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Original Article

Idaho national laboratory to demonstrate collaboration first versus competition to accelerate achieving a secure clean energy future by 2031

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ABSTRACT

Idaho National Laboratory (INL) announced at COP27 it would reach net zero greenhouse gas (GHG) emissions by 2031. As a Nuclear, Energy and Environment, and National Homeland Security laboratory, the predominant solution to closing the clean energy gap will include nuclear as a safe, clean, reliable and affordable electricity source with the additional benefit of producing heat and hydrogen to fuel INL's large transportation fleet.

INL's collaboration first vs. competition is essential to the program's success. The focused actions in INL's Nuclear Roadmap include: Infrastructure, Licensing/Regulatory, Financial, Time to Market, Fuel Cycle and Public Confidence/Communications. The roadmap also includes nuclear technology innovations and creative partnerships with utility providers, regulators, businesses, community members, and Indigenous Peoples to accelerate deployment of advanced reactors.

Through development of the Net-Zero Nuclear Roadmap, INL will offer a model to provide safe and secure energy for the nation and the world by: (1) establishing the necessary infrastructure on its 890-square mile site to support demonstration, (2) showing proven pathways through the licensing and regulation process, (3) partnering with utilities to ensure commercial application, and (4) collaborating with industry to site new technologies.

1. Introduction

Replacing fossil fuel energy production with carbon-free energy alternatives is imperative to mitigating the most severe impacts of climate change, given that burning fossil fuels is the leading cause of global warming [1]. Accordng the IPCC, nuclear is a "low-carbon alternative" energy source that can effectively mitigate greenhouse gas emissions [2]. Advanced nuclear could play a unique role by providing baseload energy (much of which is currently provided by coal and gas) that complements renewables like wind and solar, as is evidenced by recent literature [3].

In April of 2021, Idaho National Laboratory (INL) announced its commitment to achieving net zero carbon emissions by 2031 across its 890-square mile site, which includes approximately 300 buildings, 700 vehicles, 125 miles of roads, 126 miles of high-voltage transmission lines, and over 5700 employees. INL also manages four operating reactors, nine substations with interfaces to two service providers, three fire stations, a public transit system for employees, and a landfill. The size, complexity, and energy intensity of INL make it akin to a municipality and, therefore, an ideal demonstration site for net zero solutions.

INL's Net-Zero Program is leveraging the laboratory's expertise in nuclear energy, integrated energy systems, and national security to not only create solutions for INL but to develop a model for the nation and the world to reach net zero carbon emissions. This paper explores how a collaborative approach that foregrounds creative partnerships with other national laboratories, utility providers, regulators, businesses, community members, and Indigenous Peoples may be able to accelerate deployment of advanced reactors.

This paper begins by offering an overview of the current energy situation in the U.S. before outlining INL's strategy to achieving net zero emissions, including the role nuclear-enabled integrated microgrids can play, the pathway to demonstration and deployment, and strategies for ensuring these technologies can be deployed on the commercial grid.

2. Background

The U.S. electricity infrastructure was first established in the early

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1900s and expanded in subsequent decades to meet growing energy demands. Today, the grid is comprised of approximately 11,000 power plants, 3000 utilities, and two million miles of power lines that are managed by federal entities (FERC and NERC), state and local regulators, utility companies, and seven grid operators [4].

Despite its centrality to economic, energy, and national security as well as the health and safety of its citizens, the U.S. electric grid has not been regularly or systematically updated to meet current energy needs. This has resulted in a situation wherein insufficient transmission capacity and outdated transmission systems are incapable of satisfying the close to 40 % increase in energy consumption the U.S. Department of Energy is projecting to occur by 2050 [5].

The grid is also increasingly vulnerable to cyberattacks and more frequent extreme weather events. Rising occurrences of hurricanes, blizzards, and floods has resulted in a doubling of power outages in the past 20 years across the U.S. The outages are also increasing in duration, leaving customers without power during the times when power is critical for survival, including extreme heat and cold [6]. Experts predict that extreme weather events will become more common in future years.

Meeting the nation's clean energy goals and global commitments, such as those outlined in the Paris Climate Accord, is contingent upon upgrades to the existing electrical grid [7]. Current estimates to replace transmission lines and upgrade system elements range from $1 to $2.4 trillion by 2050 [8]. Grid upgrades are also complicated by the complexity of the grid management and operation system, which includes independent system operators (ISOs)/regional transmission organizations (RTOs), state regulatory commissions, and utilities, as well as key involvement from transmission developers, independent power producers, consumer advocates, unions, public interest organizations, technology providers, and other stakeholders [9].

In 2022, President Biden launched the "Building a Better Grid" Initiative, which "focused on catalyzing nationwide development of new and upgraded high-capacity transmission lines" through a $2.3 billion grant program to begin the process [10]. Grid modernization is a "linchpin" to President Biden's larger goal of "a nation powered by reliable, renewable clean energy," according to Secretary of Energy, Jennifer Granholm [11]. This program will face numerous challenges, including how to upgrade a nationwide electric grid that traverses varying landscapes, weather, and energy needs across approximately 3.8 million square miles.

Whereas updating transmission and distribution lines is economical and effective for certain parts of the country (i.e. the Northeast), it may not be practical or economically feasible for other parts of the country. For example, the distance transmission and distribution lines must run is greater in the intermountain West than many other areas in the nation. The mountainous terrain and patchwork of public lands also complicate the ability to upgrade existing transmission lines and install new ones. Thus, upgrades to the U.S. electric grid must be flexible, adaptive, and integrate multiple solutions.

Microgrids offer the ability to bring carbon-pollution free energy to targeted areas without having to add extensive transmission and distribution infrastructure, thereby making them a more nimble potential solution. Microgrids can also be used in conjunction with existing grids to add energy production where it is needed most.

3. INTEGRATED microgrids

U.S. Department of Energy identified advanced microgrids as a necessary part of the modern electrical grid in 2014 because they can deploy distributed energy resources and reduce transmission and distribution costs. In 2021, the U.S. boasted more than 450 operational microgrids providing over 3 GW of reliable electricity.

Existing microgrids are adept at leveraging variable renewable energy (VRE) sources, as has been demonstrated by the National Renewable Energy Laboratory as well as commercial and community collaborations such as the Redwood Coast Airport Microgrid [12], Borrego Springs Microgrid [13], and Castañer, Puerto Rico microgrid [14]. These sorts of collaborations are necessary to demonstrate effectiveness and share lessons learned that can improve operations for future projects.

Microgrids that integrate nuclear with other clean energies such as wind, solar, hydro, and geothermal offer vital solutions to existing problems, including the following, which DOE has identified in recent reports: (1) the projected increase in energy demand created by the accelerated electrification of buildings, vehicles, and industry [15]; (2) the need for new energy infrastructure to cope with this increased demand, including in rural areas [16]; (3) threats to the energy grid posed by extreme weather events, cyber-attacks, and physical attacks [17]; (4) scarcity of raw materials and rare earth minerals required to manufacture solar panels, wind turbines, and battery storage [18]; and (5) transmission and distribution losses associated with connecting to the existing grid. Additionally, integrating nuclear with VREs on microgrids can help to meet Millennium Development Goals (MDGs), including MDG 7, ensuring environmental sustainability and MDG 8, developing global partnerships for development, given the applicability and suitability of these systems to rural and developing areas.

Adding nuclear energy in the form of small modular reactors (SMRs) can address each of these concerns while also forging a path to energy equity. First, SMRs can provide the carbon pollution-free electricity generation needed to simultaneously meet increased demand as well as clean air objectives. New nuclear technologies also promote long-term availability of systems and effective fuel use for worldwide energy production. Further, SMRs can produce electricity independent of weather or time of day. Beyond generating electricity, SMRs can also be used to generate clean hydrogen for vehicles and peaker plants efficiently as well as heat for industry, thereby simultaneously helping to decarbonize vehicle travel, building heat, and manufacturing.

Second, nuclear integration can help to heal the U.S. electric grid by siting energy sources where they are most needed and doing so with resilient infrastructure. By adding SMRs to microgrids, utilities can supplement VREs during off-peak generation or in areas where VRE energy generation is limited due to weather, footprint, terrain, etc. Microgrids' small size also make them easier to establish and deploy in rural and geographically isolated areas to meet demand where it is needed. The ability to integrate SMRs with varying degrees of output ranging from 10 MW–300 MW per reactor combined with their ability to be configured into "packs" for areas with greater energy needs (but without the need for land to host wind or solar) make them well suited for a wide range of applications. Additionally, the ability to place nuclear-enabled microgrids in remote locations, including along rural highways and interstates, allows for the siting of charging stations for electric vehicles, thereby increasing the feasibility of EVs for long-distance travel through less developed areas.

Device	Typical MW(e) range
Microreactors	Typically up to 10 MW(e)
Small Modular Reactors (SMRs)	Up to 300 MW(e)

*As defined by the International Atomic Energy Agency.

Third, microgrids are also more resilient to extreme weather events, cyber-attacks, and physical attacks than the existing grid because microgrids can be built to function as an island or in conjunction with the current grid. They can, thus, continue to operate when the main commercial grid experiences outages due to fire, floods, or attacks. Integrated microgrids are also more reliable than the commercial grid because they utilize diverse energy sources. Those that integrate nuclear can offer uninterrupted power to communities and, importantly, critical facilities such as hospitals, fire stations, and police stations as well as transmission redundancy to ensure even greater resiliency. Increasing resilience is critical given that the U.S. energy infrastructure has become a major target of frequent and sophisticated cyber-attacks.

Fourth, nuclear integrated microgrids can also help to supplement wind, solar, and batteries as demand outpaces the availability raw materials and rare earth minerals required to manufacture these technologies. Turbine manufacturing, for example, is largely dependent on permanent magnet imports, primarily from China, as that country produces 75 % of the world's permanent magnets, which contain rare earth elements (REEs) [19]. DOE's findings on projected demand for selected rare earths used in permanent magnets for wind energy turbines, electric vehicles, and consumer electronics (neodymium, dysprosium, and terbium) show a more than doubling from 2010 to 2025 [20]. The DOE study, also predicted an increase in demand for critical minerals used in solar energy systems, including a more than doubling of demand for tellurium and gallium by 2025 [21]. DOE projects a four-fold increase in demand for lithium, and a 50 % increase in demand for manganese dioxide and cobalt that are used in the lithium-ion battery [22].

As the U.S. works to secure access to these REEs, it is also pursuing activities to secure a domestic supply of high-assay low-enriched uranium (HALEU) through the HALEU Availability Program [23]. The program was established in December 2022 under the Energy Act of 2020, "to support the availability of HALEU for civilian domestic research, development, demonstration, and commercial use" [24]. This program will help to secure access to the fuels needed to secure energy independence with nuclear.

Fifth, nuclear integrated microgrids can reduce transmission and distribution losses. When strategically placed, microgrids can also alleviate grid congestion and improve system efficiency. Because microgrids are malleable and can be scaled up or down to meet the demands of communities ranging in size from small towns to large cities without building extensive and expensive infrastructure across vast distances, they are ideally suited to bring clean energy to the traditionally disadvantaged, including rural and underserved communities, the former of which represent roughly 46 million Americans.

INL can help to discover and demonstrate the role nuclear can play in an integrated microgrid by delivering clean, secure, and reliable energy to communities across the nation. INL has the expertise and infrastructure to test numerous aspects of these modern energy systems. The lab's experts perform simulations using real-world data and hardware. They test dynamic storage and load-balancing options using a renewable energy microgrid test bed. On-site electric vehicle testing and a full-scale power grid provide unmatched demonstration opportunities. Laboratory engineers are also already testing microgrids at U.S. military bases around the world without nuclear, which can inform its addition.

The aforementioned nuclear and microgrid technologies have the potential to eliminate barriers to access for those in rural and underserved regions. By working with industry leaders, we will be able to bridge the gap between concept and market implementation. The INL site is an ideal place to start given its size, energy intensity, and existing infrastructure. In addition to demonstrating the role of nuclear in achieving net-zero, the lessons we learn onsite can inform future policies and regulations concerning microgrids to ensure safe and efficient integration within the existing systems.

Our approach to answering this grand challenge will be to construct a microgrid that can demonstrate a nuclear resource in the form of a microreactor and/or SMR as it works in concert with renewables, geothermal, and battery storage. In addition to being one of DOE's 17 national laboratories, INL is an applied lab and has historically operated a non-nuclear microgrid that is portable and provides a test bed for clients. This resource is composed of a control station, solar panels, wind turbine(s), and storage devices for electrical energy. This work has given us the background to tackle the nuclear-enabled microgrid in a thoughtful three step method, as outlined in what follows.

4. Microreactors & small modular reactors

In 1949, the U.S. Atomic Energy Commission established the National Reactor Testing Station, now known as Idaho National Laboratory (INL), to take on the top-priority mission of harnessing the power of the atom for peaceful applications. Since then, thousands of world-class scientists and engineers made Idaho their home and devoted their careers to advancing nuclear research and development (R&D). From developing the first reactor to produce useable amounts of electricity, to prototyping nuclear propulsion plants for Navy submarines and aircraft carriers, INL is known for its innovations in the field of nuclear energy.

INL is and has been the world leader in nuclear technology. Fifty-two nuclear reactors have been developed and built at the INL – including the first reactor to generate useable electricity and the U.S. INL is also slated to demonstrate the first microreactor, MARVEL, in 2025. Innovations such as this contribute to INL's reputation as being able to convert scientific ideas into actual operating equipment and to provide science and engineering solutions to complex nuclear safety, energy and security problems. Collaborations with industry and utilities are essential to bringing these new technologies to market so they can be used to decrease national and global emissions.

INL will be at the epicenter of development for Gen IV nuclear reactor systems. Gen IV promises safe, economically competitive, proliferation-resistant nuclear power without the danger of increasing greenhouse gas emissions.

From the early beginnings of nuclear energy in the 1940s to the present, three generations of nuclear power reactors have been developed: early prototype reactors, commercial power reactors and advanced light water reactors. These three generations of nuclear energy systems have been successful in many ways. In the United States, nuclear energy provides 20% of the electricity, without emitting carbon pollution.

Challenges face the nuclear industry in the form of public perceptions of nuclear safety, high capital costs of constructing new plants, and the need to establish final repositories for spent nuclear fuel. Proliferation of materials suitable for making nuclear weapons has also been a great concern. In spite of this, the nuclear energy industry has experienced economic and regulatory recovery in many parts of the world in recent years. In fact, venture funding for startups focusing on nuclear energy in 2021 was upwards of $3.4 billion compared to $381 million the year prior [25]. As of 2022, 53 new reactors were under construction across the world.

4.1. Demonstrating microreactors

INL, as an applied laboratory, is taking concrete steps to demonstrate microreactors and small modular reactors. The U.S. Department of Energy (DOE) Microreactor Program supports research and development (R&D) of technologies related to the development, demonstration and deployment of small, factory fabricated, transportable reactors to provide power and heat for decentralized generation in civilian, industrial and defense energy sectors. The term "micro-reactor" can be defined as an advanced nuclear reactor that has an electric power production capacity that is not greater than 20 MWth.

Led by Idaho National Laboratory, the Microreactor Program (Program) conducts both fundamental and applied R&D to reduce the risks associated with new technology performance and manufacturing readiness of microreactors. The intent is to ensure that microreactor concepts can be developed, licensed and deployed by commercial entities to meet specific use case requirements.

The Microreactor Program coordinates work and activities across participating laboratories, universities, and industry as well as other DOE programs. National laboratories participating in the Microreactor Program are INL, Argonne National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory and Sandia National Laboratory.

The unique microreactor-related activities this program performs can directly reduce the technology risks and uncertainties of near-term designs and next-generation microreactor applications and concepts. Because microreactor designs under development are novel and possess unique technology features—such as autonomous operation, inherent safety, and full transportability—there is a specific need for R&D

support. The DOE national laboratory complex is uniquely positioned to fulfill those needs to support industry and other stakeholders. This program performs R&D in areas pertaining specifically to civilian commercial microreactors, recognizing synergies with ongoing defense microreactor R&D efforts.

The key objectives of this Program are to meet critical cross-cutting R&D needs of existing developers that require national laboratory, university and industry expertise and capabilities; develop R&D infrastructure to support design, demonstration, regulatory and safety-related tests and to collect data to validate modeling and simulation tools; and develop advanced technology and technology concepts that enable improved performance, economics, or integration of microreactors.

This paper highlights two microreactor programs led by INL that can provide valuable information to industry and utilities. The first is a thermal-hydraulic test capability called the Microreactor AGile Non-nuclear Experimental Testbed (MAGNET). MAGNET will use electrical heating elements to simulate core thermal behavior, primary heat exchanger performance, and passive decay heat removal for heat pipe and gas-cooled microreactors.

MAGNET will support verification and validation of detailed microreactor thermal hydraulic models applicable under startup, shutdown, steady-state, and normal transient behavior in steady-state operation, transient operation and load following conditions. Non-radioactive thermal system component testing will prove out component designs and functionality prior to nuclear system demonstration. MAGNET is available for use by national laboratory, university, and industry partners. MAGNET will ultimately be integrated into the broader INL Energy Systems Laboratory, which includes thermal and electrical energy users such as steam electrolysis, real-time digital simulators for power systems emulation, a microgrid test bed, a thermal energy distribution system (TEDS), and renewable energy generation.

MAGNET can be broadly used to test microreactor structures and systems. Specific examples include: (1) Heat transfer within microreactor components, including core structures and heat exchange components and for alternative heat removal approaches, (2) Structural performance of core structures, including evaluating thermal stress, strain, aging/fatigue, creep and deformation, (3) Evaluation of heat pipe performance and integration for transfer of heat from core structures to heat exchangers for heat pipe functionality, heat transfer capabilities and geometric compatibility, (4) Investigation of high-performance integral heat exchangers for high-efficiency heat transfer from core structures to power cycle working fluids, (5) Testing of components produced by advanced manufacturing, including heat exchangers, core components and other structures, (6) Testing advanced sensors, instrumentation and control through instrumented test articles and control systems, (7) Cyclic load testing to understand material and component behaviors for transient and load following operations, and (8) Validation of modeling and simulation tools through experiments and direct engagement with computational model and tool developers.

Microreactor Applications Research Validation and Evaluation Project (MARVEL) is another project housed under the DOE Microreactor Program. Development of the MARVEL test bed provides an opportunity to establish and exercise key capabilities to support future microreactor demonstrations by addressing: (1) the need identified in engagements with potential end users of microreactor systems wanting more information about how microreactors meet their application needs; (2) development of a small-scale reactor for R&D purposes for the first time in nearly 50 years; (3) engagement and outreach with end users and stakeholders to perform research and development on the integration of microreactors with a range of anticipated applications, such as load-following electricity demand, process heat, hydrogen production, and water purification; and (4) research and development to investigate and address issues and challenges related to the fabrication, assembly, rapid installation, deployment, authorization, and operation of microreactors to facilitate end-user adoption.

The MARVEL development project coordinates work and activities across participating laboratories, universities, and industry as well as other DOE programs. Participating national laboratories are Idaho National Laboratory, Los Alamos National Laboratory, and Argonne National Laboratory, as well as private organizations including Walsh Engineering, Creative Engineers Inc, and Qnergy.

MARVEL will be installed and operated at INL's Transient Reactor Test (TREAT) facility. MARVEL will encompass a 100-kW thermal fission reactor inspired by an existing design and technology with TRIGA fuel, which has a high safety pedigree, that is expected to be operational in 2025. The reactor will be a sodium-potassium cooled reactor with natural circulation cooling and an operating temperature of 500–550 °C. Off-the-shelf Stirling engines will convert thermal energy to ~20 kW electrical power. The system is anticipated to operate for approximately 2 years.

MARVEL operation has the potential to enable important R&D in three main areas. First, it can enable testing, demonstrating, and addressing issues related to installation, startup, and operation. In particular, MARVEL has the potential to (1) simplify siting and environmental review process; (2) create a startup methodology for microreactors; (3) harden cyber and physical security; (4) *demonstrate seamless integration of nuclear onto a net-zero, electrical microgrid* and (5) demonstrate high and low-grade heat extraction. This includes the potential to demonstrate MARVEL's suitability for powering an electric vehicle charging station. These tests will help resaerchers better understand the potential of microreactors in supporting electric vehicle infrastructure, especially across rural areas that lack transmission and distribution lines.

Second, MARVEL can enable R&D related to autonomous operation technologies. These include: (1) automating operator functions, while maintaining reactor safety; (2) demonstrating radiation and temperature-hardened sensors and instrumentation to enable remote monitoring, advanced sensor reliability tests, and online calibration; (3) creating real-time data that can feed a digital twin of the reactor to "train" an artificial intelligence-based control system; (4) demonstrating wireless transmission of live data of both electrical and thermal power output during startup, operation, and shutdown to allow real-time feedback on system output, performance, and prediction of any unplanned maintenance needed in an operating microreactor.

Third, MARVEL can enable seamless application integration because the control systems manage the energy grid demand and reactor power and heat supply. This management requires a carefully designed control system that can predict the interplay of controls, thermal inertia, and reactivity feedback. In addition, MARVEL can demonstrate integration approaches for a range of applications investigating both reactor power management and load management approaches. These lessons can then be shared to help industry development of other similar technologies.

4.2. Small modular reactors

The term "small modular reactor" means an advanced nuclear reactor (A) with a rated capacity of less than 300 electrical megawatts; and (B) that can be constructed and operated in combination with similar reactors at a single site. DOE initiated the SMR LTS program in 2012 "to support the development, licensing, and eventual commercial deployment of SMRs as another clean, affordable electricity generation option" [26]. DOE's program focuses on the early design, certification, and licensing of domestic SMR technologies. These actions support their vision: "By 2050, advanced reactors will provide a significant and growing component of the nuclear energy mix both domestically and globally, due to their advantages in terms of improved safety, cost, performance, sustainability, and reduced proliferation risks" [27]. Such collaborations are essential to generating carbon pollution-free energy at the scale necessary to help meet national decarbonization targets.

In 2020, DOE announced three categories of awards under the Advanced Reactor Demonstration Program. The first category, with funding for demonstration pathways, supports TerraPower and GE-Hitachi for their Natrium sodium colled fast reactor (SFR) with molten salt energy storage and X-energy for the Xe-100 high-temperature gas-cooled reactor (HTGR). The second category, for risk reduction projects, supports Kairos Power for the KP-FHR, BWX Technologies for the BWXT Advanced Nuclear Reactor, Southern Company for the Molten Chloride Reactor Experiment, Holtec International for the SMR-160, and Westinghouse for the eVinci heat pipe microreactor. The third category, for concept development over the next 20 years, supports Advanced Reactor Concepts for the Advanced Sodium-Cooled Reactor Facility, General Atomics for the Fast Modular Reactor, and MIT for the Horizontal Compact Fast Modular Reactor.

The National Reactor Innovation Center (NRIC) is coordinating with recipients of DOE funding by identifying infrastructure resources and needs across the national laboratory complex and partnering institutions. NRIC is also preparing demonstration sites for advanced reactor projects at INL and elsewhere.

NRIC uses digital engineering and MBSE tools, including Innoslate (https://www.innoslate.com), to bring together multiple stages of projects and multiple sources of information in an integrated, comprehensive, and efficient manner. MBSE is used in modern engineering projects across many industries to serve as the "authoritative source of truth" for all information management.

Several of the advanced reactor developers also use Innoslate as their primary MBSE tool. Innoslate provides traceability, in a single model or linked models, via a digital thread from data sources, such as requirements in linked documents, through to system components or functions within the model. Collaboration between NRIC and developers with this tool facilitates effective and complete data exchange and shared focus.

Innoslate is a useful tool for multiple aspects of test bed and advanced reactor demonstration projects. It integrates requirements management, systems architectures, functional flow diagrams and process simulation, cost and schedule tracking for program management, action item tracking, and risk identification and mitigation. For potential test bed users, it assists with collecting test hardware to test bed interface requirements, calculating costs for nuclear energy test bed activities, and simplifying process simulation. Managing the project requirements, processes, and costs in Innoslate facilitates future activities in the test beds.

Through Innoslate, the project team follows the systems engineering process of identifying stakeholders and required functions with use cases and action diagrams, developing acceptable architectures and subsystems, then synthesizing the system design. Process flow diagrams can be created in the tool at appropriate levels of detail and simulated to evaluate overall system performance. During design iteration, Innoslate helps the team manage requirements, track action items, and mitigate risks. Once the design has matured to a sufficient level of detail, the project leverages the digital engineering integration between Innoslate and drafting tools (e.g., Autodesk) to advance the design to completion.

In addition to coordinating with advanced nuclear developers and preparing a network of demonstration infrastructure, NRIC supports identification and implementation of cost-reduction strategies to ensure the financial viability of commercial nuclear plants in future energy markets. In 2020, NRIC issued an EOI request and subsequent request for proposals to fund demonstration of advanced construction technologies [28]. Although some features of advanced nuclear plants could increase their costs per kWe (such as exotic materials or fuels for some designs and adverse economies of scale for small and micro designs), they could achieve cost reductions through combinations of inherent safety systems, design simplification, standardization, modularity, factory or shipyard manufacturing, additive manufacturing, novel construction techniques, fast installation, digital twins, remote monitoring, automation, and learning by experience across multiple unit deployments.

4.3. Integrated energy systems

Integrated Energy Systems (IES) incorporate multiple energy-generation resources and energy-use pathways to provide affordable, reliable, and resilient energy, simultaneously reducing GHG emissions [30] [31] as part of the Crosscutting Technology Development (CTD) program. Nuclear IES increase the value proposition of nuclear energy by increasing the flexibility of nuclear electricity generation, allowing it to better complement with variable renewables and to support controllable and flexible loads (e.g., water desalination, electric vehicle charging, hydrogen electrolysis); producing hydrogen or synthetic fuels as secondary revenue streams; and providing low-carbon heat for industrial processes.

This also provides new mechanisms for decarbonizing the three largest sources of GHG emissions in the U.S.: the electric grid, transportation, and the industrial sector [32]. The CTD IES program (https://ies.inl.gov) conducts R&D to expand the role of nuclear energy beyond conventional nuclear power plants that produce electricity for the grid. Possible direct applications of thermal energy from nuclear reactors include industrial processes, hydrogen production through high-temperature methods (e.g., high temperature electrolysis), and desalination.

The CTD IES program also considers strategies to ensure that electricity from nuclear plants will complement variable renewable resources in future low-carbon systems. In addition, thermal energy storage (such as sensible, latent, or other forms) could provide more flexibility for nuclear plants to provide electricity, hydrogen, or other services when they are most highly valued. Led by INL, the program encompasses researchers and facilities across several national laboratories. It involves detailed analysis of enabling technologies, such as thermal connections, heat exchangers, thermal energy storage media, heat augmentation alternatives, cutting-edge digital controls, hydrogen production pathways, and carbon conversion processes. It also provides close scrutiny of market scenarios and financial viability necessary to optimize IES design and operation.

Nuclear IES can be configured to produce multiple energy products simultaneously and/or dynamically manage the dispatch of heat and electricity to vary production rates of different products according to market conditions.

4.4. Green hydrogen production

Hydrogen is increasingly seen as a key component of future energy systems if it can be made without carbon dioxide emissions. Most hydrogen today is made by steam reforming of natural gas or coal gasification, both with CO2 emissions and is termed "blue" hydrogen. Future demand is expected to be mainly for zero-carbon, "green" hydrogen. Clean hydrogen production could be accomplished by electrolysis using electricity from variable renewable sources or nuclear reactors.

Low temperature electrolysis (LTE) of water to produce hydrogen occurs at ambient temperatures and requires about 55 kWh per kilogram of hydrogen produced, which equates to a process efficiency of 60 %, according to the U.S. Department of Energy. Efficiency could potentially increase to 70 % with improved catalysts. LTE is undertaken on a small scale today, producing only about 2 % of world supply, according to the International Energy Agency in 2019. Abundant, clean, and low-cost hydrogen can be subsequently utilized in many aspects of the chemical industry (e.g., biomass gasification, synfuel production, and steel).

High-temperature electrolysis (HTE) uses solid oxide electrolysis cells to electrochemically separate hydrogen and oxygen in steam at temperatures around 800 °C, achieving a substantially higher efficiency than LTE [33]. The higher efficiency for HTE gives nuclear IES a significant advantage over using renewable energy for hydrogen production. Higher capacity factors for nuclear reactors than variable renewables also provide an advantage for capital cost recovery [34].

Hydrogen is a highly versatile energy carrier that can be used immediately, stored, or transported to another site for use. Hydrogen from this process may also be used to create other energy carriers, such as synthetic hydrocarbon fuels (synfuels), ammonia, methanol, and synthetic methane.

4.5. Nuclear thermal energy storage

Thermal energy storage could enhance the value of nuclear energy systems by storing thermal energy for later release when the value of heat, electricity, or other potential products is high.

Advanced reactor designs being supported by the DOE Advanced Reactor Demonstration Program include the Natrium design by TerraPower and GE-Hitachi, which uses molten salt as thermal energy storage medium. The energy storage aspect of this demonstration project could serve as the basis for other designs and partnerships on nuclear and storage systems in the proposed NRIC/CTD IES demonstration program outlined in this report. INL installed a Thermal Energy Distribution System (TEDS) as part of the Dynamic Energy Transport and Integration Laboratory (DETAIL), located at the Energy Systems Laboratory building complex. This oil-filled heat transfer system will be used to demonstrate and analyze thermal-energy-storage modes and transport to and from various co-located systems, will allow evaluation of hardware associated with off-take of thermal energy from a power plant, and provides a platform for verification and validation of various computational models of such a system.

TEDS is equipped with a 200 kW controllable heater that can be driven variably to emulate how heat from a commercial power plant might be supplied. TEDS can be connected to various heat loads, such as an HTE test system, as well as heat sources, such as the co-located Microreactor Agile Non-Nuclear Experimental Test (MAGNET) described above.

5. Demonstrating replicable solutions

INL's Net-Zero Program is dedicated to demonstrating solutions and sharing lessons learned to make meeting U.S. net-zero emissions goals a reality. Future opportunities for additional collaborations on INL's site may be made possible by Secretary Granholm's Cleanup to Clean Energy Initiative, which launched in July 2023. The goal of the initiative is to engage a diverse range of stakeholders, including industry, federal entities, tribes, state, and local officials to explore opportunities to lease federal land for the buildout of clean energy projects. INL was selected as one of the five sites on which projects could potentially be sited. Projects could include advanced nuclear as well as wind, solar, and geothermal energy production, which could also result in clean hydrogen production. Many hydrogen applications are realizable, and a number of experts predict hydrogen applications as among the first to be realized in global markets, which is detailed in a 2022 Nuclear Energy Agency report.

INL has established programs to help make advanced nuclear energy a viable solution. For example, the Gateway for Accelerated Innovation in Nuclear (GAIN), which is led by INL, provides the nuclear energy community with access to the technical, regulatory, and financial support necessary to move new or advanced nuclear reactor designs toward commercialization while ensuring the continued safe, reliable, and economic operation of the existing nuclear fleet.

Through GAIN, DOE is making its state-of-the-art and continuously improving RD&D infrastructure available to stakeholders to achieve faster and cost-effective development of innovative nuclear energy technologies toward commercial readiness.

The National Reactor Innovation Center (NRIC) is another national DOE program led by INL that allows collaborators to harness the world-class capabilities of the U.S. National Laboratory System. NRIC supports the construction and demonstration of advanced reactor systems through a suite of services and capabilities and are committed to their charge to demonstrate advanced reactors by the end of 2025.

INL has more than seven decades of experience researching and demonstrating nuclear. The RD&D happening today has the potential to change the world's energy future. Collaborations with DOE, utility providers, developers, industry, universities, and other national laboratories are necessary to realizing the massive potential advanced nuclear has to help the U.S. and other countries meet their decarbonization commitments. The work occurring at INL will help to develop a roadmap to nuclear energy via collaboration, integration, and teamwork.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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