NARUC
National Association of Regulatory Utility Commissioners

Advanced Nuclear Technology Workshop Summary
July 1, 2021

Welcome
Commissioner Tim Echols, Georgia Public Service Commission
Commissioner Anthony O'Donnell, Maryland Public Service Commission

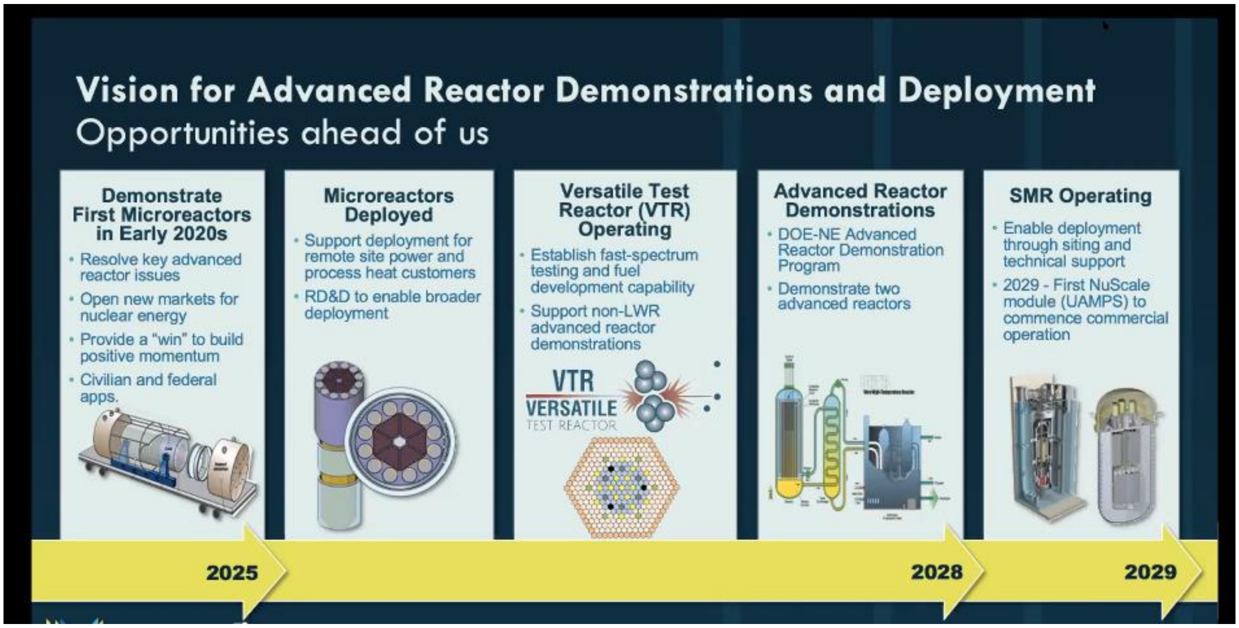
The NARUC-DOE Nuclear Energy Partnership was launched in 2021 with support from the U.S. Department of Energy Office of Nuclear Energy. It is an educational partnership that provides opportunities for state public service commissioners and commission staff to better understand barriers and possibilities related to the U.S. nuclear fleet. Members of the partnership represent 20 states and territories, and the partnership includes associate members from the Coalition for Advanced Reactor Solutions, University of Michigan Nuclear Engineering and Radiological Sciences, and the University of Illinois Nuclear, Plasma & Radiological Engineering.

This workshop builds upon the Introduction to Advanced Nuclear webinar on June 4, 2021 by featuring advanced nuclear technology researchers and experts from the public and private sectors. The workshop highlights the role of public-private partnerships in the commercialization of advanced nuclear technologies and identifies information gaps and state needs and challenges in advanced nuclear development. View the agenda.

Overview of the pathway to technology commercialization and demonstrations supported by the DOE Office of Nuclear Energy
Ashley Finan, Director, National Reactor Innovation Center, Idaho National Laboratory

The Nuclear Reactor Innovation Center (NRIC) is headquartered at Idaho National Lab (INL) and is a national program that works with DOE and many national labs to support advanced nuclear projects. INL's vision for advanced reactor demonstrations and deployment (Figure 1) includes initial microreactor demonstrations in the early 2020s, and their deployment later in the decade. The Versatile Test Reactor is a significant research effort that enables research on advanced materials and advanced reactors. Advanced reactor demonstrations are expected in the late 2020s and include reactors that are supported by DOE's Advanced Reactor Demonstration Program (ARDP) as well as Utah Associated Municipal Power Systems.

Figure 1. Nuclear Reactor Innovation Center vision for advanced reactor demonstrations and deployment



ARDP represents a significant investment of funds and effort from the DOE that was awarded in late 2020. Several of the companies represented in this workshop were awarded ARDP awards. Objectives for the ARDP include are to:

- Develop, construct, and demonstrate several advanced reactors with beneficial capabilities, such as more versatility, higher safety, non-proliferation, lower waste profile and critically lower cost
- Support a diversity of advanced designs
- Stimulate private sector companies and the supply chains that are needed to establish the reactors into commercial deployment scale.

The ARDP has three funding pathways that are aligned with the varied maturity levels of these technologies:

- The Advanced Reactor Demonstration (Demos) awards are commercial demonstrations that are ready to be put on the grid once built
- Risk Reduction for Future Demonstration (Risk Reduction) awards are for technologies that are a little further out - near the 7-12 year time frame.
- Advanced Reactor Concepts-20 (ARC-20) awards are more R&D focused and further out in terms of commercialization

The ARDP awards do not represent the totality of advanced reactors being brough to market. NRIC also supports additional products including those by Oklo, Micronuclear, Radiant, the U.S. Department of Defense.

The NRIC vision is to demonstrate at least two advanced reactors in partnership with the private sector by 2025 and see commercial advanced nuclear by 2030. NRIC is working to achieve this mission by

inspiring stakeholders and the public, empowering innovators to test and demonstrate their technologies, and to deliver successful outcomes through efficient coordination of partners and resources throughout the national laboratories and the private sector. NRIC is empowering innovators by facilitating a Demonstration Resource Network which sets up facilities throughout the labs that can support demonstrators in their efforts to do key experiments, find test sites, and build reactors.
While it was not a focus in the initial development of nuclear power, NRIC is focusing on addressing costs and markets in this advanced reactor demonstration cycle by:

- developing a public-private partnership to demonstrate some advanced construction technologies;
- using digital engineering to manage the design and construction process;
- partnering with the Nuclear Energy Institute, Electric Power Research Institute and the Tennessee Valley Authority on construction readiness; and
- working on integrated energy systems.

The role of public-private partnerships (PPPs) for advanced nuclear

Alex Gilbert, Project Manager, Nuclear Innovation Alliance

The Nuclear Innovation Alliance (NIA) is a think-and-do tank which focuses on advanced reactors for climate mitigation. Last fall, NIA met with stakeholders throughout the nuclear industry to develop the "Conditions for Success," which outlines the conditions necessary to achieve nuclear industry goals. NIA found that a whole-society effort is needed: from government, civil society, customers, communities, and investors (see joint NIA-Partnership for Global Security U.S. Advanced Nuclear Energy Strategy). Deployment at the state level is also essential and will most likely determine the success of the industry overall.

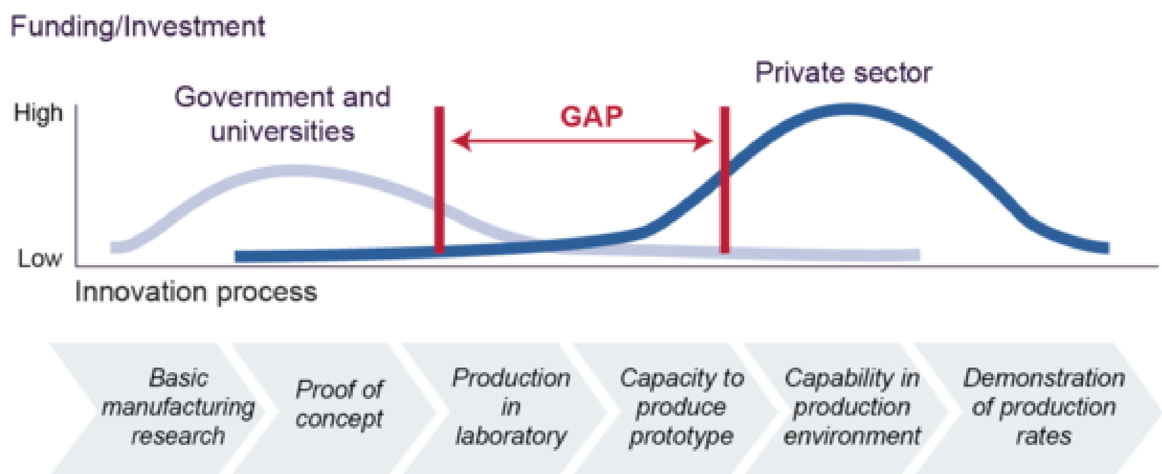
NIA identified that the success of advanced reactors comes down to four factors, and each factor has a role for demonstration projects and public-private partnerships to play. These factors are:

- Competitive cost
- Getting to market
- Public acceptance
- Scaling

Advanced nuclear involves dealing with a fundamentally new industry. Because these reactor types are much smaller, more diverse, and modernized, they can be used in a variety of applications. While nuclear reactors have been traditionally used for electricity generation, they can also be used for applications such as heat production, hydrogen or ammonia production, and maritime transit. The consequence is that nuclear can help meet carbon reduction goals in many other sectors (i.e., buildings, industry, transportation). Public-private partnerships are important for figuring out which of these areas to expand into.

Figure 2 shows a simplified representation of the technology development pathway through commercialization. It is important to emphasize that there is a gap in funding and investment around the demonstration and pilot phase. There is usually a lot of funding and investment in early research and development and proof of concept. However, there is a gap when things transition from where the public sector plays a role to where the private sector plays a role. Public-private partnerships are intended to address this gap between public funding in early stages and private funding at commercialization by having both stakeholder groups invest in the process. Advanced nuclear projects are currently approaching this gap.

Figure 2. Representation of the technology development pathway to commercialization



Source: GAO adapted from Executive Office of the President. I GAO-21-202

Advantages of public-private partnerships:

- Combines the best of government and private sectors, allowing for the balancing of technical and economic risks
- Bridges the commercialization gap by combining resources to address concurrent risks
  - Demonstration and advanced R&D projects reduce technical risk by proving operational feasibility
  - First-of-a-kind projects reduce financial risk by establishing commercial viability
- Early movers can establish innovation hubs and use the opportunity to build up business, public support, and policy around the initial project.

NIA Resources;

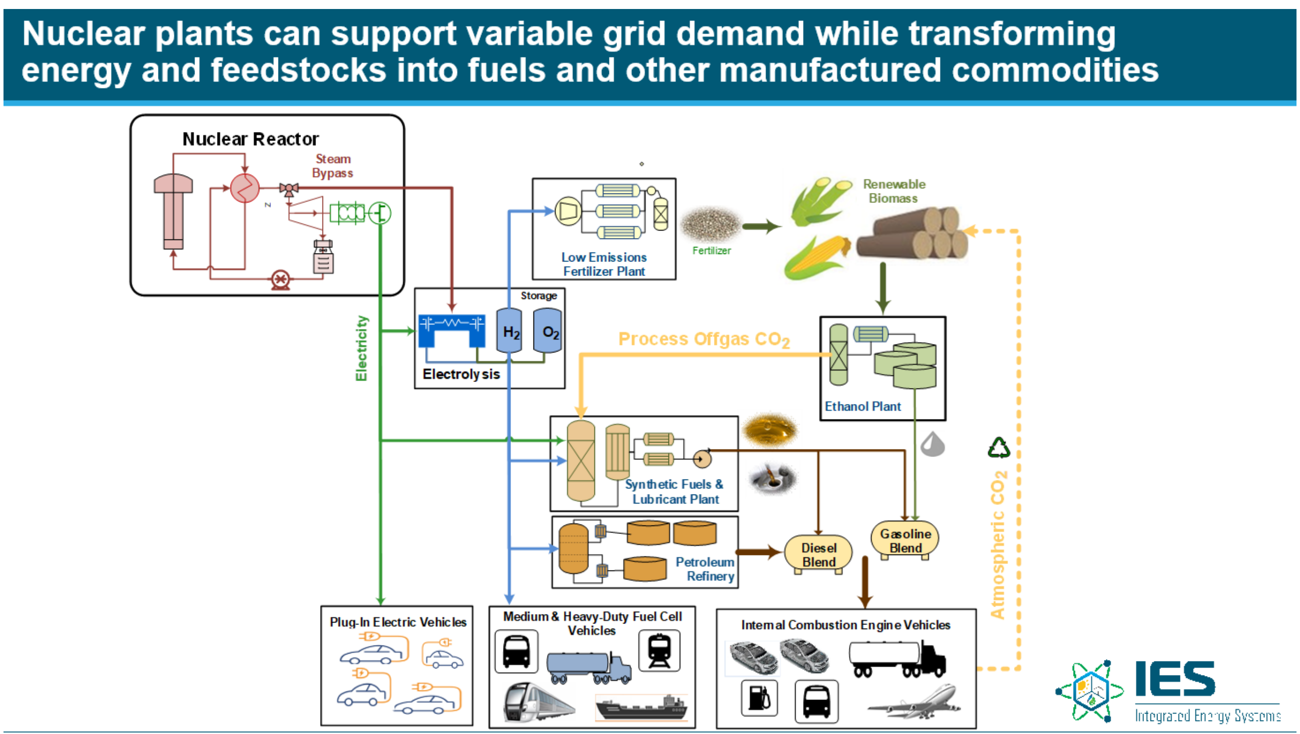
- In Search of a SpaceX for Nuclear Energy – This report looks at how the public-private partnership that the National Aeronautics and Space Administration (NASA) used to encourage SpaceX to develop a domestic commercial launch capability can be used for advanced nuclear.
- Upcoming
  - Primer on Advanced Reactor Technologies
  - Advanced Nuclear Energy Guide for State Policymakers
  - Due Diligence Guide for Investors

Christine King, Director, Gateway for Accelerated Innovation in Nuclear, Idaho National Laboratory

While there are a variety of different decarbonization models, the models generally agree on the near-term importance of renewables deployment, the medium-term role of gas capacity to fill the gap to 2050, and the long-term need for clean firm generation and companion technologies to wean off natural gas.

As we look at future energy systems, it makes sense to look at many scenarios and plan for multiple futures. To start approaching this, think about the desired goals for the future energy system (i.e., performance based, lowest cost, greatest net benefit). This comes from understanding, at a regional level, the availability of resources today and how they can be used or adapted for future energy systems. This survey of resources can include existing facilities, current industries, and lab/university capabilities. It is critical to understand how each sector is thinking about the clean energy transition and investigate how to integrate and optimize resources. Figure 3 shows that nuclear power plants can provide electricity to a variety of feedstocks to support different industries. States are likely to start at the bottom of the figure and work backwards to the technology asking: What are the industries we are trying to support? How do we get the right energy mix to them? And in what form do they need the energy?

Figure 3. Representation of an integrated energy system with nuclear energy



There are many options for public-private partnerships (as shown in Table 1), and each PPP was designed to support different aspects of commercialization and development.

Table 1. Public-Private Partnerships for nuclear technologies

Funding Opportunity	Unique Feature	Timing	Size, Length	Cost Share
NE Voucher (GAIN)	$ to Hire Labs Quick Turnaround	Continuously Open, Award Quarterly	<$500K, 1 year	80/20
Advanced Nuclear Technology Development (iFOA-1817)	$ to Industry	Continuously Open, Award Quarterly	$10-40M, 3 year $500K – 20M, 2 year $50 – 500K, 1 year	50/50 80/20 80/20
Consolidated Innovative Nuclear Research (CINR)	Material and Fuel Experiments	Annually RFP August Award July	<$500K, 3 yr R&D <$4M, 7 yr Irradiation Work	100/0
NSUF Rapid Turnaround Experiments	Irradiation Effect Experiments	3 times per year	<$50K, 9 months	100/0
Small Business Innovation Research (SBIR)	targeted entrepreneur	Various topics/timing varies SBIR.gov	Phase 1: $150K, 6 months Phase 2: $1M, 2 Years Phase 3: refer to website	
Technology Commercialization Fund (TCF)	Technology is Market Focused NL is awardee	Annually Announced Topics September Award Late Spring	Topic 1: <$250K, 18 months Attract private partner Topic 2: <$1.5M, 36 months Have private partner	50/50 50/50
Advanced Reactor Demonstration Program	FOAK Demos & Risk Reduction	One time Funding Opportunity Awarded Fall 2020	$160M, within 5-7 years $30M, within 10-14 years $20M, demo in mid 2030s	50/50 80/20 80/20

Table 2 shows advanced nuclear projects which have been completed over the last 5 years. This table also shows that we are approaching parity on the federal and private investment, highlighting the significant private investment occurring in this space.

Table 2. Public-Private Partnerships related to advanced nuclear over the past 5 years

Name	#	Size, Length	Cost Share	Federal ($M)	Private ($M)	Total ($M)
NE Voucher (GAIN)	60	<$500K, 1 year	80/20	19	5	24
Industry Funding Opportunity Announcement (FOA) -1817						
First of a Kind	6	$10-40M, 3 year	50/50	70	72	142
Adv Rx Dev	23	$500K – 20M, 2 year	80/20	89	38	127
Reg Assist	9	$50 – 500K, 1 year	80/20	4.2	1.5	5.7
Advanced Reactor Demonstration Program						
Demo	2	$160M, within 5-7 years	50/50	2,620	2,620	5,240
Risk Reduction	5	$30M, within 10-14 years	80/20	602	403	1,005
Adv Rx Con	3	$20M, demo in mid 2030s	80/20	56	14	70
				3,460	3,153	6,614

2016 $2M   2017 $4M   2018 $157M   2019 $87M   2020+ $6.4B

GAIN resources:

- Energy Calculator
- Directories
    - Advanced Nuclear Directory
    - University Directory
- Trends in State Level Energy Markets

Technology expo

Advanced nuclear developers, X-energy, TerraPower, NuScale, GE Hitachi, and Kairos Power, introduced their companies and provided high-level overviews of their technologies during the technology expo. Each company discussed their technologies in development including small modular reactors (SMRs), molten salt reactors, high-temperature gas reactors, and fuel.

Eben Mulder, SVP/Chief Scientist, X-energy

About X-energy

- X-energy is a design house that is developing both reactors and fuel. X-energy received ARDP funding for the Xe-100 reactor (more information below). In addition to Xe-100, X-energy is looking to develop a smaller reactor, the Xe-Mobile, for U.S. Department of Defense (DOD) applications. The reactors use a proprietary tri-structural isotope particle fuel (TRISO-X). The company is also looking at space applications, and the NASA, DOE, and DOD are exploring their technology and fuel for nuclear thermal propulsion and fission power for the lunar surface.
- Table 3 shows some of the opportunities that X-energy has pursued to deploy their technologies:

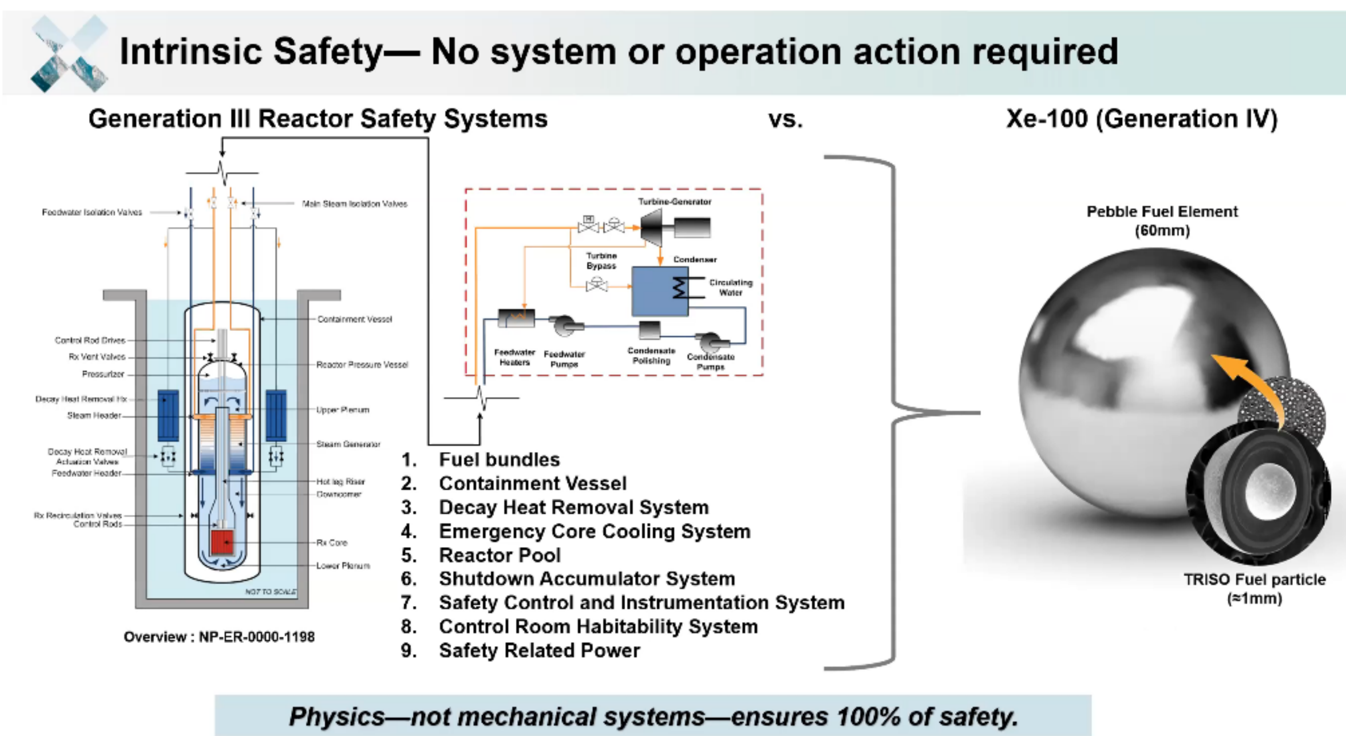
Table 3. Funding opportunities for X-energy

Program	Entrants	Status and Award	Down-Selection
U.S. DOD Mobile Microreactor Program	9	• DOD will make final down-selection March 2022 • Winners will benefit from ~300 MW of DOD demand through 2040	X energy, BWXT
ONTARIO POWER GENERATION OPG SMR Deployment	10	• OPG will make a final down-selection to a single winner no later than Q4'21 • Winner will build reactor at Darlington site • Consortium of Canadian utilities has stated desire to build a *fleet*	X energy, GE HITACHI, TERRESTRIAL ENERGY
U.S. DOE Advanced Reactor Demonstration Program	37	• Final two winners selected • DOE cost contribution of $1.2 bn to X-energy Project	X energy, TerraPower

Xe-100 technology

- The Xe-100 high-temperature gas-cooled reactor is the most mature GEN IV advanced reactor to date.
- The Xe-100 design is a cutting-edge design deployable in the next 5-6 years while providing a cost competitive, low risk, carbon free, and versatile energy solution.
- The TRISO particle fuel differentiates this design from others. The TRISO particles retain 99.999% of the fission products within the fuel without requiring complex safety systems. This can reduce licensing complexity, system costs, and construction times. Due to the fuel design, X-energy was able to eliminate of a lot of the typical safety systems in conventional reactors (some of which may never be used during the lifetime of a plant). The safety of the Xe-100 relies on the physical attributes of the fuel, and not on the mechanical systems. (See Figure 4)
- Elements of the Xe-100 reactor design include:
    - Proven high temperature pebble bed reactor with intrinsic safety characteristics
    - Derived from 50+ years of design and development to significantly reduce costs to enable cost-competitive deployment
    - Proven fuel technology (DOE Advanced Gas Reactor Irradiation program)
    - Conservative design that does not require new material development and / or code case
    - Steam pressure and temperature designed to provide steam to commercially off the shelf (COTS) steam turbine / generator sets

Figure 4. Comparison of a conventional reactor safety system with the Xe-100 design



Jeff Navin, Director of External Affairs TerraPower

About TerraPower

- TerraPower was founded in 2006 by Bill Gates and Nathan Myhrvold as a solution to meet the dual challenge of the growing global demand for energy and global climate crises. TerraPower uses all of the capabilities offered by the 21st century and is looking to develop technologies that are step change improvements from the 20th century fleet of light water reactors. TerraPower is aiming to make safety improvements, reduce the risk of proliferation, minimize waste production, more efficiently use uranium supplies, and reduce cost.

Natrium™ Reactor Technology

- TerraPower was selected to demonstrate the Natrium™ reactor through the ARDP. Natrium was developed in partnership with GE Hitachi and will be deployed in Wyoming with Rocky Mountain Power at the site of a retiring coal plant. Under ARDP, DOE will fund 50% of the project and TerraPower is responsible for securing financing for the additional 50%. Once the plant is built, Rock Mountain Power will own and operate the plant as part of their generation fleet. TerraPower is assuming the risk of cost overruns and schedule delays, and the ratepayers in Wyoming will not be responsible for any such increases. The PPP thus allows TerraPower to find a power partner they can engage with and protect their customers as the technology is being developed.
- The Natrium™ reactor is being designed to meet the needs of a 21st century grid and 21st century utilities. For example, heat from the Natrium reactor will be used to power a molten salt energy storage system that allows the reactor to store up to 500MW of power for 5.5 hours. In terms of storage potential, this is four times larger than the largest lithium lion battery storage facility that currently exists in the world. This can be a value to utilities as they work to decarbonize their grids and adapt to more intermittency on the grid.
- Natrium™ will be able to provide carbon-free firm and flexible power. The reactor will also offer significant safety improvements over conventional designs. Natrium will not require active safety systems, will eliminate the need for diesel engines for cooling system pumps, and will not require backup systems and human intervention under most emergency scenarios.
- The reactor will use a sodium coolant. Sodium has a boiling point of 882°C and the reactor's operating temperature is hundreds of degrees below that boiling point, in the mid-500s. This significantly reduces the likelihood of an accident since the coolant will not get boiled off. The high boiling point also allows TerraPower to operate at atmospheric pressure, eliminating the need for a pressurized system and associated redundancies to deal with a high-pressure rapid coolant release.
- Similar to X-energy, TerraPower also relies on the physics to maintain the safety of the plant without needing operator intervention of auxiliary power.
- The reactor is approximately one-third the size of the larger plants that are currently operating in the U.S. The reactor is a 345-MW electric rated reactor. This is significant because the cost to build is significantly smaller. Additionally, the smaller size and coolant technology dramatically reduces the likelihood of an accident, and if an accident were to happen, also reduces the scale.
- TerraPower's demonstration in Wyoming is advantageous since they will have access to grid interconnection, access to sources of water, and access to a skilled workforce that is knowledgeable about running complex energy systems.

Chris Colbert, Chief Strategy Office, NuScale Power

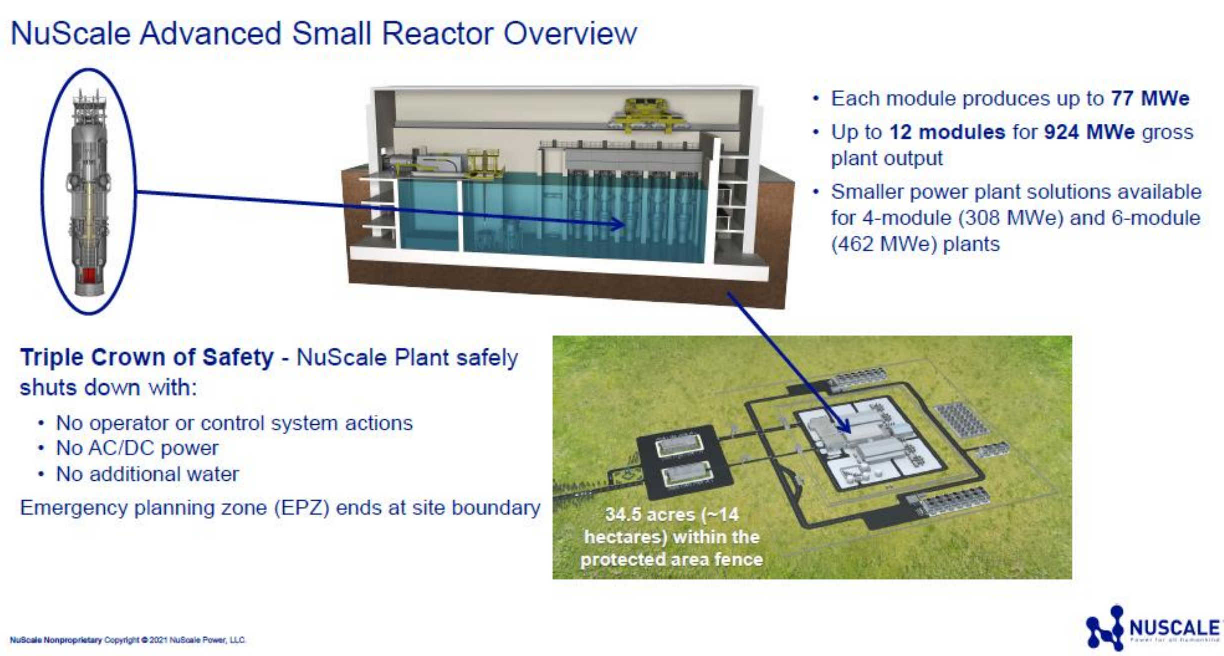
About NuScale

- After a public-private partnership with DOE in 2000, the company was formed in 2007 by co-founder and CTO Jose Reyes. Approval of design by Nuclear Regulatory Commission in August 2020. NuScale received an additional award from DOE to complete commercialization of technology to get to next phase and ultimate deployment before the end of the decade.

NuScale Technology

- Advanced small modular reactor: less than 300 MWe. Idea is for them to be modular, safer, affordable, and flexible. NuScale module is 76 ft tall, 15 ft diameter. Produces approximately 1 GW power (1/15 the power) at 1/100 the volume of a typical large boiling water reactor.
- Prospective NuScale reactor sits in a pool of water in a reactor building within a steel-reinforced concrete building, seismically robust and aircraft impact resistant on a 34.5-acre site. 12 modules at 77 MWe produces 924 MWe gross output (See Figure 5). Great deal of flexibility in terms of how many modules make up an installation.

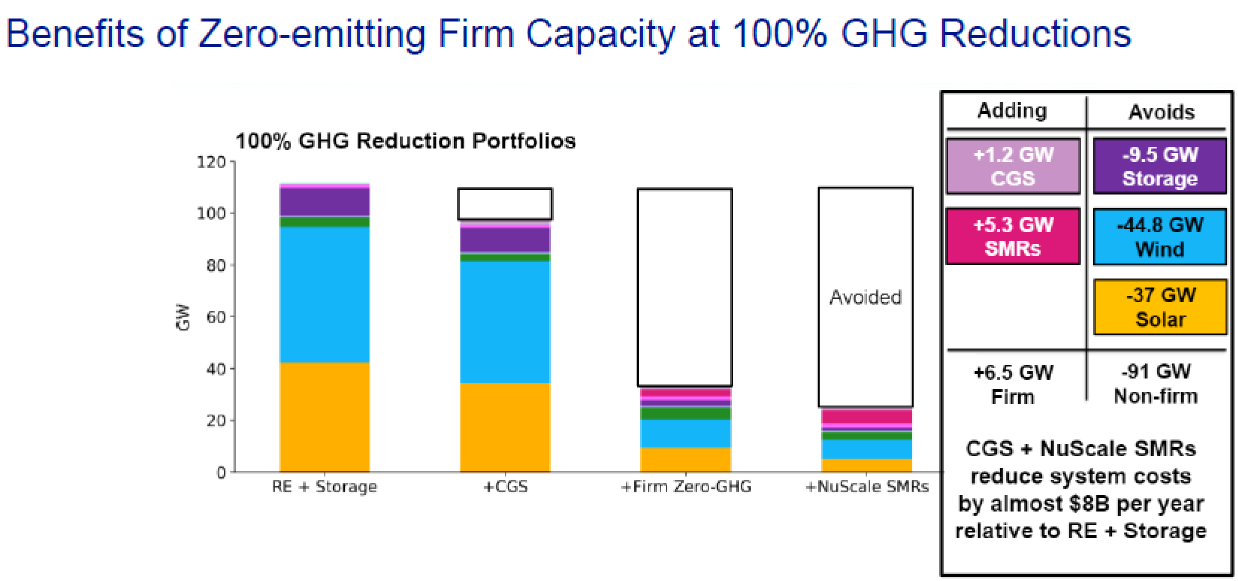
Figure 5. NuScale Overview



- NuScale has demonstrated that in case of a blackout or Fukushima-like scenario, it can safely shut down the plant without power or water. Because the amount of radioactive material in the core is small, the likelihood that radioactive material could escape the reactor is miniscule, and by the time it gets to the site boundary, it would not be harmful to people or the environment. Emergency planning therefore can end at site boundary with no need for off-site evacuations. This gives NuScale the ability to locate closer to communities or other partnering infrastructure. Modules can power critical facilities, oil refiners, hydrogen production, desalination, and other uses. Modules can cycle output rapidly (<35 minutes) and do not require a grid connection in order to operate.

- Key to affordability is a new approach to construction and operation: build reactor and containment in a factory while, in parallel, constructing reactor building and other facilities on-site. Reactors are transported by truck or rail to the site and installed.
- Complimentary with renewable generation: recent E3 study for Energy Northwest in Washington state found that relying solely on renewables and batteries for a 100% carbon-free power system requires a much larger capacity build-out than relying on reactors for some power needs. Adding small modular reactors brings needed capacity down from ~110 GW (with RE + storage only) to ~30 GW, about half of which is wind and solar (See Figure 6). Adding small modular reactors saves costs and land use.

Figure 6. Role of Small Modular Reactors in GHG Reduction Scenarios



- Design certification application was approved in August 2020, at a cost of over $500 million and 42 months of NRC review. NuScale's is the first small modular reactor to undergo licensing in the U.S.
- NuScale received an additional award from DOE to make sure parts that go into NuScale plants are readily available. When plants or projects go wrong, it is often because the planning is insufficient.
- UAMPS Carbon Free Power Project will be first deployment in U.S. UAMPS represents 47 members throughout West, about half of which are part of the project with NuScale. By end of 2020s, members need to replace 750 MW of retiring coal generation. Members have wind, solar, and energy efficiency, but still need baseload dispatchable power source for customers. The project received a $1.4 billion, ten-year award from DOE to de-risk the early front end of NRC licensing and bring down first-time cost associated with first plant. This award makes NuScale affordable to members so ratepayers aren't facing rate shocks with completion of the first plant.
- NuScale and other advanced nuclear companies are considering repurposing coal power plant sites to host future advanced nuclear projects. Benefits include reuse of existing transmission,

water supply, and other infrastructure to lower costs for nuclear projects, as well as repurposing coal workforce in plant construction, maintenance, and operations positions.

- More than 145 GW of retiring coal through 2050
- Large opportunities for job creation/preservation, clean energy investment, and CO2 reductions

Chrissy Borskey, Global Government Affairs and Policy, GE Hitachi

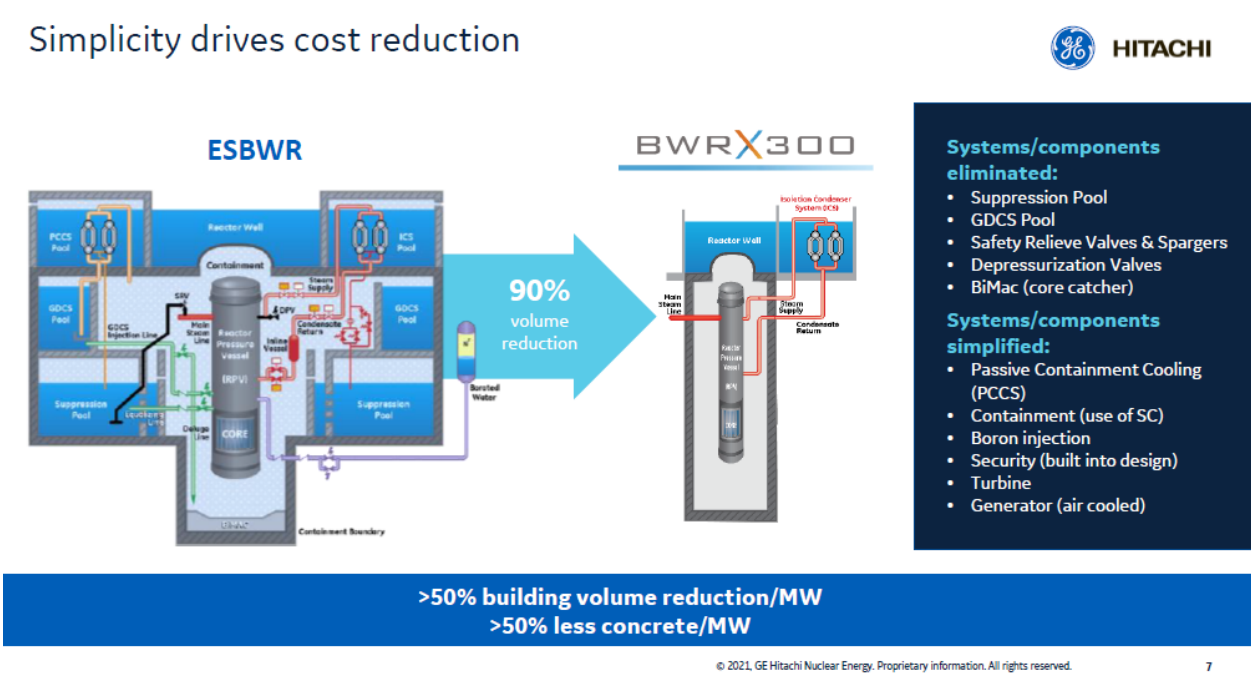
About GE Hitachi

- Advanced nuclear, fuels, field services, and plant solutions businesses at GE Hitachi

GE Hitachi Technology

- In 2017, launched BWRX-300 based on desire from customers for nuclear to be cost-competitive with natural gas combined cycle plants. In 2018, EPRI issued a report saying nuclear needed to get to $2000/kW to significantly grow. GE Hitachi's small modular reactor is being designed to meet that target.
- 10th generation boiling water reactor, 300 MW water cooled. Scaled down large boiling water reactor, built using design-to-cost approach with safety as a critical consideration. The reactor is capable of load-following and will be operational by 2028.
- Simplicity drives cost reduction: GE Hitachi created an interval isolation valve (patented and NRC-approved) that allows removal of cooling systems and simplification of the system. This enables a 90% volume reduction (50% reduction of building size per MWh) which removes much of the capital costs of a traditional nuclear plant (See Figure 7).

Figure 7. GE Hitachi Overview



- GE Hitachi benefits by using proven technology without the need to re-test, re-manufacture, or re-create components. GNF2 fuel is manufactured in Wilmington, NC. This approach allows greater certainty and cost reduction by using the existing supply chain that supplies current fleet of boiling water reactors.
- GE Hitachi is developing virtual reality to train field services staff.
- Ontario Power Generation has an opportunity for advanced nuclear: X-energy, GE Hitachi have been down-selected. TVA, Dominion Energy, Exelon, Xcel, Southern Nuclear, MIT are domestic partners for GE Hitachi.
- Recommendation for state regulators: as states and the country look at net-zero targets, nuclear --- especially small modular reactors --- must be part of the solution.

Peter Hastings, Regulatory Affairs & Quality, Kairos Power

About Kairos

- Kairos mission: enable the world's transition to clean energy with the goal of improving people's quality of life while protecting the environment. Only possible if we think differently about nuclear and prioritize efforts to produce affordable, safe, clean energy technologies.
- Kairos emerged from a DOE-sponsored research project. Researchers formed the commercial company in 2016. Currently 170 employees are based in Alameda, CA. The company is privately funded and focused on licensing and demonstration by 2030 and rapid deployment ramp-up in 2030s.
- Facilities outside of Alameda headquarters: licensing office in Charlotte, NC; engineering test unit in Albuquerque, NM; strategic collaboration with Materion in Elmore, OH; Hermes test reactor site in Oak Ridge, TN.
- Kairos aims to seize the opportune moment of retirement of natural gas generating assets and the need for non-carbon-emitting generation technologies.

Kairos Technology

- Taking an iterative approach to development: rapid lab with real-time prototype testing, salt lab testing with molten salt, component test facility in New Mexico, low-power demonstration reactor at Hermes (owned and operated by Kairos) at East Tennessee Technology Park. Kairos received an Advanced Reactor Demonstration Project risk reduction award from DOE.
- Striving to reduce advanced reactor deployment risk. Each stage reduces risk in different ways (See Figure 8):
    - Technical risks: iterative lab scale development and testing, closely integrated with design and deployment of engineering test unit and eventual demonstration reactor
    - Regulatory risk: comprehensive engagement with NRC staff in advance of license application
    - Commercial risk: demonstration of actual cost and effort to construct a full-scale nuclear island in U-Facility

Figure 8. Kairos Approach to Risk Reduction