few pilot projects are currently underway, and significantly more are planned, with significant results expected in the next 3-5 years or so
  - The high utilization / baseload nature of the technology may find it hard to integrate into a high renewables system
  - Data centers, with their flat loads, could be a key future customer, especially where there are connection limitations, but access to water will be key
  - Our analysis shows that the flat load profile makes a modular reactor competitive with a solar + wind + BESS solution, economically speaking
- **Recommendations**
  - Undertake more sophisticated modeling of nuclear and alternative resource mixes, including battery storage and regional dynamics
  - Monitor the outcomes of small modular reactor pilots in the US and around the world to see if they deliver on timelines and cost targets
  - For data centers, and other major industrial loads, consider the value of flexibility to maximize grid connection capacity and minimize stand alone costs
  - It will also be important to monitor the cost of alternative technologies, esp. long-duration storage

Charging Ahead

Q & A

Next Charging Ahead Topic



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Energeia's Charging Ahead Webinars

- Q&A
  - Add your questions in the chat
  - Unanswered questions will be answered via email

Review the 2024 Charging Ahead Series on our website:

- **The Future of Data Centre Electrical Grid Impacts**
- **Industrial Decarbonisation: Hard-to-Abate Sectors**
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Watch for a follow-up email with recording and presentation links to share

Thank You!

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