

Small Modular Nuclear for the Chemical Industry: Cracking Atoms to Make Molecules

A Special Report



June 2024

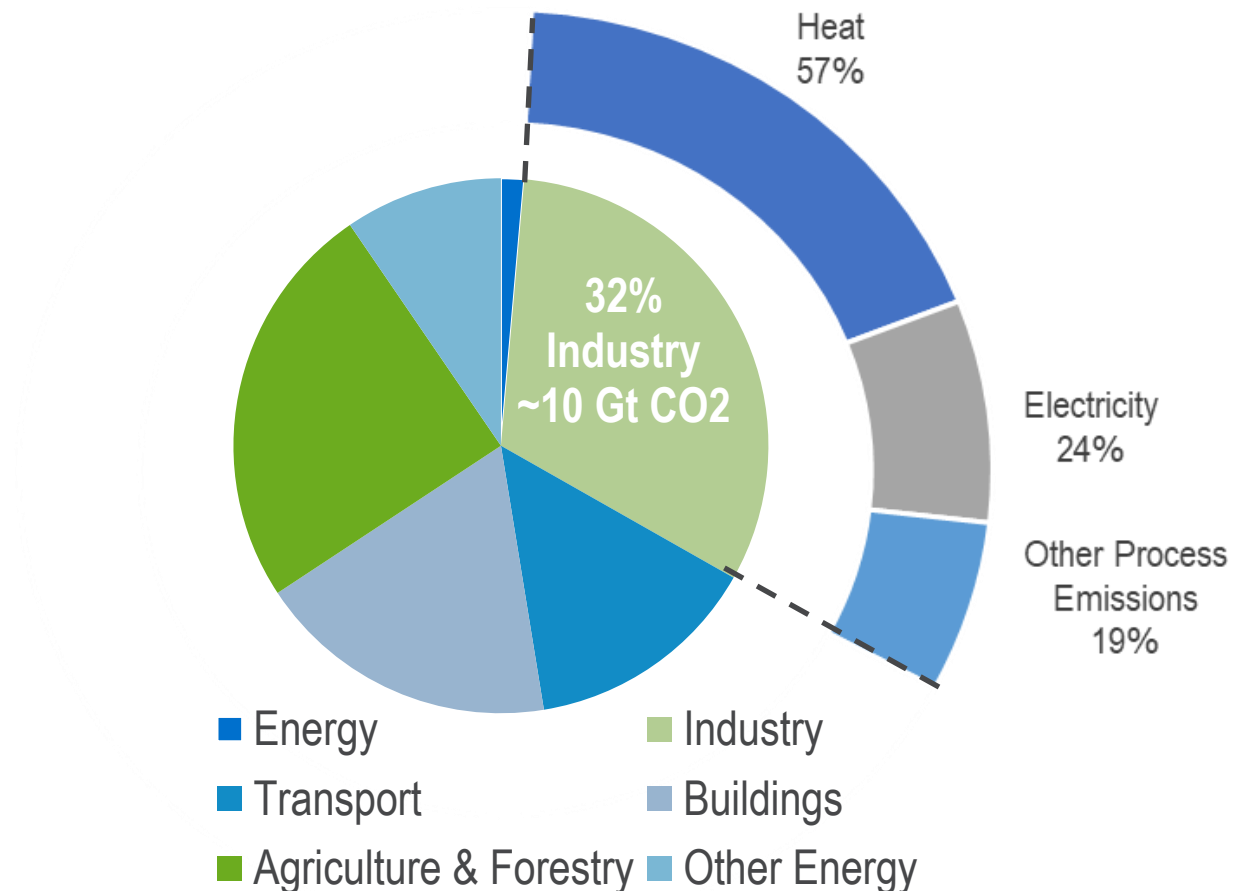
The net zero transition for industry will require shifting all process heat and electricity needs to low/zero carbon alternatives by 2050

Nuclear is a low carbon option for both heat and power

Key Advantages:

- Baseline generation for high reliability
- Able to address both electric power and process heat needs
- Well-established Low Lifecycle CO₂ Emissions
- Low land footprint
- Zero air pollution at point of use

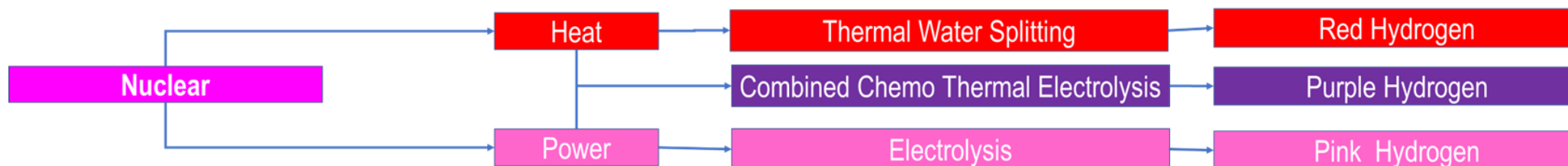
Annual Global GHG Emissions by End-Use



Sources:

IEA World Emissions Dataset, 2021
IPCC AR5 Working Group 3 Report (2014)

Nuclear energy also offers a low-CI lifeline to the growing need for green H₂ – without the transmission-constrained geography of conventional renewable power

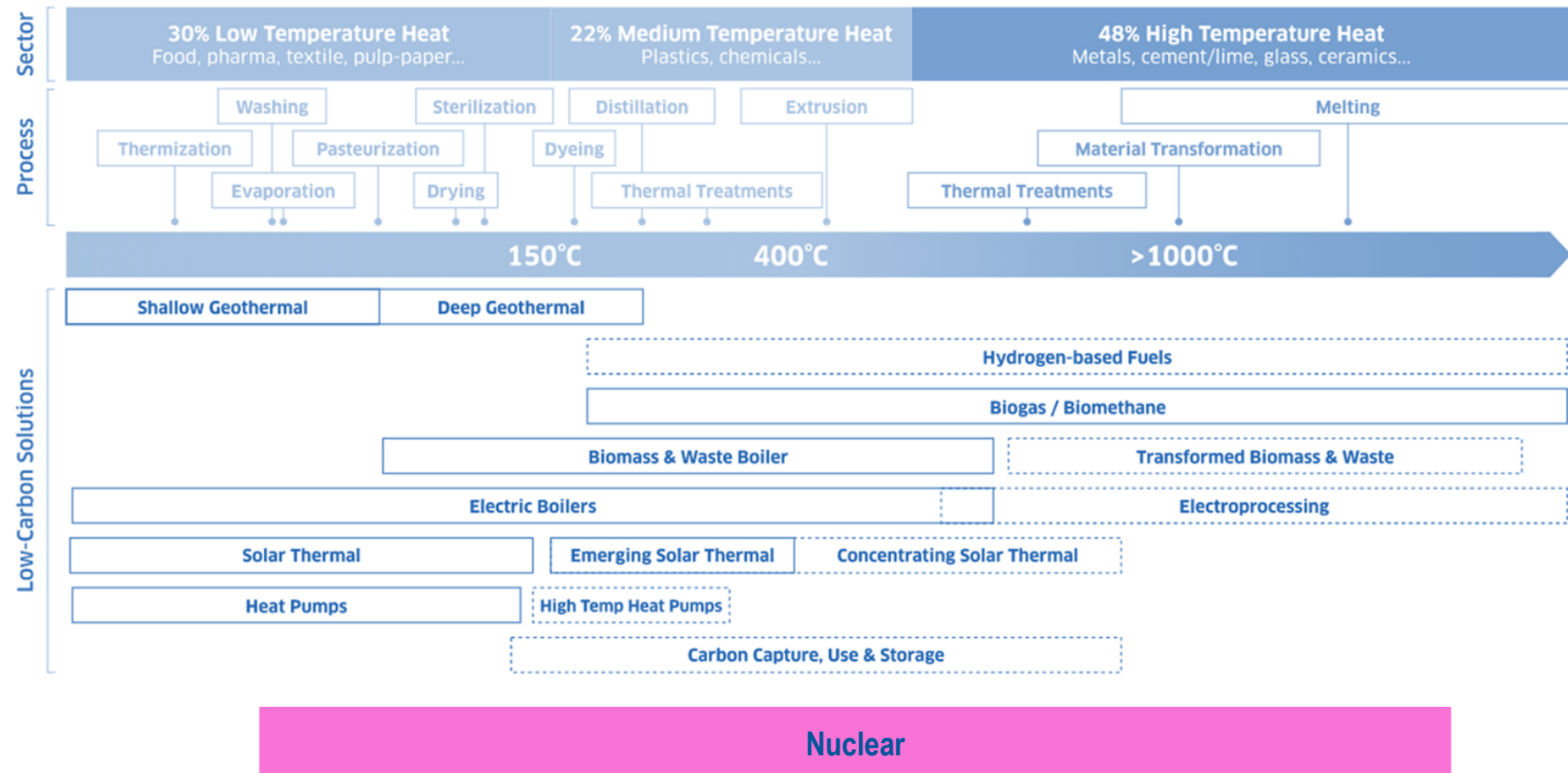


Nuclear Technologies Allow Access to Proven and Innovative Clean Hydrogen Processes

- Low-CI nuclear power is fungible; all conventional water electrolysis processes can be used with nuclear to make “pink hydrogen”
- Nuclear is ideal for emerging high-temperature solid oxide electrolysis (for both H₂ and CO), which features much greater efficiency than the current standard but requires clean heat sources
- Nuclear thermolysis processes (e.g., Sulfur-Iodine cycle) for hydrogen become viable with Gen IV high temperature reactors
- Combined water electrolysis methods (e.g., Westinghouse Cycle) can take advantage of abundant thermal energy and greatly reduced electricity consumption in Gen IV high temperature reactors

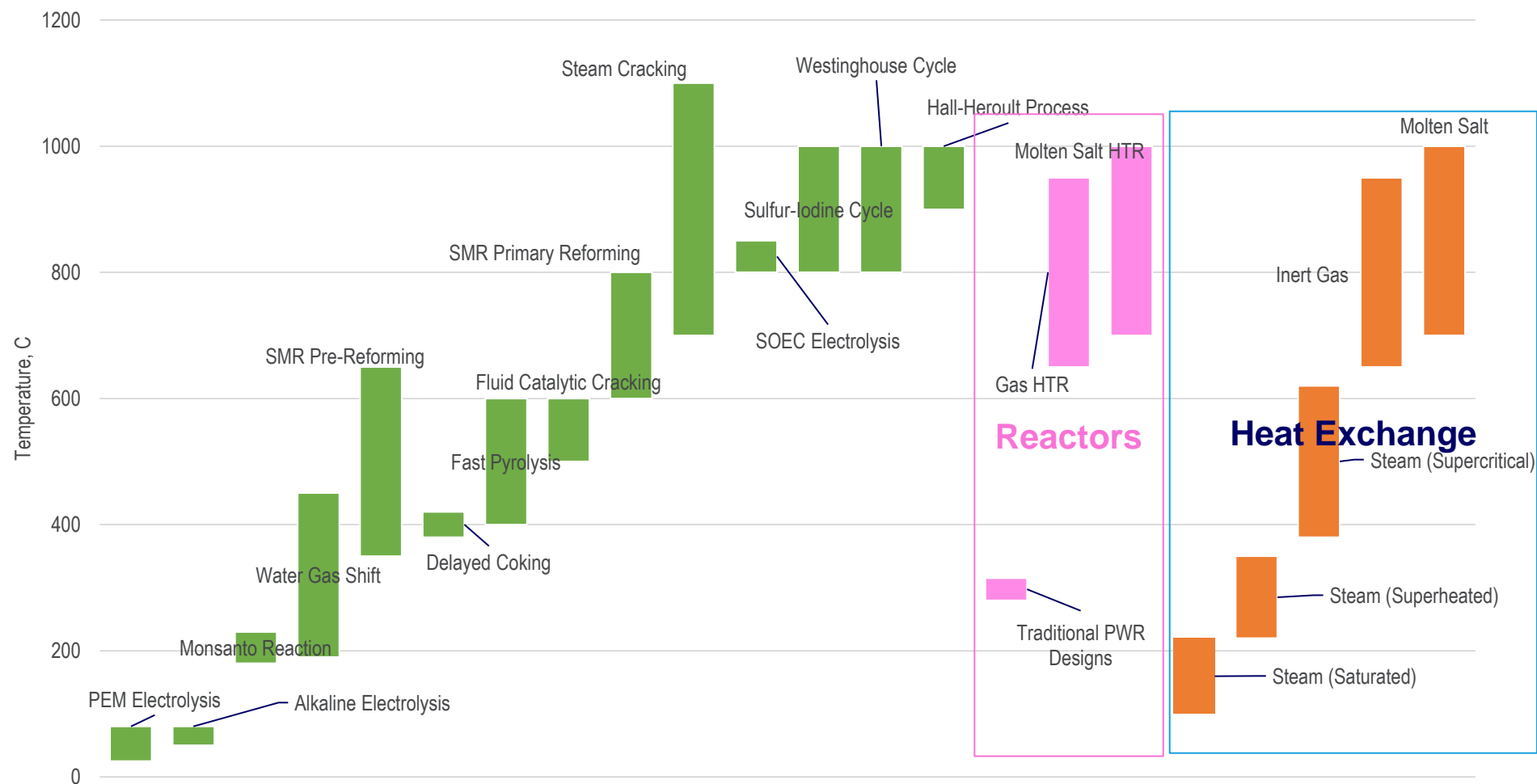
Nuclear is a proven option for providing high grade thermal energy without electricity as an intermediate

- The green transition means that the cost of high-grade thermal energy may no longer be cheaper than electricity due to a paucity of low/zero carbon options
- When compared against precombustion carbon capture, solar thermal, and electrical heating options, thermal power becomes significantly more expensive relative to electricity than previously
- This provides a niche for nuclear power...



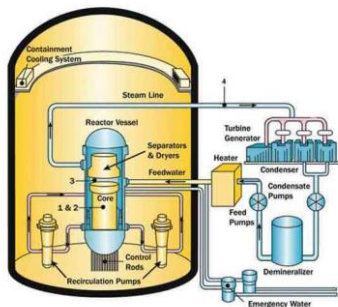
Nuclear power can provide for process thermal energy needs but not all reactors or heat transfer mechanisms can work

Process Technology Applications Require Newer High-Temperature Reactor Designs and Exotic Heat Exchange Media

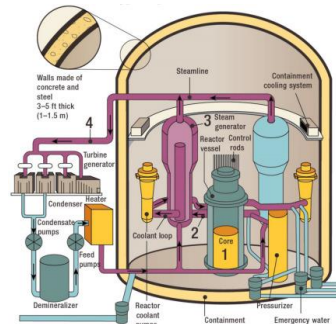


New generations of small, modular nuclear reactor (SMR) designs promise low-cost deployment packages in the range of hundreds of megawatts potentially suited for individual facilities

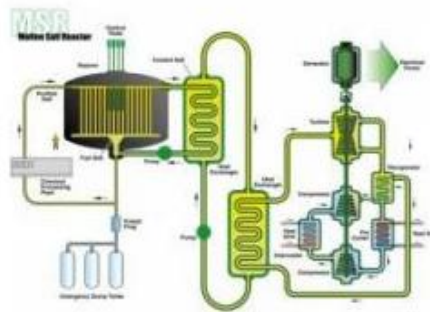
Design Types of Major Nuclear SMRs



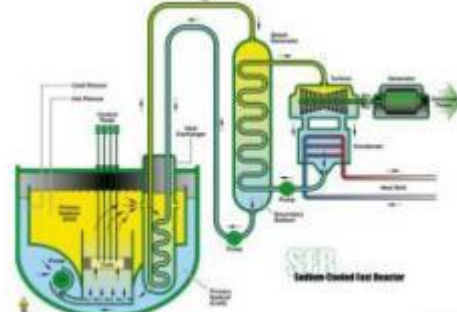
Boiling Water Reactor (BWR)



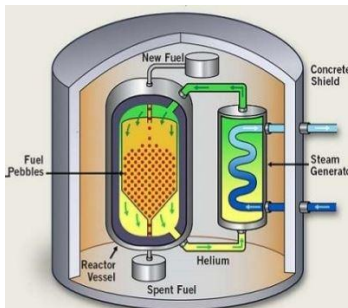
Pressurized Water Reactor (PWR)



Molten Salt Reactor (MSR)



Sodium Fast Neutron Reactor



High Temperature Gas-Cooled Reactor (HGTR)

Scale of Reactors



LARGE, CONVENTIONAL REACTOR
700+ MW(e)



SMALL MODULAR REACTOR
Up to 300 MW(e)



MICROREACTOR
Up to ~10 MW(e)

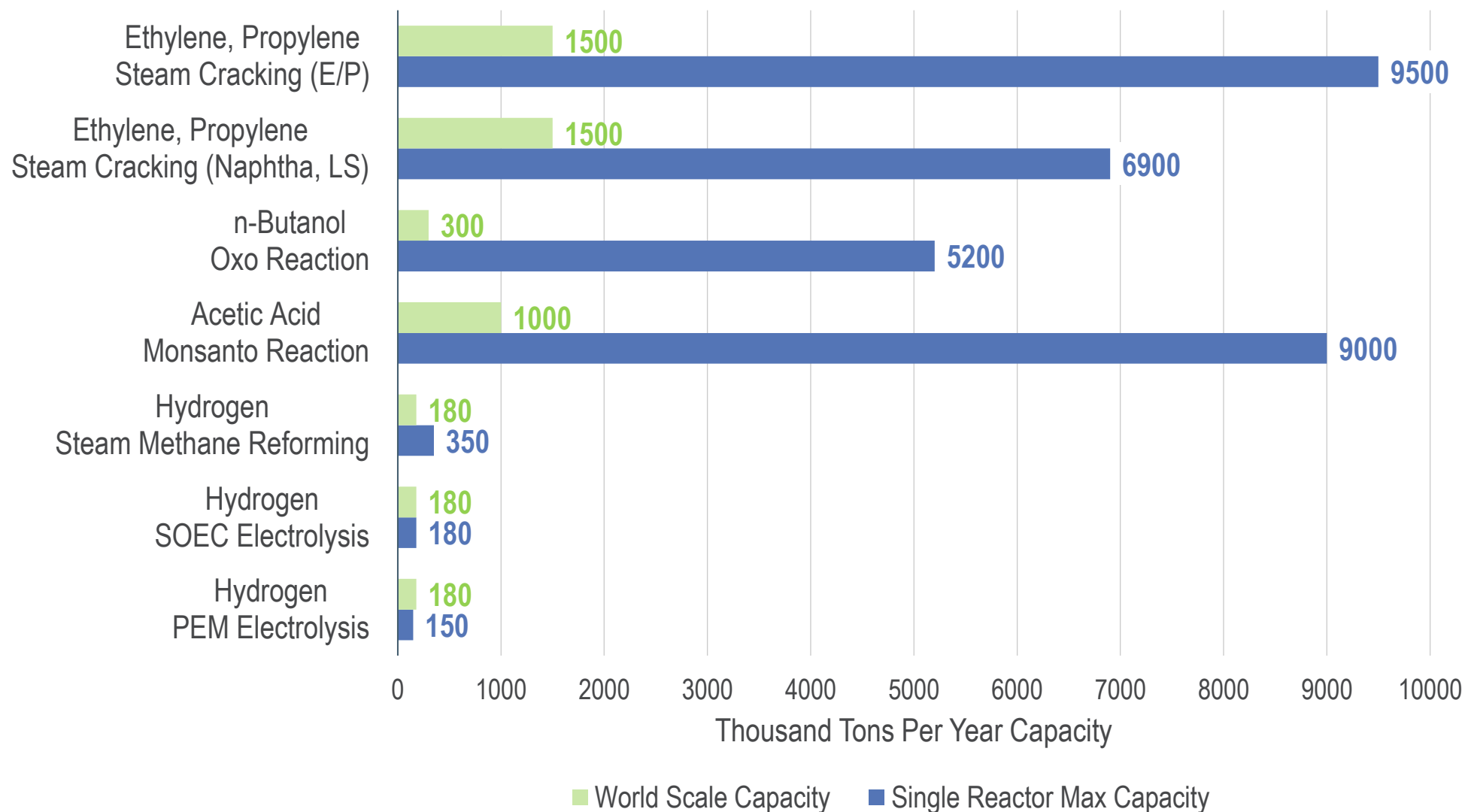


Some Risk Remains...

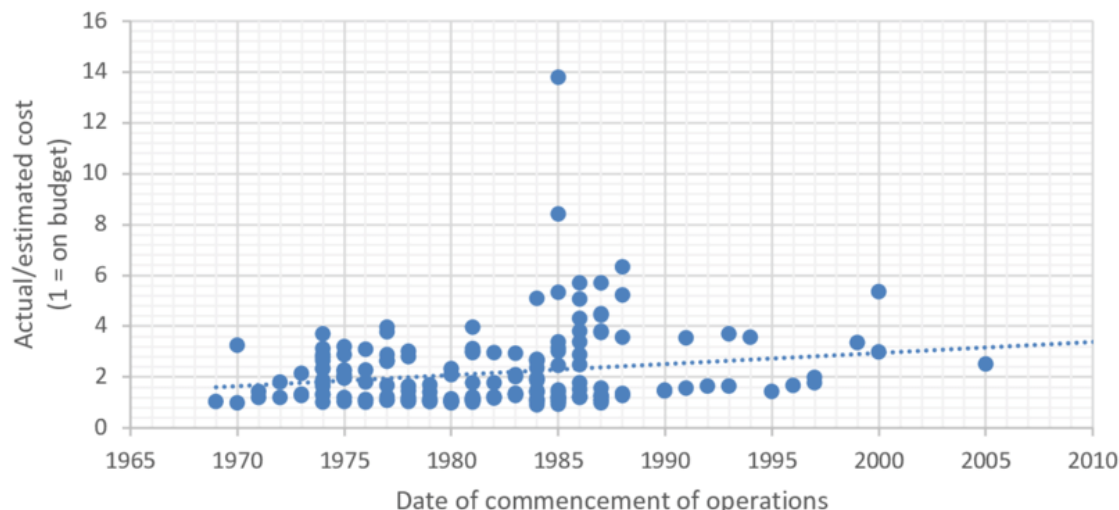
- Few current worldwide deployments
- Cost reductions in serial production not proven
- Poor track record of Gen III and Gen III+ reactor deployment due to cost overruns

However, modular reactor designs are fixed in scale, and may be more suited to large manufacturing complexes rather than standalone plants

Chemical Process Support Capacity of 300 MWe Nuclear SMR



A key question for the process industries is cost – over the past 50 years, nuclear has had a very poor record of capital cost overruns for deployment and SMRs threaten the same



Buzier, A., Flyvbjerg, B., et al. "Quantitative Cost and Schedule Risk Analysis of Nuclear Waste Storage", SSRN Electronic Journal, 2018

European Pressurized Reactors (EPRs) Suffer Cost Overruns, Delays

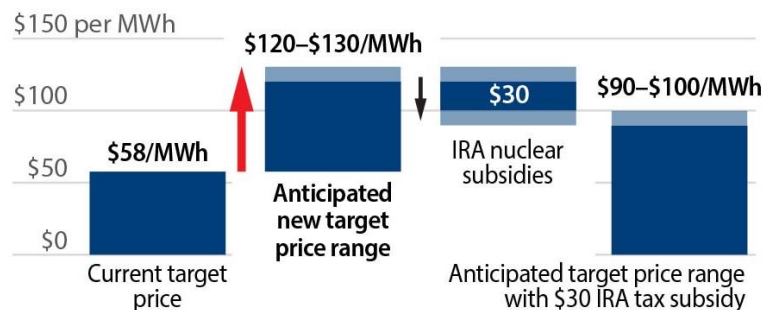
A new generation of nuclear reactors known as European Pressurized Reactors (EPRs) suffer from the same issues as other nuclear projects: Massive cost overruns and years of construction delay



Source: <https://ieefa.org/resources/european-pressurized-reactors-eprs-next-generation-design-suffers-old-problems>

Disappearing Promise of Cheap Power From SMRs

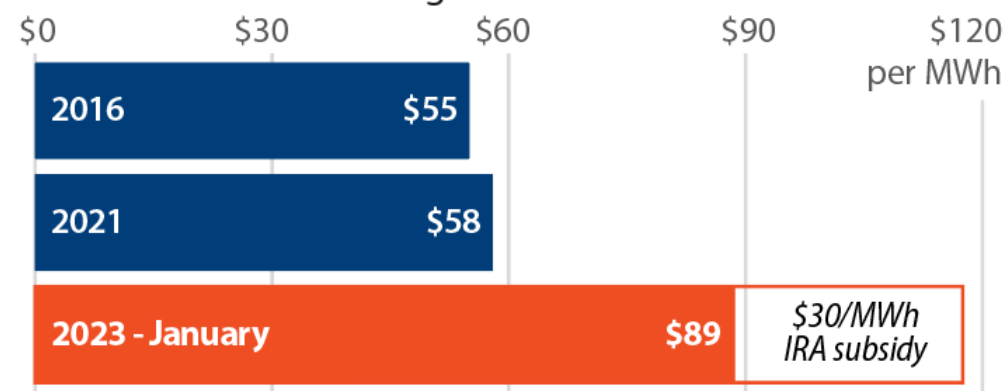
Even new nuclear subsidy in the IRA cannot make up for shocking increases in estimated construction costs



Sources: IEEFA, Community Power Board meetings IEEFA

Source: <https://energypost.eu/small-modular-reactor-cost-overruns-the-same-old-problems-haunt-new-nuclear-in-utah/>

UAMPS NuScale SMR Target Price of Power



Sources: UAMPS statements; January 3, 2023 Talking Points IEEFA

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

NexantECA's special report aims to answer key questions about small modular nuclear in the chemical industry

NexantECA will explore the compatibility of major electric and thermal energy using processes with nuclear reactors:

- What process adaptations are needed
- What reactor designs are available, their deployment history, and their compatibility with thermal energy needs
- How operational factors with nuclear reactors and major processes align or conflict

The study will also focus on key economic questions:

- What technology risks are associated with deploying nuclear SMRs in the process industries?
- What are manufacturers cost claims and what would the implications be in major electric and thermal energy-intensive processes?
- What are the sources of the capital cost escalation seen in recent deployment of nuclear reactors, and which factors apply to the chemical and fuel industries?
- What are manufacturers' claims of capital cost reduction over the course of serial deployment, and can these claims be corroborated?

NexantECA has approached this report in our capacity as techno-economic and cost engineering experts, rather than as nuclear engineers. As such we will not critically comment on the safety, efficacy, or deep regulatory aspects of nuclear SMRs in this report



NexantECA's detailed nuclear SMR developer coverage includes credible technology offerings nearing commercialization by 2034, including all those in development with chemical companies

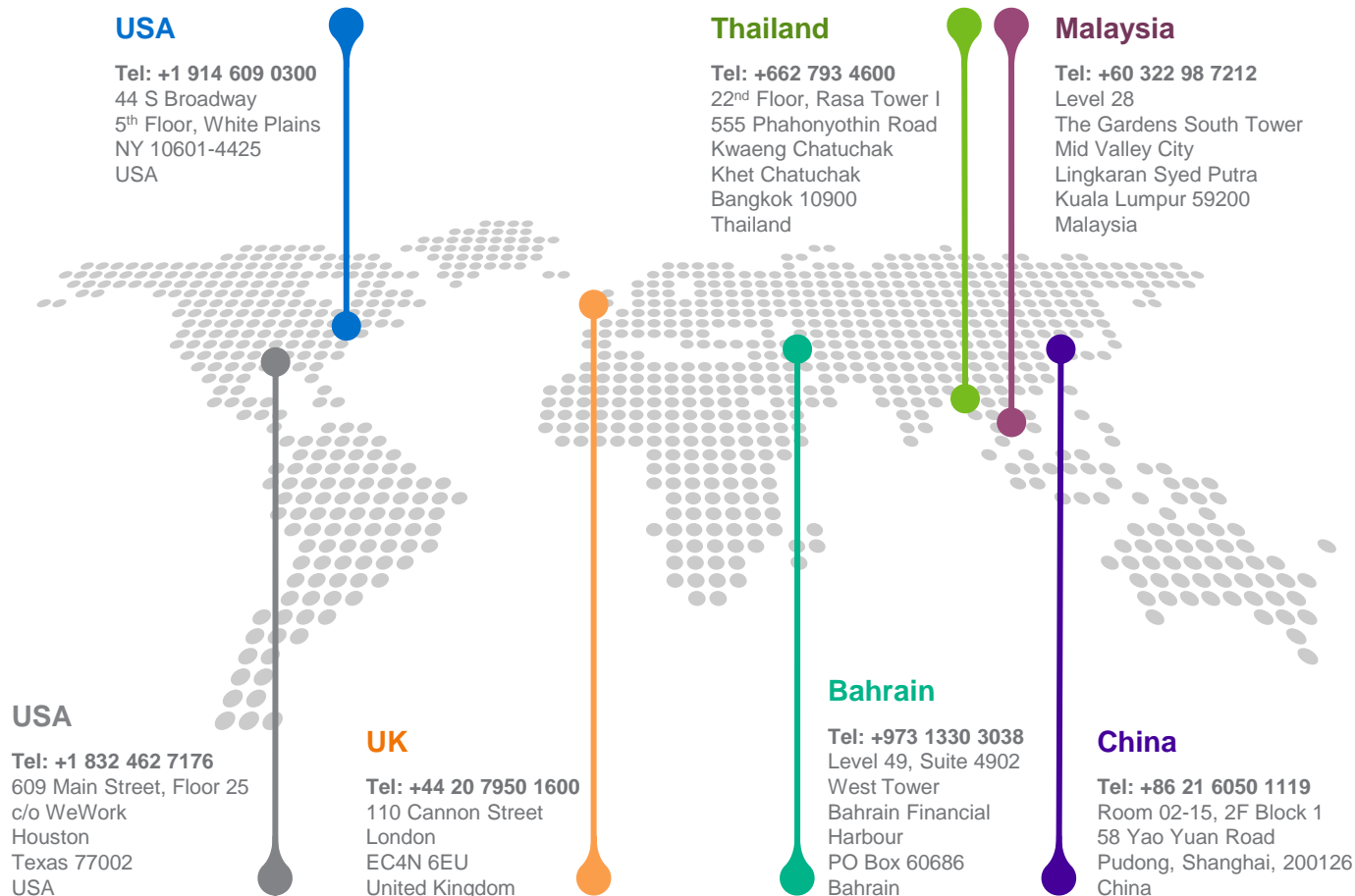
Technology Name	Single Module Capacity (MWe)	Installation Capacity	Type	Developer
NuScale Voygr	77	460, up to 925	Pressurized Water Reactor	NuScale
SMR-300	150	300	Pressurized Water Reactor	Holtec (SMR, LLC)
AP-300	300	300	Pressurized Water Reactor	Westinghouse
Rolls Royce SMR	470	470	Pressurized Water Reactor	Rolls Royce SMR LLC
BWRX-300	300	300	Boiling Water Reactor	GE Hitachi
Xe-100	80	320	High Temperature Gas-cooled	X-Energy
HTR-PM	105	650	Sodium Fast Neutron	CNNC-Tsinghua

Published Table of Contents for the report now available!

1	Executive Summary	3.6.2	Proposed Nuclear SMRs.....	6.1.2	Cost of Nuclear SMR Deployment
1.1	Overview and Major Conclusions.....	4	Nuclear SMR in the Process Industries	6.2	Cost Estimation of Nuclear SMRs in Industrial Manufacturing.....
1.2	Nuclear Technologies	4.1	Business and Risk Considerations	6.2.1	Methodology
1.3	Nuclear SMR Integration into Manufacturing	4.1.1	Ownership and Project Finance	6.2.2	Steam Methane Reforming
1.3.1	Business Considerations	4.1.2	Owner's Risk Exposure	6.2.3	High Temperature Electrolysis
1.3.2	Process Considerations	4.1.3	Nuclear Technology Vendor Relationships.....	7	Strategic Analysis
1.3.3	Design Considerations	4.1.4	Changes to Traditional Nuclear Project Ownership and L Structure	7.1	Overview.....
1.4	Cost of Nuclear SMRs.....	4.2	Manufacturing Process Compatibility with Nuclear SMRs	7.2	Strategic Outlook for Nuclear SMRs in the Process Industries
1.4.1	Cost of Production Models	4.2.1	Methodology	7.2.1	Overall Costs and Benefits of Nuclear Energy
1.4.2	Sources of Cost.....	4.2.2	Primary Coolant Isolation.....	7.2.2	Implementation Risks for Nuclear Energy.....
1.4.3	Controlling Capital Cost Inflation	4.2.3	Coolant Temperature Constraints	7.2.3	Economic Outlook for Investment in Nuclear Energy
2	Introduction.....	4.2.4	Commercial Process Scale	7.2.4	Strategic Case for Investment in Nuclear Energy.....
2.1	Nuclear Reactors in the Chemical Industry.....	4.3	Design and Operational Integration of Nuclear Reactors	7.3	Technical Outlook for Nuclear SMRs
2.2	Scope of the Report	4.3.1	Heat Transfer Materials and Media.....	7.3.1	Overall Deployment Trends
2.3	Small Modular Nuclear Reactors	4.3.2	All-Electric Energy Input	7.3.2	Outlook for Profiled Technology Developers.....
2.4	Key Drivers	4.3.3	Operational Reliability	7.4	General Risks and Issues.....
2.4.1	Sustainability	4.4	Current Developments.....	7.4.1	Social License
2.4.2	Regulatory and Policy Drivers	5	Critical Assessment of Nuclear Reactor Economics	7.4.2	Nuclear Nonproliferation
2.4.3	Geopolitical Drivers	5.1	Historical Background.....		
3	Nuclear SMR Technology Review	5.2	Major Cost Items in Civil Nuclear Power		Appendices
3.1	Civil Nuclear Reactor Operation	5.2.1	Introduction	A	Glossary
3.1.1	Nuclear Reactor Basics	5.2.2	Overnight Capital Costs	A.1	Civilian Power Reactor Designs.....
3.1.2	Common Nuclear Reactor Operations	5.2.3	Interest During Construction	A.2	Reactor Generations
3.1.3	Reaction to Unexpected Behavior	5.2.4	Fuel Cycle Costs	A.3	Technical Terms
3.1.4	Refueling and Turnarounds	5.2.5	Nuclear Waste Handling and Decommissioning	B	Nuclear Fuel Materials
3.1.5	Waste Handling and Decommissioning.....	5.2.6	Liability Insurance.....	B.1	Sources of Fissile Material
3.2	Pressurized Water Reactors (PWRs).....	5.2.7	Nuclear-Specific Regulatory Compliance Costs.....	B.1.1	Naturally Occurring Uranium.....
3.2.1	Common Design Characteristics.....	5.3	Sources of Cost Inflation.....	B.1.2	Plutonium
3.2.2	Major Nuclear SMR Technologies	5.3.1	High Regulatory Design and Materials Standards.....	B.1.3	Uranium-233.....
3.3	Boiling Water Reactors (BWRs).....	5.3.2	Regulatory Instability.....	B.1.4	Fast Spectrum Fuel Materials
3.3.1	Common Design Characteristics.....	5.3.3	Technology Risk.....	B.1.5	Waste Risks
3.3.2	Major Nuclear SMR Technologies	5.3.4	Project Management Risk	B.2	Fuel Particles.....
3.4	High Temperature Gas-Cooled Reactors (HTGRs) ..	5.4	Cost Reduction Strategies	B.2.1	Chemical Composition
3.4.1	Common Design Characteristics.....	5.4.1	Regulatory Engagement.....	B.2.2	Fuel Elements
3.4.2	Major Nuclear SMR Technologies	5.4.2	Managing Technology Risk.....	C	Nuclear Reactor Cores.....
3.5	Molten Salt Reactors (MSRs)	5.4.3	Project Management	C.1	Fuel Assemblies
3.5.1	Common Design Characteristics.....	5.4.4	Economies of Scale from Series and Clustering Construction	C.1.1	Ceramic Fuel Rods.....
3.5.2	Proposed Nuclear SMRs.....	5.4.5	Policy Framework.....	C.1.2	Metallic Fuel Rods.....
3.6	Fast Neutron Reactors (FNRs)	5.5	Nuclear SMR Claims and Addressable Risks.....	C.1.3	Pebble Bed Reactor Fuels
3.6.1	Common Design Characteristics.....	6	Cost of Production Models.....	C.1.4	Prismatic Coated Particle Reactor Fuels
		6.1	Analysis of Nuclear SMR Cost Claims	C.2	Reactor Core Types
		6.1.1	Methodology		



NexantECA partners with clients to help them navigate the big global energy, chemicals and materials issues of tomorrow. We provide independent advice through our consulting, subscriptions and reports, and training businesses using expertise developed in markets, economics and technology through our fifty years of operation. We are entirely dedicated to supporting sustainable development of the industry and provide expert advice with efficiency, speed, and agility.



Disclaimer

This Report was prepared by NexantECA, the Energy and Chemicals Advisory company. Except where specifically stated otherwise in this Report, the information contained here is prepared on the basis of information that is publicly available, and contains no confidential third party technical information to the best knowledge of NexantECA. Aforesaid information has not been independently verified or otherwise examined to determine its accuracy, completeness or financial feasibility. Neither NexantECA, Client nor any person acting on behalf of either assumes any liabilities with respect to the use of or for damages resulting from the use of any information contained in this Report. NexantECA does not represent or warrant that any assumed conditions will come to pass.