The Potential of Small Modular Nuclear Reactors (SMRs) in Clean Energy Transition

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TNChE Asia 2024
3rd Thailand International Chemical Engineering & Chemical Technology
Dusit Thani Pattaya Hotel, Chonburi, Thailand
June 19-21, 2024

Why Nuclear?

- Clean energy

  Greenhouse-gas emissions
  - 1/273th those of coal
  - 1/163th of gas
  - 60% of solar.
  - 75% of wind

  Source: Ourworldindata.org/nuclear-energy
- Small footprint on Land Use
  - 1/2,000th of wind,
  - ~ 1/400th of solar

Source: Jacopo Buongiorno (MIT)'s presentation

Energy security

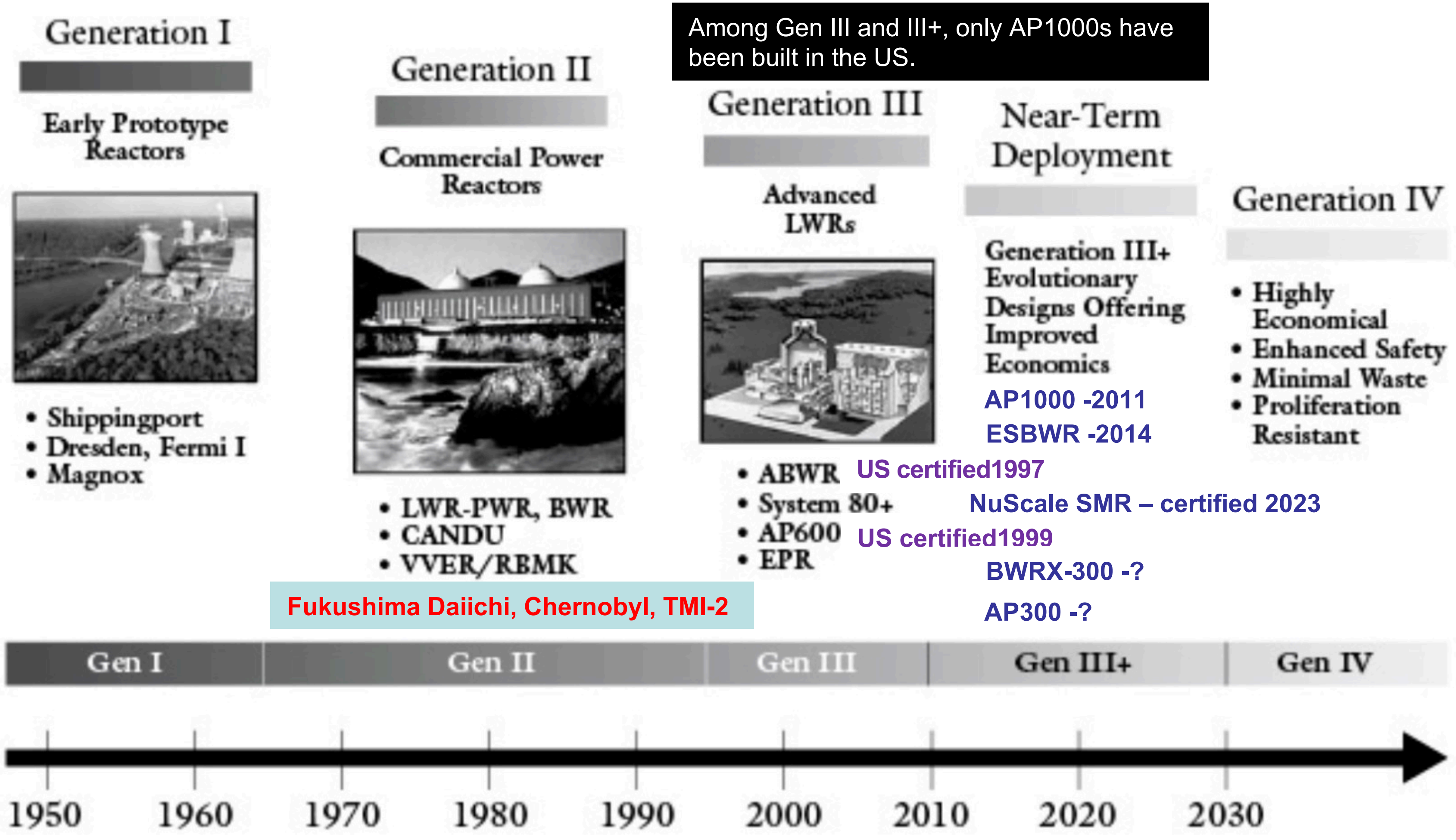
- Reliable power delivery, day and night, every season, almost anywhere, on a large scale
- Complementing intermittent renewable energy

IEA: The path to net zero emissions is narrow. Staying on it requires immediate and massive deployment of all available clean and efficient energy technologies.

Evolution of Nuclear Power Technology

adapted from US DOE- http://nuclear.energy.gov.genIV/neGenIV1.html

Among Gen III and III+, only AP1000s have been built in the US.



AP1000 -2011

ESBWR -2014

US certified1997

NuScale SMR – certified 2023

US certified1999

BWRX-300 -?

AP300 -?

Fukushima Daiichi, Chernobyl, TMI-2

Safety Improvement from LWRs to Non-LWR Advanced Reactors

LWR Reactors

Gen 2, 3, 3+

- Use low boiling point water as coolant
- Use high pressure to raise the BP of water.
- Coolant can boil-off during LOCA accident
- Vulnerable to core melt accident
- Core melt accidents at TMI-2 and Fukushima Daiichi

After Fukushima- Innovation in better materials for LWR fuel rods for enhanced tolerance to accident conditions

- Develop fuel cladding materials that are resistant to steam oxidation at high temperature
- Coated Zircaloy cladding

Advanced Reactors (Non-LWRs) Gen 4

- Use high boiling point liquid metal or salt (sodium, lead or molten salt) as coolant
- Reactor pressure is near atmospheric pressure.
- Large margin to prevent coolant boiloff during an accident
- Core-melt accidents can be prevented by the design.

What is the safety of nuclear power plants today and how much does it impact the cost?

Past accidents and safety concerns in Generation II's reactors (mid 1970s-mid 1990s) have kept nuclear energy expensive

Utilization of passive safety improvement in Gen III+ Reactor (from ~2018) should lead to cost reduction.

First demonstration of SMR and advanced reactors with inherent safety features (from late 2020s to 2030)

zero or near zero emergency planning zone and lower cost?

Causes of Major Nuclear Accidents

TMI-2	**March 28, 1979**	**USA**	**Human errors, inadequate training, Effect: Improvement in plant design and equipment, INPO established.**
Chernobyl	April 26, 1986	Soviet Union	Flawed reactor design, inadequate trained personnel Effect: Use of RBMK 1000 design was terminated.
Fukushima Daiichi	March 11, 2011	Japan	Station blackout caused by extreme natural disaster, lack of safety culture NRA and JANSI established

Problems with old Gen II plants

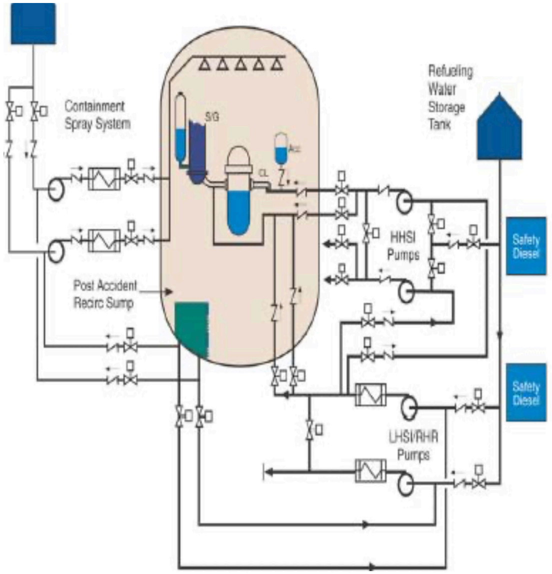
- Nuclear plants depend on external power to operate.
- Nuclear plants designed 40 years ago need power to prevent overheating.
- Without power during station blackout event, fuel meltdown is unavoidable.
- SBO has been taken as a very low-chance, high-consequence accident scenario.
- **New plants with passive safety system are designed to survive SBO.**
- **However, with lessons learned from Fukushima accident, old plants with emergency preparedness have been modified to prevent this kind of accident.**

How the Technology Innovation has Changed?

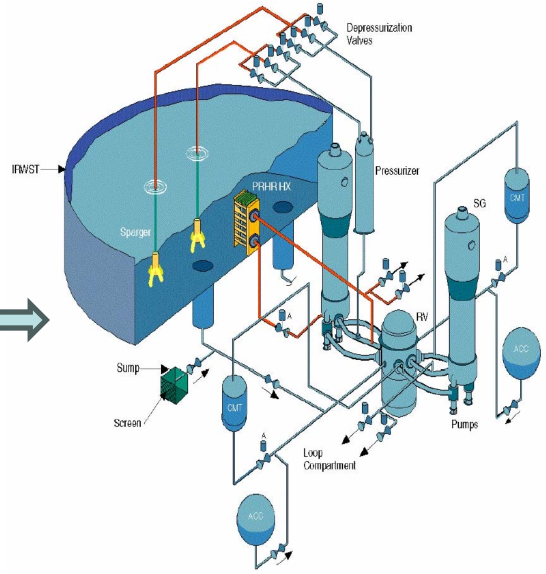
- The evolution of the small modular reactors from these large LWRs.
- The revolution of further safety improvement
- The risk reduction in new nuclear plant investment by starting from smaller plants.

Safety Design Innovation in PWR

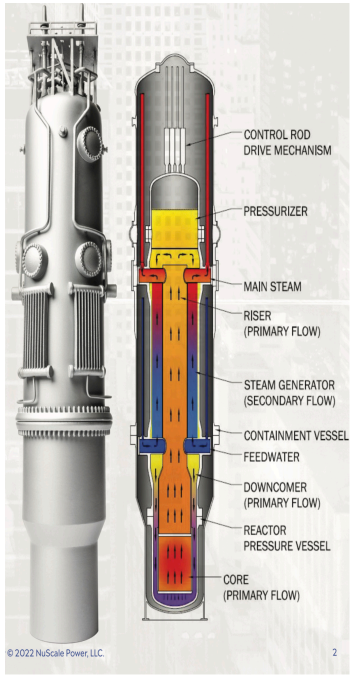
Gen II PWR
Active safety system



Gen III+ PWR
Passive safety system



(Passively-cooled)
Integral PWR SMR



www.westinghousenuclear.com

www.nuscalepower.com

Gen II reactors will not survive an extended station blackout (SBO) w/o restoring power.

Westinghouse AP1000 can survive a SBO for 72 hrs w/o human intervention

NuScale can safely survive a SBO for 30 days and beyond without human intervention.

SMRs and Advanced Reactors

under development currently

Company	Westinghouse	Ultra Safe Nuclear Corporation	X-energy	NuScale Power	Kairos Power	Holtec	GE Hitachi (GEH)	Terra Power
Reactor model	e-Vinci	Micro modular reactor (MMR)/ Nuclear Battery	Xe-100	VOYGR	KP-FHR	SMR-160	BWRX-300	Natrium
Energy Storage	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Molten salt-based, 500 MWe for 5.5 hrs
Electrical output/Thermal output	5 Mwe	5MWe/15 MWt	80 MWe/200 MWt, scalable to a 4-pack 300 MWe plant	77 Mwe/250MWt	144MWe/320 MWt	160 MWe	300 MWe	345MWe
Reactor type	sodium-cooled heat pipe	High temperature gas-cooled reactor	High temperature gas-cooled reactor	Integral PWR SMR	Fluoride salt-cooled high temperature reactor	Integral PWR SMR	Boiling water SMR	Fast reactor, 4x more efficient than LWR
Coolant/moderator	Sodium/graphite?	Helium/Graphite	Helium/Graphite	light water/light water	Fluoride salt FLiBe/graphite	light water/light water	light water/light water	sodium
Neutron spectrum				Thermal	Thermal	Thermal	Thermal	Fast
Primary Circulation	fully passive natural circulation in 12-ft pipe	Forced circulation	Forced circulation	Natural circulation	forced circulation	Natural circulation	Natural circulation	
Primary flow rate			71.1 kg/s helium flow rate		1200-1400 kg/s		company website has no technical details.	
NSSS operating primary pressure	1 bar?	3 MPa Helium primary	6 MPa Helium	13.8 MPa	< 2bar			
secondary pressure	Air-Brayton cycle	0.5 MPa secondary solar salt system	16.5 MPa -steam	4.3 MPa	<2 bar? Nitrate salt			
Core inlet temperature		300 C	260 C - Helium	258.11	550 C -LiF/BeF2			
Core outlet temperature	up to 800 C?	630 C	750 C - Helium	310.06	650 C - LiF/BeF2			
Intermediate inlet temp					500 C - NaNO3/KNO3			
Intermediate outlet temp					600 C - nitrate salt			
Secondary inlet temperature		275 C			300 C - steam			
Secondary outlet temperature		565 C	565 C - Steam		585 C - steam			
Average core power density			4.81 MW/m^3					
Effective core height (m)			9.18 m					
Effective core volume (m^3)			41.56 m^3					

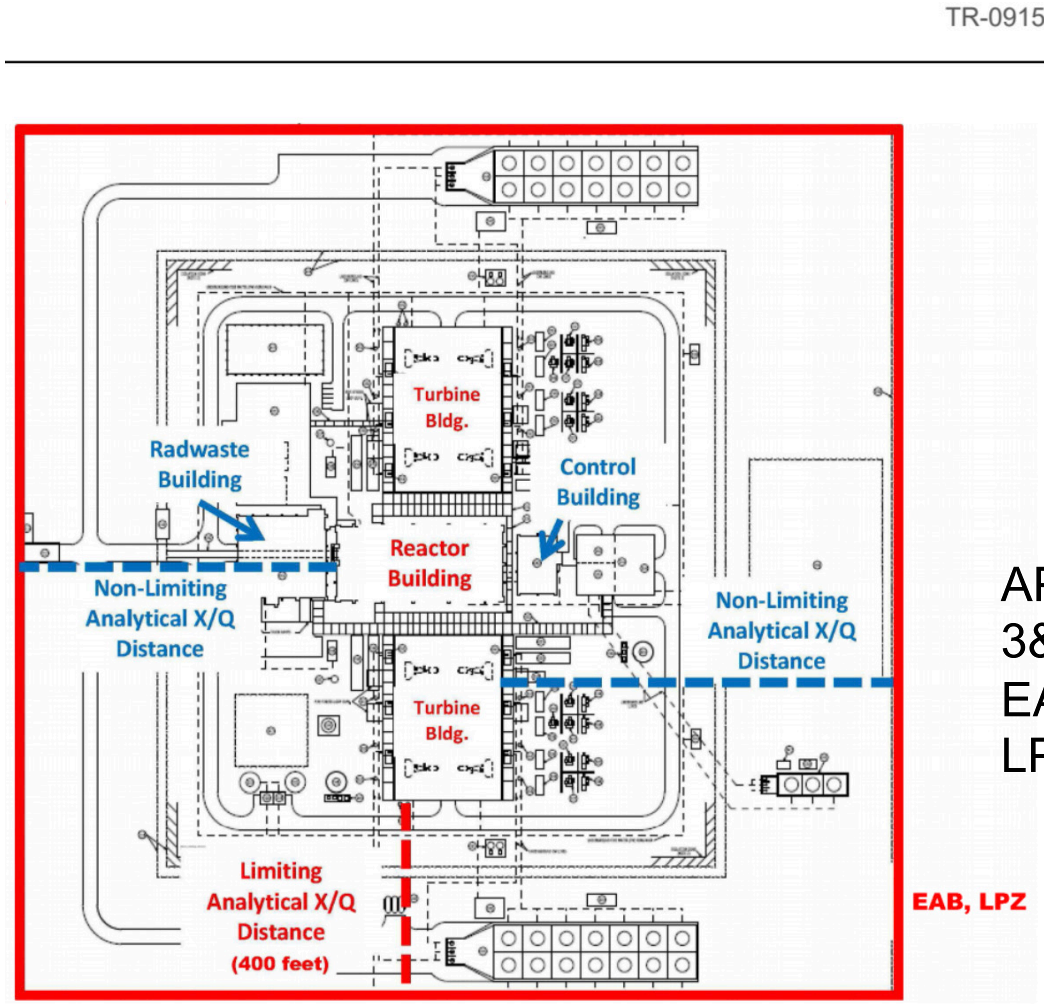
Additional reactors: Oklo's 1.5 MWe micro-reactor, BWXT's 5 Mwe micro-reactor, Arc's 100 MWe SFR, Framatome's 272 MWe HTGR, Moltex's 300 MWe MSR, Rolls-Royce's 470 MWe LWR. See NEA SMR Dashboard for more SMRs worldwide.

SMRs and Advanced Reactors

under development currently

Reactor Model	e-Vinci	Micro modular reactor (MMR)/ Nuclear Battery	Xe-100	NuScale VOYGR	KP-FHR	SMR-160	BWRX-300	Natrium
Fuel type/assembly array	TRISO fuel	FCM (TRISO-based)/Hexagonal	TRISO particles in pebbles	17x17 square, each 2 m long	TRISO particles in pebbles			
No. of fuel assemblies in the core		180 fuel blocks (172 800 FCM pellets) -fully micro encapsulated	220,000 60mm-diameter graphite pebbles with 18,000 of 1mm-diameter TRISO particles in each pebble.	37				
Fuel enrichment		HALEU?	HALEU?	4.95%	19.75% HALEU			
Core discharge burnup		Average - 82.227 MWd/kg						
		Max - 131.287 MWd/kg	160 MWd/kg?					
Refueling cycle	Never	Never - for lifetime		up to 24 months	online/continuous			
Design life	8 years -factory built	20 years	60 years	60 years				
Reactivity control mechanism		Negative temperature coefficient; control rod insertion						
Plant footprint		130 x 96 m^2		12-pack 924 MW module: 140000 m^2 (280x500 m^2)				
EAB distance			400 m radius - meltdown proof, walk-away safety	280m x 500 m				
RPV dimensions		Height - 13.25 m including lid and stand-pipes	16.4 m height	17.7 m height	6.1 m height			
		Diameter - 3.5 m	4.78 m O.D.	2.7 m diameter	3.9 m diameter			
RPV wall thickness			95 mm					
RPV weight		30.1 metric tons						
Seismic design (SSE)		0.3 g		0.5 g ZPA				

EAB and LPZ for NuScale SMR vs Large LWR



NuScale SMRs (77 MW):
EAB – Plant boundary
LPZ – Plant boundary
280 m x 500 m?

AP1000 (1150 MW) : VEGP 3&4 UFSAR Rev. 3, p.2.0-11
EAB – 0.5 mile radius(800 m)
LPZ – 2 mile radius (3.2 km)

https://www.nrc.gov/docs/ML2005/ML20057G132.pdf, p. 232 of 327

Radiological consequences of Design Basis Accidents at EAB and LPZ

NuScale SMRs

Table 5-6. Example dose results for design-basis source terms

Event	Location	Acceptance Criteria (rem TEDE)	Dose (rem TEDE)
rod ejection accident (containment release)	EAB	6.3	0.011
	LPZ	6.3	0.144
	CR	5	0.131
rod ejection accident (primary system release)	EAB	6.3	0.001
	LPZ	6.3	0.001
	CR	5	0.004
fuel handling accident	EAB	6.3	0.362
	LPZ	6.3	0.362
	CR	5	0.313
main steam line break (pre-incident iodine spike)	EAB	25	0.004
	LPZ	25	0.019
	CR	5	0.023
main steam line break (coincident iodine spike)	EAB	2.5	0.0004
	LPZ	2.5	0.0014
	CR	5	0.0013
steam generator tube failure (pre-incident iodine spike)	EAB	25	0.637
	LPZ	25	0.663
	CR	5	0.720
steam generator tube failure (coincident iodine spike)	EAB	2.5	0.039
	LPZ	2.5	0.040
	CR	5	0.002
primary coolant line break	EAB	2.5	0.062
	LPZ	2.5	0.062
	CR	5	0.075
iodine spike DBST* (pre-incident iodine spike)	EAB	25	<0.01
	LPZ	25	<0.01
	CR	5	<0.01
iodine spike DBST* (coincident iodine spike)	EAB	25	<0.01
	LPZ	25	<0.01
	CR	5	<0.01

*Note: The iodine spike DBST is not an event, but rather a bounding source term associated with DBEs that result in primary coolant entering the containment.

https://www.nrc.gov/docs/ML2005/ML20057G132.pdf

AP1000 (Vogtle 3&4)

Transient and Accident Analyses

Table 15.3-1 Staff-Calculated Radiological Consequences of Design-Basis Accidents (Total Effective Dose Equivalent (TEDE))

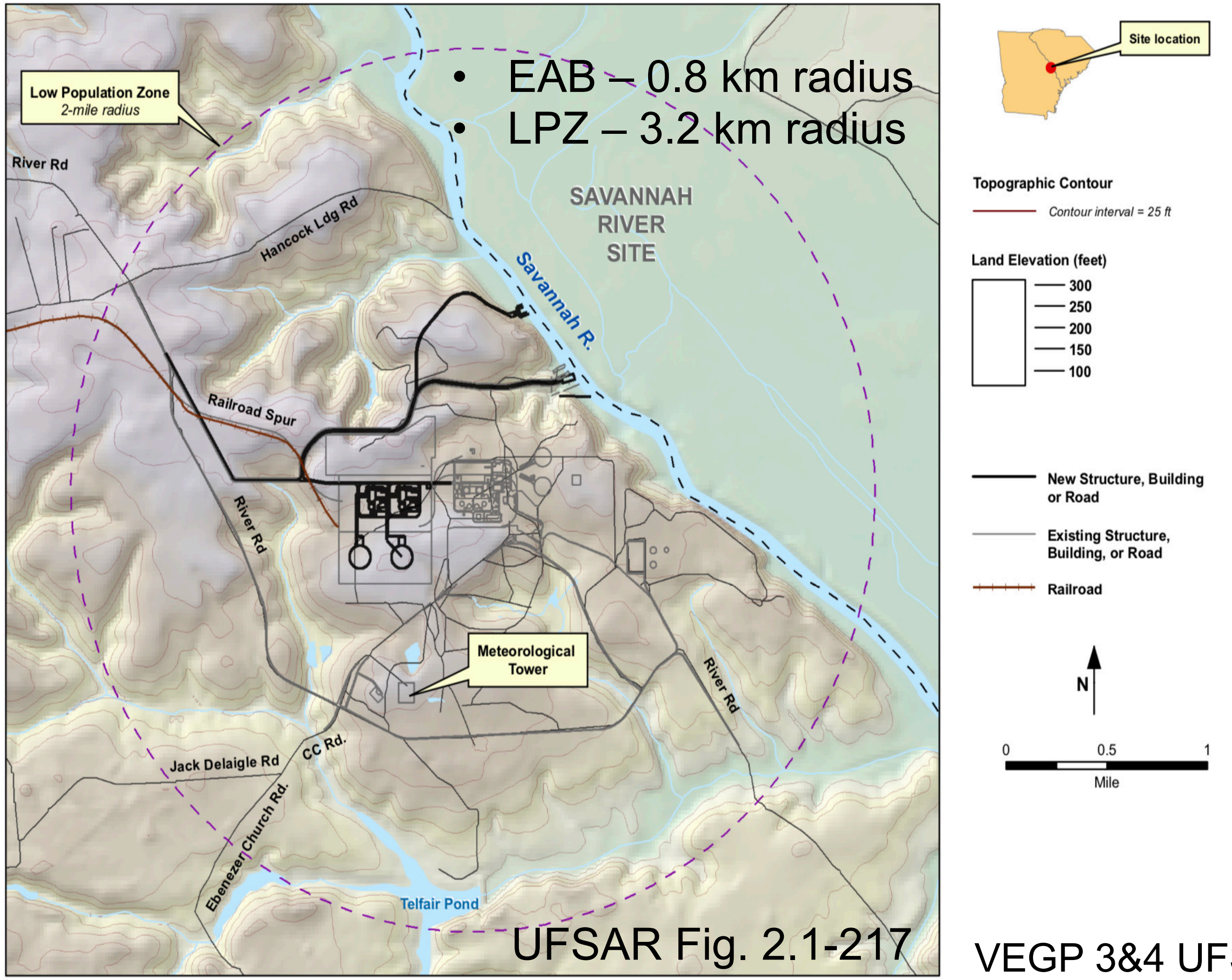
Postulated Accident	EAB	LPZ	Control Room
Loss of coolant accident	190 mSv (19 rem)	150 mSv (15 rem)	34 mSv (3.4 rem)
Main steamline break outside containment			
With accident-initiated iodine spike	2 mSv (0.2 rem)	8 mSv (0.8 rem)	13 mSv (1.3 rem)
With preaccident iodine spike	<1 mSv (<0.1 rem)	1 mSv (0.1 rem)	9 mSv (0.9 rem)
Reactor coolant pump shaft seizure			
With feedwater available	<1 mSv (<0.1 rem)	<1 mSv (<0.1 rem)	8 mSv (0.8 rem)
Without feedwater available	<1 mSv (<0.1 rem)	<1 mSv (<0.1 rem)	12 mSv (1.2 rem)
Rod ejection accident	15 mSv (1.5 rem)	24 mSv (2.4 rem)	11 mSv (1.1 rem)
Fuel-handling accident	24 mSv (2.4 rem)	10 mSv (1.0 rem)	29 mSv (2.9 rem)
Small line break accident	10 mSv (1.0 rem)	4 mSv (0.4 rem)	14 mSv (1.4 rem)
Steam generator tube rupture			
With accident-initiated iodine spike	5 mSv (0.5 rem)	7 mSv (0.7 rem)	26 mSv (2.6 rem)
With preaccident iodine spike	10 mSv (1.0 rem)	6 mSv (0.6 rem)	50 mSv (5 rem)
Spent fuel pool boiling	n/a*	<0.1 mSv (<0.01 rem)	<0.1 mSv (<0.01 rem)

* n/a, not applicable

https://www.nrc.gov/docs/ML0332/ML033290632.pdf

EAB and LPZ for AP1000s at Vogtle 3&4

- EAB – 0.8 km radius
- LPZ – 3.2 km radius

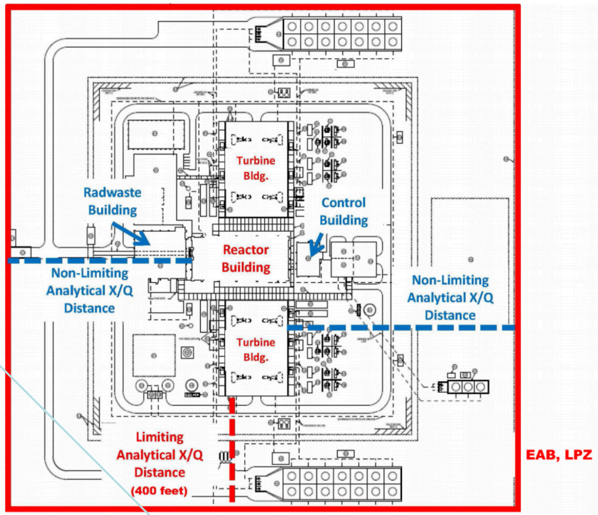


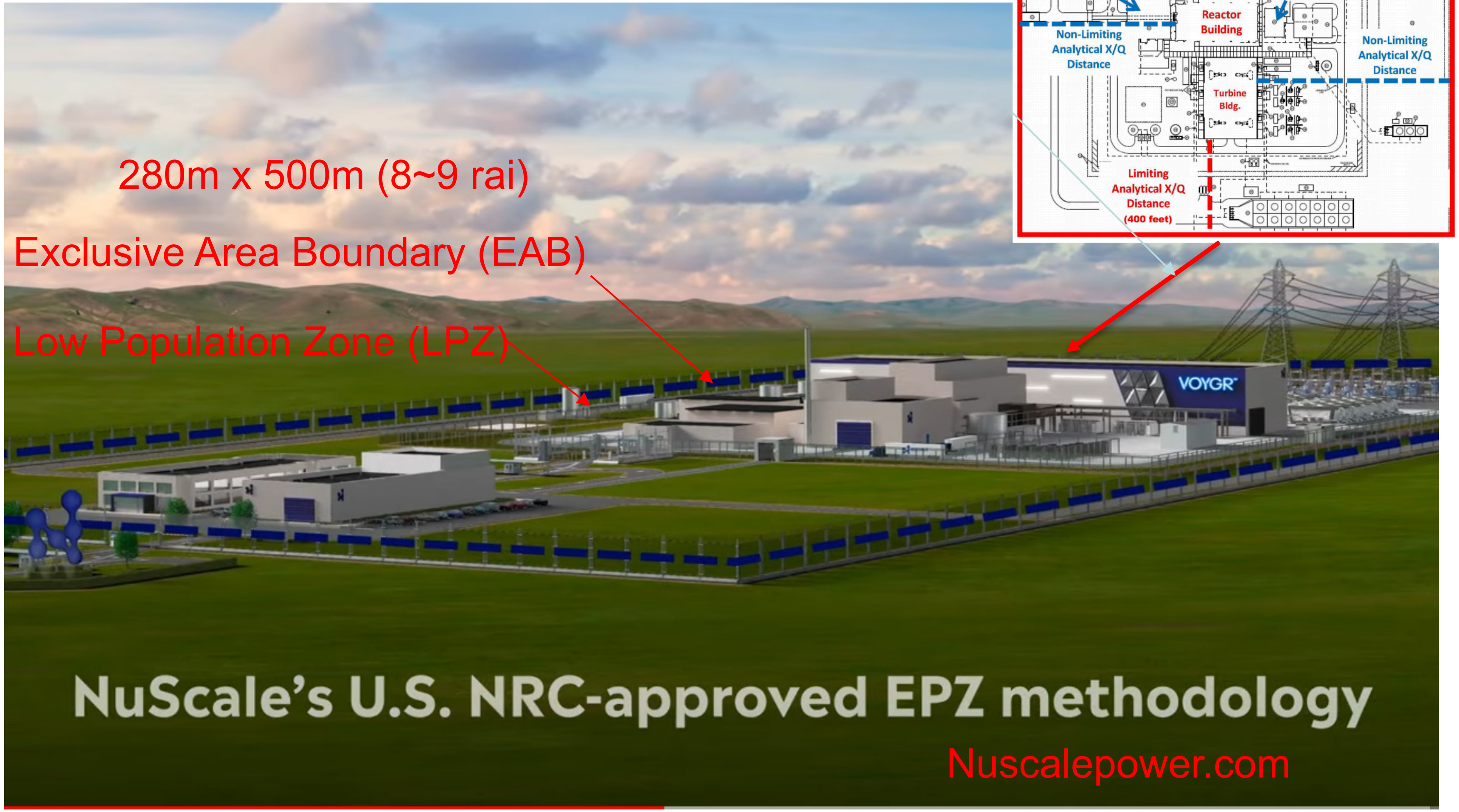
UFSAR Fig. 2.1-217

https://www.nrc.gov/docs/ML1817/ML18179A268.pdf

VEGP 3&4 UFSAR Rev. 3, p.2.0-11

NuScale SMR Plant Footprint





Parameters indicating significant safety improvements in SMRs vs Large LWRs

Core damage frequency

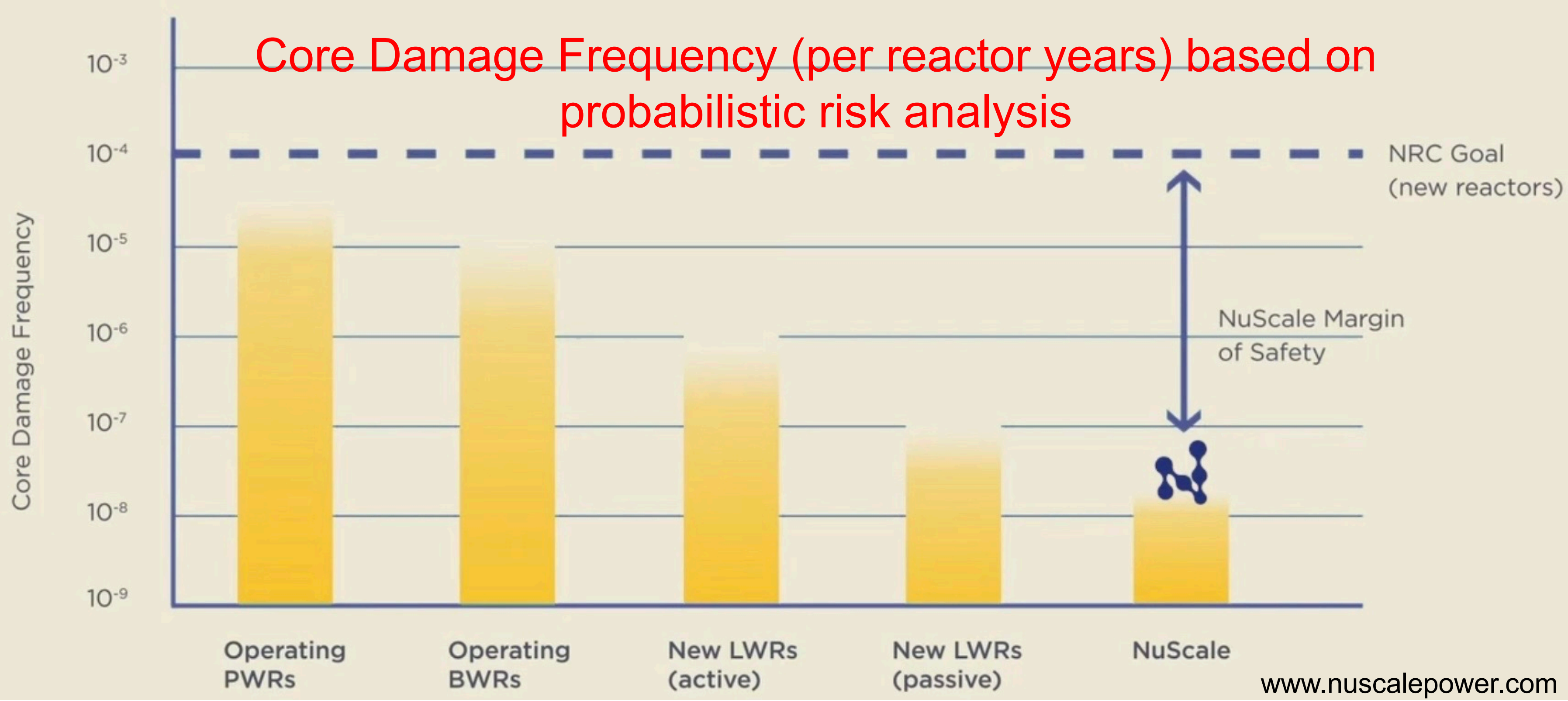
Large LWR vs SMR: $5x10^{-6}$ vs $3x10^{-10}$

Low DBA accident dose

Small EAB, LPZ, &
(emergency planning zone)

Large LWR vs SMR: EAB -0.8 km vs 0.5 km
LPZ – 3.2 km vs 0.5 km

Accident Frequency (calculated) of Old and New Reactor Designs



Demonstration of SMRs and Advanced Reactors

Reactor Technology	Company (reactor power)	Demonstration Schedule
LWR-based SMRs	NuScale (462 MWe), GEH (300 MWe), Holtec, Westinghouse (300 MWe)	NuScale by 2029-2030? GEH by 2028-2029? Westinghouse 2033?
Liquid metal fast reactor	Terra Power (345 MWe)	Terra Power by 2030-2031?
High-temperature gas reactor	USNC (5MWe) X-Energy (80 MWe)	USNC by 2026? X-Energy* by 2029?
Fluoride Salt-cooled reactor	Kairos Power (134 MWe)	Demonstration of reduced-scale 35 MWt prototype is planned by 2030?
Heat-pipe-cooled micro reactor	Westinghouse (5 MWe)	Demonstration by 2026-2027?
Molten salt-fueled-cooled reactor	Terrestrial Energy (392 MWe)	Likely in Canada

* X-Energy plans to build 12 more units by 2030s.

Economics of Nuclear Plants

US AP1000 Construction Delay and Cost Overrun

2024

- Vogtle 3 reaches first criticality on March 6, 2023, connects to grid on April 1, and reaches full power on May 29.
- Vogtle 4 reached initial criticality in February 14, 2024, began commercial operation April 30, 2024

2006
Early Site Permit applied : Vogtle 3&4 Georgia
Approved by NRC in 2009

2008
COL submitted
Approved by NRC in 2012

2013
Construction started

2016-2017
Original date for operation
10 years delay

2023-2024
Commercial operation

Construction of Summer 2&3 follows similar schedule with the completion date about 1 year behind, but by Aug. 2017 the project was suspended.

2008

Contract agreement signed for a fixed price of ~$14B for two units.

COL – combined license application submitted

2011 - 2013

March 11, 2011- Fukushima accident occurred.

December 11, 2011, NRC certified the AP1000 design revision 19

2012 – NRC approved the COL

March/November 2013 – Unit 3 /4 construction started

2015-2018

2015 – Construction contractor CB&I exited the project.

March 31, 2017 – WEC filed for bankruptcy with a $9B loss on the project.

Aug 31, 2017- Bechtel took over construction.

New cost estimate: $19.8 B (Aug. 2017),

New cost estimate: > $30 billion (as of Aug. 2022) including Fukushima + bankruptcy + pandemic-related delays

Construction began before the detailed design completion. Design changes during construction were a prominent source of delays.

A MIT Study on the Capital Cost of AP1000 at Votgle 3&4

https://web.mit.edu/kshirvan/www/research/ANP193%20TR%20CANES.pdf

- AP1000 remains attractive option for US market, according to an MIT study (Apr. 2022)
- An overnight capital cost of $5100[1] per kilowatt for the next AP1000 series in the USA is achievable

Large PWRs	Overnight cost ($/kWe)	Construction time (months)	Total cost ($ billion)
Pre-TMI	4,700	100	11
Post-TMI	9,512	150	21
Estimated post-TMI Vogtle 3&4	9,200	130	32
Vogtle 3&4 projected cost (2021)	7,956	120	30
Next AP1000 cost	5,100[1] (6800[2])	60 (100)	11.2[1]
10th AP1000 cost	3,400[1] (4500[2])	50 (60)	7.72[1]

[1] 20% price inflation multiplied to original values
[2] if labor productivity reduced by 2x.

AP1000 Potential Deployment

- Ukraine 2 units at Khmelnytskyi by 2030-2032 with total of 9 units. Work under way for first AP1000 in Ukraine as of April 2024 (Cost estimate - $5 billion per unit, $4476/kWe)
- Poland, first unit to begin construction in 2026 and finish by 2033, then 6 units by 2040 as of April 2024
- Bulgaria signed a front-end engineering and design contract with Kozloduy NPP for an AP1000 unit (June 14, 2023)

> - AP1000 remains attractive option for US market, according to an MIT study (Apr. 2022)
> - Next AP1000 is projected to cost $4300/KWe in the US (in 2018 dollars) and be cheaper in countries with lower labor rates and other costs than the US.
>
> https://world-nuclear-news.org/Articles/AP1000-remains-attractive-option-for-US-market-say

NuScale SMR Construction Cost Projection

NuScale

2013- $226M from DOE

- 2007 founded
- 2011 Fluor Corp. provided funding and took over management with Dr. Reyes as CTO.

2015- $16.6 M from DOE

- 2012 UAMPS became a customer with a carbon-free power project.
- December 2016 DCA summitted

2018 - $40M from DOE

- May 23, 2019 Sargent & Lundy became a NuScale investor signing an MOU to provide additional architect engineer support.
- May 2022, Flour corporation is the contractor for engineering, procurement, and construction. Majority owned by Flour

- Sep. 2020 DCA approved,
- Dec 2020 IPO issued
- Feb 21, 2023 Design certification received
- Nov 2023, UAMPS project was cancelled
- 2024 COLA submit for a 6-module, 460 MWe SMR plant at the INL site for UAMPS?
- 2024 Construction begins?
- 2029 First reactor online?

The first SMR design was certified by the USNRC on February 21, 2023.

Producer price index during pandemic (2020-2022) have raised the cost of:
Fabricated steel plate by 54%
Carbon steel piping by 106%
Electrical equipment by 25%
Fabricated structural steel by 70%
Copper wire and cable by 32%

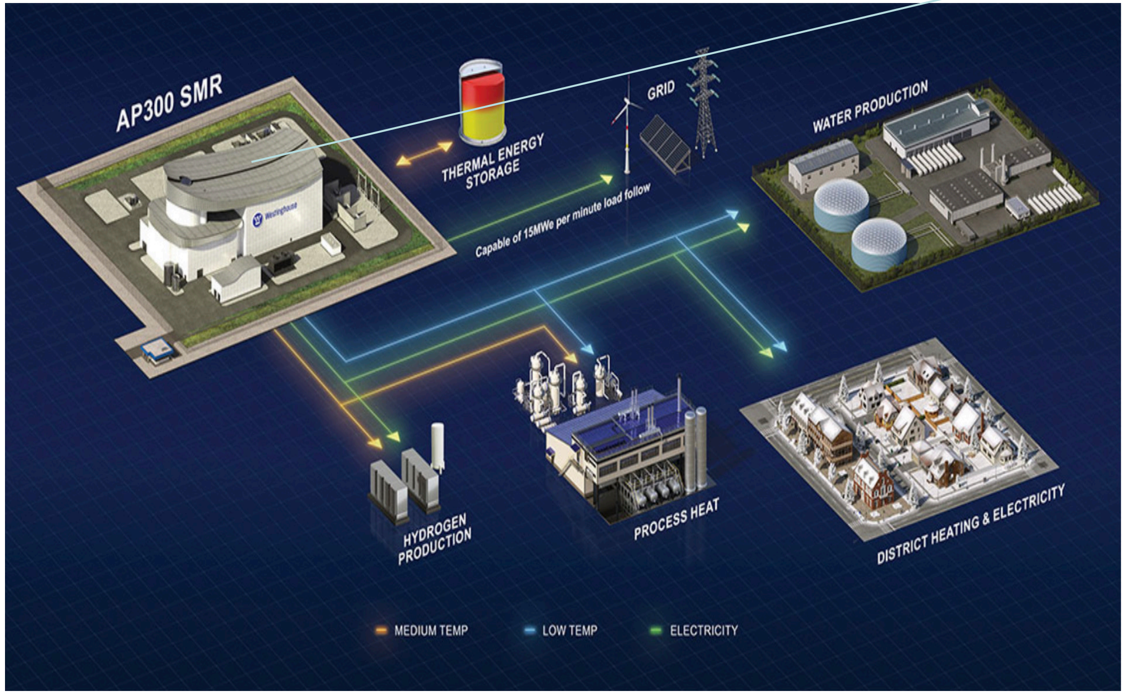
Summary of the Cost of SMRs vs Large LWRs according to the MIT Study

- 9 BWRx-300 SMRs are cheaper than 36 module NuScale SMRs for a single site with 2.7 MWe capacity.
- Two large ABWRs are cheaper than nine BWRX-300s for a single site with 2.7 MWe capacity.
- The SMRs overnight costs per kWe are estimated to be 1.4-1.75 the cost of the next AP1000 due to lack of economy of scale.
- If a large power station is needed, a few large reactors like AP1000 would be cheaper than multiple SMRs like NuScale SMRs.
- SMRs are an attractive option for certain markets where only a fraction of power of a large reactor is needed.

NuScale Potential Deployment

- US – INL site, $9.3 billion, 462 MWe SMRs for UAMPS was cancelled in November 2023.
- Romania - Earlier in 2023, NuScale and RoPower Nuclear—a joint venture of Nuclearelectrica and Nova Power & Gas — commenced front-end engineering and design work for a site in Doicești, Romania for the 462 MWe VOYGR plant, by the end of the decade.
- Poland - April, 2023- applied for site and construction permit of NuScale SMR for energy use by a mining company KGHM. (April 2023, during the G7 meeting, US ready to lend Poland $4 billion ($3B from EXIM, $1B from DFC) for SMR development.)
- In May 2023, Nucor, after investing in NuScale IPO, signed an agreement to a cost evaluation of installing SMRs on the site of Nucor's Electric-Arc-Furnace steel mills.
- Indonesia -March 2023 - received a grant from the USTDA and select to assess the technical and economic viability of a 462 MWe NuScale nuclear power plant.

Potential Deployment of SMRs in various Applications



www.westinghousenuclear.com/energy-system/ap300-smr

Data centers next to Nuclear plants

US Data centers - 4% of US electricity
Worldwide - 2% of global production

In the US 2700 Data centers (+crypto mining) sapped more than 4+2 percent of the US total electricity in 2022. A total of about 6% is not a trivial number at all. Worldwide, there are 8000 data centers, typically at least 100 MW for each center. The growth projection for the coming years would be astonishing since the world is just starting an AI boom.

Currently there is exploding demand for computational power to create and use AI systems.

We are in the race against climate change.
The race is both
a marathon and a sprint

Thank You