## Technical Summary of the MIT/CANES Symposium
## *Nuclear Everywhere?: How new technologies, regulations and policies may finally make the use of nuclear energy mainstream and ubiquitous*

In recent years, interest in nuclear energy has surged, driven by a combination of geopolitical, environmental, and economic factors. The invasion of Ukraine has sparked a renewed focus on energy security, while international climate conferences and evolving policies have facilitated the inclusion of nuclear energy in climate strategies. Notable developments include China's ambitious nuclear expansion, South Korea and Sweden reversing their nuclear phaseout plans, and Japan's commitment to restarting idle nuclear power plants. Additionally, several European countries are pursuing new nuclear power plant projects, and the US government has allocated significant funding for existing and new plants through the Inflation Reduction Act and the Infrastructure Bill. This renewed interest is further evidenced by the launch of Small Modular Reactor (SMR) and next-generation reactor projects in the US and Canada, Dow Chemical and X-energy's plans for nuclear heat in chemical plants, California's decision to extend the Diablo Canyon plant, and increasing attention in popular culture.

Nuclear energy's unique potential to provide abundant, low-carbon, scalable, and reliable power has fueled its resurgence. As concerns over climate change, energy security, and economic development mount, nuclear power may offer a versatile solution to address these challenges. By integrating nuclear energy into broader strategies, the US and countries around the world can begin to bridge the gap between growing energy demands and the need to reduce greenhouse gas emissions.

Despite the renewed interest, uncertainties remain that could limit the role of nuclear energy in the global energy mix. A major accident anywhere could undermine public confidence everywhere and hinder the expansion of nuclear power. Additionally, enthusiasm for SMRs could diminish if early deployments encounter cost overruns and schedule delays like those that have hampered projects in the US and Europe over the past 15 years. Together with those possibilities are concerns that nuclear energy will remain confined to commodity markets and so fail to find its competitive edge in the broader energy landscape.

The MIT Center for Advanced Nuclear Energy Systems (CANES), with support from the MIT Nuclear Science and Engineering Department, Kairos Power, and Constellation, organized a symposium (March 28 - 29, 2023) at MIT to explore the future of nuclear energy, emphasizing new markets, applications, enabling technologies, and the regulatory, policy, and geopolitical context. Key topics included small modular reactors, nuclear hydrogen, nuclear biofuels, and decarbonizing college campuses using microreactors. Discussions also covered the U.S. government's role in expanding the domestic nuclear industry by addressing the need for high-assay low-enriched uranium (HALEU), new fuel forms, and high-level waste management for both existing and new nuclear reactors. Discussions and presentations during the two-day symposium emerged with findings in four key areas:

- Decarbonization and the clean-energy transition
- Diversifying the applications of nuclear technology
- Enhancing the affordability and innovation of advanced nuclear systems
- Addressing policy, regulatory, and fuel cycle challenges

Discussed below, the insights derived from each key area underscore the need for strategic coordination of government support and policy, technological and process innovation, fuel supply, and regulation to guarantee an expanding role for nuclear in the clean-energy transition.

Steve Moore, 2023

### *Decarbonization and the clean-energy transition*

The need to reduce greenhouse gas emissions and transition to a clean-energy future has highlighted the importance of harnessing nuclear energy to supply carbon-free electricity for baseload generation. Besides reducing the consumption of coal, oil, and natural gas, use of nuclear energy minimizes fuel transportation costs and limits the supply-chain vulnerabilities that come with reliance on fossil fuels. As a key example, symposium participants discussed efforts to turn shuttered coal plants into nuclear plants to take advantage of existing BOP and transmission infrastructure while bringing clean-energy jobs to local communities.

Leaders from the Nuclear Energy Institute (NEI) emphasized the substantial contributions of nuclear power thus far (including the annual reduction of 476.5 million metric tons of carbon emissions) and showcased commitments from utilities that envision a growing role for nuclear energy, projecting 100 GW of new nuclear generation by 2050. A presentation from Westinghouse emphasized the role of nuclear energy in the sustainable energy transition, propelled by several intrinsic technological advantages, and called out the alignment of nuclear energy with many of the United Nations' Sustainable Development Goals, in particular the call for affordable and clean energy.

At the center of the symposium's discussion on decarbonization was a panel that welcomed representatives from colleges and universities to discuss the decarbonization of their campuses, including Penn State, Purdue, Abilene Christian, the University of Illinois, and MIT. Penn State's focus involves creating a campus microreactor hub to accelerate the development of low-cost microreactors for applications in heat markets and other regional needs while supporting the development of simple, innovative supply chain solutions. Purdue's campus initiative centers on a small modular reactor nuclear study, aiming to provide safe, reliable, and affordable energy for their West Lafayette campus's steam and power generation needs while reducing greenhouse gas emissions to achieve sustainability goals. Abilene Christian University has established the Nuclear Energy Experimental Testing (NEXT) Lab on campus to address energy poverty, clean water, and cancer research, with plans to deploy a molten salt reactor within their new Science and Engineering Research Center. The University of Illinois is developing a campus microreactor demonstration project with the mission to produce electricity, district heat, hydrogen, and integrated thermal storage. At MIT, the 6MW reactor within the Nuclear Reactor Lab primarily facilitates innovative research rather than energy production; however, the Institute's bold climate goals have begun to spark discussions about incorporating microreactors as a source of carbon-free power on campus.

A lunchtime presentation from Sweden's Kärnfull Energi showcased their efforts to provide electricity sourced exclusively from nuclear power. By offering certificates that guarantee the origin of the electricity, they emphasize the ability of nuclear energy to provide low-carbon, reliable, and abundant electricity. They also have plans to deploy a new series of SMRs in Sweden for both electricity and heat applications.

### *Diversifying the applications of nuclear technology*

The emergence of smaller reactors and new reactor designs is already enabling nuclear energy to penetrate new markets beyond conventional electricity generation, including the production of clean hydrogen, biofuels, and process heat for industrial applications. This trend is set to continue in the coming decades with the deployment of low-cost microreactors, molten salt reactors, and other advanced designs. Inspired by an agreement between X-energy and Dow, industrial offtakers are recognizing that co-locating reactors with end-use applications offers benefits in a world of geopolitical and climate uncertainty — benefits that include reliability, security, price stability, self-sufficiency, and the dynamic provisioning of electricity and heat.

At the symposium, Constellation representatives discussed using nuclear energy to drive clean hydrogen production. They have recently started to produce small amounts of nuclear hydrogen at their Nine Mile Point nuclear site and plan to demonstrate it on a larger scale in response to the provision in the recent Bipartisan Infrastructure Law that calls for at least one nuclear hydrogen hub to be deployed in the US. If successful, this hub could confirm that nuclear-produced clean hydrogen has a cost advantage over alternative hydrogen sources in most regions.

In a presentation from MIT, a comprehensive proposal for nuclear biofuels outlined a method to replace crude oil with economically viable drop-in liquid hydrocarbon fuels and chemical feedstocks generated with nuclear energy. Expanding the application of nuclear energy from generating electricity to producing hydrocarbons could open a large market for reactors of different sizes and designs. For example, individual microreactors would power small depots for refining local biomass that would then travel to centralized refineries powered by larger reactors.

Experts from the DOE's Office of Nuclear Energy and other presenters pointed to a wide range of additional applications on the near horizon, from supplying energy for desalination to indoor farming, data centers, carbon capture, and more.

### ***Enhancing the affordability and innovation of advanced nuclear systems***

Across the nuclear energy ecosystem, efforts are underway to make nuclear energy more affordable and versatile through innovations in design, advanced manufacturing, materials, safety systems, and the handling of fuel and waste. These innovations often span the realms of technology and process, as researchers iterate through new hardware, new designs, and new approaches to experimentation, validation, and systems integration.

A wide-ranging presentation from MIT proposed that advances in key technologies are needed to achieve competitive cost targets, even with the efficiencies expected from modular construction, standardization, and learning curve effects. In particular, enabling technologies are needed for advanced manufacturing, passive safety system designs, compact heat exchangers, and balance-of-plant improvements. Another presentation called attention to the lifecycle of graphite as a neutron moderator, in particular the difficulties that face its safe disposal. Meanwhile, engineers at Los Alamos are exploring the behavior of materials under extreme conditions with an eye toward tailored, predictable performance, all while juggling complex trade-offs between economics, fuel temperature, hydrogen loss, and the ability of different materials to function well together. Researchers at the University of Tennessee are examining the evolution of structural materials used in light water reactors, where innovation is often hindered by regulations restricting the use of newer materials that are cheaper, better performing, and more reliable. A presentation from the University of Buffalo made the case for seismic isolation to protect reactors and proposed a matrix of standards for lowering the engineering and fabrication costs of isolators as well as reducing the amount of plant design modifications required by site-specific ground motion.

Other presentations served as vital reminders that innovation extends to process and protocols. Kairos Power offered a view into the engineering, design, and manufacturing workflow that is moving their fluoride salt-cooled high-temperature reactor (FHR) closer to commercialization — a workflow that emphasizes iterative hardware demonstrations and in-house manufacturing to achieve disruptive reductions in costs. A similar approach is propelling work on the MARVEL reactor at the Idaho National Lab, where the team has adopted a hands-on approach to design and prototyping a full-scale, electrically-heated primary coolant apparatus test (PCAT) to validate the microreactor's performance and to ensure its design meets reliability and safety expectations. Work at the National Nuclear Security Administration (NNSA) demonstrates that process innovation even extends to the work of managing the limited supply of HALEU fuel, as NNSA teams look for novel ways to meet the needs of advanced reactor projects, research reactors, and medical isotope production with a steadily depleting HEU stockpile. Finally, the team at the Office of Spent Fuel and Waste Disposition has launched the Back-End Management of Advanced Reactors (BEMAR) initiative to assess the range of advanced reactor fuels and to anticipate how TRISO, metallic, and other spent fuels and waste will need to be handled, stored, moved, and disposed of. At Sandia, researchers are evaluating geologic disposal as a potential option, taking into account factors like the waste's degradation rate, thermal output, and reactivity to water to determine its feasibility.

### ***Addressing policy, regulatory, and fuel cycle challenges***

The growth of nuclear energy still hinges on government support, public-private partnerships, and a ready fuel supply, as well as ongoing efforts to improve regulatory throughput and dispose of spent fuel and waste.

Several presentations took note of well-funded programs and incentives within the Bipartisan Infrastructure Law and the Inflation Reduction Act, with special attention to direct allocations for advanced reactor demonstrations, civil nuclear credits, loan guarantees, and HALEU production. The legislation also offers indirect support to nuclear energy as an enabling technology for the DOE Energy Earthshots for hydrogen, industrial heat, and long-duration storage. The new legislation builds on past R&D funding and public-private partnerships that helped to launch initiatives within Westinghouse, Nuscale, Kairos, and other firms in position to lead the next waves of deployment.

Presenters from NEI also pointed to other policies that support nuclear energy, including the CHIPS and Science Act of 2022 that funds university research, and the workforce development programs offered by the DOE. And while 123 agreements and CMOUs have established helpful guidelines for the exchange for nuclear materials, technology, and information, the NEI would like to see the agreements standardized and made available to more countries around the world.

Despite positive developments and trends, other concerns remain. Many at the symposium voiced a now-familiar urge for policy changes or other interventions that could prompt the Nuclear Regulatory Commission (NRC) to modernize processes for review and licensing, especially to adapt those processes for advanced reactor designs whose mechanisms for safety and security often differ from traditional light water reactors. While attendees often reported positive and productive working relationships with regulators, NRC processes are still generally considered to be expensive and slow, prompting a worry that regulators are unprepared for the influx of applications headed their way in the coming years.

A presentation from INL also expressed apprehension over the decades-long decrease in domestic mining, enrichment, and disposition of waste – a state of affairs that contributes to a lack of robust protocols ready to be adapted for advanced reactors and their specific fuels, moderators, burnup rates, refueling cycles, and waste streams. Many at the symposium, including attendees from MIT, INL, DOE-NE, NNSA, NuScale, Westinghouse, Ultra Safe, and others, also voiced concern that even the $700M in funding for HALEU is not enough to generate enough domestic HALEU to break the US reliance on HALEU from Russian suppliers.

Shortages are likely to hinder the progress of new reactor projects that require HALEU. Efforts to recover HALEU from recycled waste or by down-blending uranium from decommissioned weapons or naval reactors face security and licensing challenges.

Symposium presentations also described back-end fuel challenges. The DOE is working toward an integrated waste management system that will include one or more federal consolidated interim storage facilities, as well as provisions for transportation of spent nuclear fuel between locations, and yet a presentation from the Office of Spent Fuel and Waste Disposition acknowledged that the DOE is not actively pursuing a long-term repository site at this time. The plan to store waste at the Yucca Mountain site was halted in 2009, and so US plant operators currently store spent fuel in dry casks on site, as will the operators of new reactors including Plant Vogtle units 3 & 4 and Nuscale's VOYGR-6. A presentation from Ultra Safe acknowledged the difficulty of developing an approach to used nuclear fuel management, given variability and uncertainty in the regulatory landscape.

***Conclusions***

Nuclear energy may be having its long-awaited renaissance, driven by concerns over energy security, climate change, and economic development. Progress has been decades in the making and has happened largely behind the scenes, but nuclear energy now finds itself in the spotlight. Fulfilling its promise as a source of abundant, safe, reliable, versatile, low-carbon power will mean seizing opportunities and navigating challenges.

Perhaps the greatest opportunity for nuclear energy is to lead the way through the clean-energy transition. Doing so will mean stepping into markets beyond conventional electricity generation, building on successes with hydrogen and biofuels in order to power a wider array of applications across sectors of the domestic and global economy. Along the way, improvements in design, materials, manufacturing, regulation, fuel supply, and waste handling will need to drive down costs.

As the nuclear energy sector continues to evolve, increased collaboration between stakeholders, governments, and industry will be crucial for addressing the challenges it faces, including development of an efficient supply chain and workforce, as well as streamlining the licensing process and building trust and understanding with the public.

Whether nuclear energy will find its place as a mainstream and ubiquitous source of green energy is yet an open question, but many of the stars are aligning and the work that remains is coming into focus.