GLOBAL NATIONAL LABORATORIES

INTEGRATED ENERGY SYSTEMS

ANNUAL REPORT 2023

CONTENTS

EXECUTIVE SUMMARY

The transition to a net zero future demands the integration of diverse energy sources, including renewables and nuclear power, and energy storage to deliver clean electricity, heat, hydrogen, and more.

Recognising this imperative, eight national laboratories from Canada, France, Japan, the UK, and the USA have joined forces to spearhead advancements in integrated energy systems. This annual report showcases the highlights from the first year of their collaborative efforts.

In January 2022, the eight national laboratories convened for their inaugural Summit, emphasising the pivotal role of integrated energy systems for deep decarbonisation worldwide. Leaders from each laboratory expressed their commitment to international cooperation and highlighted the critical role of national laboratories in driving scientific breakthroughs and fostering innovation. The Summit culminated in a joint commitment to collaboration across four key areas: engaging end users, energy system modelling, hydrogen technologies, and operational sustainability.

In November 2022 at COP27 in Egypt, the collaboration hosted a panel session and launched an impact paper co-authored by the eight laboratories. The session featured a distinguished guest keynote from Paul Kearns, Director of the US Argonne National Laboratory and past Chair of the US Department of Energy National Lab Directors' Council. Joining the panel were UK's National Nuclear Laboratory, the US National Renewable Energy Laboratory, and the World Nuclear Association. The impact paper made a series of recommendations on advancing research, development, and deployment (RD&D) in integrated energy systems.

In January 2023, the national laboratories met in London to develop and agree upon a plan forward for the collaboration. This gathering marked the first face-to-face meeting of the steering group, enabling in-depth discussions on shared challenges and opportunities across nations. The workshop was structured around the key areas of engaging end users, models and data, and hydrogen technologies, with the labs sharing experiences and aspirations in each area. Industry experts from Weinerberger, DNV, and ITM Power joined as guest speakers, sharing insights on industrial energy decarbonisation, the conversion of gas networks to hydrogen, and electrolyser development, respectively. As a result of the workshop, the laboratories have agreed to establish technical working groups to foster deeper collaboration.

In addition to these collaborative endeavours, each lab continues to conduct its own cutting-edge research and development activities in integrated energy systems. This report presents a snapshot of the achievements and advancements made by each laboratory.

In conclusion, the collaboration between these eight national laboratories represents a bold and innovative approach to addressing the urgent need for integrated energy systems in achieving a net zero future. By combining their expertise and resources, these laboratories can drive transformative change in the energy sector. The activities described in this annual report lay the foundation for deeper collaboration and knowledge sharing in the years to come.

THE COLLABORATION BETWEEN THESE EIGHT NATIONAL LABORATORIES REPRESENTS A BOLD AND INNOVATIVE APPROACH TO ADDRESSING THE URGENT NEED FOR INTEGRATED ENERGY SYSTEMS IN ACHIEVING A NET ZERO FUTURE

ABOUT THE GLOBAL NATIONAL LABORATORIES INTEGRATED ENERGY SYSTEMS COLLABORATION

Integrated energy systems (IES) combine multiple energy sources (renewables, nuclear, fossil, bioenergy), converting these into multiple vectors (electricity, heat, hydrogen, fuel) for delivery to multiple users (in buildings, industry, transport). An integrated approach allows countries to leverage the benefits of different technologies to provide reliable, low-cost energy with minimal impact on the environment. Although individual components in an integrated energy system may be mature, in many cases integrating these into coherent, functioning systems will require further research, development and demonstration.

National laboratories exist around the world to deliver cutting edge science to solve some of society's most complex challenges. Discoveries made in these laboratories have already improved the lives of billions of people. Our global national laboratories collaboration on integrated energy systems brings together labs from across the energy sector, encompassing nuclear, renewables and other low carbon solutions. Through knowledge sharing and collaborative research, this initiative is helping progress a holistic understanding of what future integrated energy systems will look like, in order to help evolve technologies to be fit and ready to deliver.

OUR MEMBERS

CANADIAN NUCLEAR LABORATORIES (CNL)

www.cnl.ca

Canadian Nuclear Laboratories

CNL is Canada's premier nuclear science and technology organization, and a world leader in developing nuclear technology for peaceful and innovative applications. Using our unique expertise, we are restoring and protecting the environment, we are advancing clean energy technology, and our medical breakthroughs continue to improve the health of people around the world.

"Canadian Nuclear Laboratories (CNL) welcomes a new era of international collaboration to accelerate the global adoption of clean energy and the critical role of integrated energy systems. CNL's clean energy mission is driving research and development in hydrogen technology, advanced reactors and fuels and the sustainable operation of our current CANDU fleet. And CNL is leading innovation as we look to explore how we can build a clean-energy systems demonstration platform around a small modular nuclear reactor. Collective knowledge is a powerful tool, and we look forward to sharing our expertise, research and learning to help shape the energy systems of the future."

Dr Jeff Griffin
VP Science & Technology, CNL

FRENCH ALTERNATIVE ENERGIES AND ATOMIC ENERGY COMMISSION (CEA)

www.cea.fr

The French Alternative Energies and Atomic Energy Commission (CEA) is a key player in research, development and innovation in four main areas: defence and security, low carbon energies (nuclear and renewable energies), technological research for industry, fundamental research in the physical sciences and life sciences. Drawing on its widely acknowledged expertise, the CEA actively participates in collaborative projects with a large number of academic and industrial partners.

The CEA is established in nine centers spread throughout France. It works in partnership with many other research bodies, local authorities and universities. Within this context, the CEA is a stakeholder in a series of national alliances set up to coordinate French research in energy (ANCRE), life sciences and health (AVIESAN), digital science and technology (ALLISTENE), environmental sciences (AllEnvi) and human and social sciences (ATHENA).

"CEA is proud to participate in this initiative that encompasses the R&D work we performed, especially since the creation early 2020 of the Energy Division, whose main purpose is to promote innovation towards and integrated energy system. This is also in line with French Energy policy, based on the use and convergence of nuclear and renewable energies, and is an integral part of the joint efforts made at the European Union level through the cooperation between the Member States Research and Technology Organizations active in the energy field."

Dr Stéphane Sarrade
Director of Programmes, Energy Division, CEA

JAPAN ATOMIC ENERGY AGENCY (JAEA)

www.jaea.go.jp/english

The mission of JAEA is to contribute to the welfare and prosperity of human society through nuclear science and technology.

JAEA's Executive Director for International Affairs, Mr. Kentaro FUNAKI, stressed, while presenting a concept model of nuclear and renewable integrated energy systems and highlighting high temperature gas-cooled reactor as a key to such systems:

"We are already partners in nuclear research and innovation to move forward towards a future net-zero carbon society, and we all have solid grounds to design, develop and deploy nuclear-renewable hybrid systems. This Summit will lead us to a shared vision of future integrated energy systems as well as enhanced international collaboration."

Mr. Kentaro FUNAKI
JAEA's Executive Director for International Affairs

OUR MEMBERS

THE INSTITUTE OF ENERGY ECONOMICS, JAPAN (IEEJ)

eneken.ieej.or.jp/en

The Institute of Energy Economics, Japan (IEEJ), founded in 1966, is an energy think tank that focuses on energy, economic and environmental issues, as well as the geopolitics of the Middle East. It has been ranking among the top three energy think tanks in the world in the past many years. Based on facts, objective analysis as well as projections for the future, IEEJ focuses on the current energy and environment challenges including simultaneous achievement of energy security and carbon neutrality. IEEJ also recommends to the world sound and innovative solutions that reflect the Japanese and/or the Asia-Pacific perspectives.

"The world is now under the ongoing energy transition to address emerging challenges in climate change and energy security. To achieve carbon neutrality and energy security simultaneously, comprehensive and full-fledged initiatives will be required. In addition to this, substantial contribution by innovation is essential for the successful energy transition. From this perspective, the activities of and recommendations by GNL collaboration on IES is very meaningful, to which IEEJ hopes to continue to contribute as a leading global energy research institute."

Dr. Ken Koyama
Senior Managing Director and Chief Economist, IEEJ

ENERGY SYSTEMS CATAPULT (UK)

es.catapult.org.uk

Energy Systems Catapult are Net Zero energy innovation experts, accelerating the transformation of the UK's energy system and ensuring UK businesses and consumers capture the opportunities of clean growth. The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research.

We take a whole system view of the energy sector – from power, heat and transport to industry, infrastructure and consumers – helping us to identify and address innovation priorities and market barriers to decarbonise the energy system most efficiently and effectively. We work to unleash the potential of innovative companies of all sizes. Helping them to develop, test and scale their solutions, to achieve the UK's ambitions for net zero and support organisation in other countries on their energy transition path.

"If we're to unleash the innovation we need to get to a net zero global economy, it's essential we take an integrated approach that understands the roles of different technologies, of markets, of digital technology and, crucially, of people. That's why we're delighted to support this initiative. It puts a whole system, integrated approach at the heart of our future innovation. COP26 showed what global collaboration can achieve in the push towards net zero – through this initiative we have an opportunity to work together to help deliver our shared ambitions for a cleaner, more affordable energy future."

Guy Newey
CEO, Energy Systems Catapult

NATIONAL NUCLEAR LABORATORY (UK)

www.nnl.co.uk

At NNL we are focused on harnessing nuclear science to benefit society. In Clean Energy we are helping deliver environmentally and financially affordable solutions to one of the biggest challenges of the twenty-first century, the achievement of net zero. NNL is accelerating the UK's demonstration programme for advanced modular reactors and working to ensure this is delivered as part of an integrated energy system approach.

"With the transition to net zero driving fundamental changes globally to energy supply, demand, transmission, distribution, storage and use, research and innovation is required to help us develop, design and operate the right systems for a net zero future. But given the complexity of the challenge, there is no straight forward swap – we need to work together to maximise the efficiency and suitability of these systems and ensure they are affordable for current and future generations."

Dr Paul Howarth
CEO, NNL (UK)

OUR MEMBERS

IDAHO NATIONAL LABORATORY (US)

inl.gov/integrated-energy/ and ies.inl.gov

As one of 17 national labs in the U.S. Department of Energy complex, Idaho National Laboratory is home to more than 5,700 researchers and support staff focused on innovations in nuclear energy and related technologies, renewable energy systems and security solutions that are changing the world. From discoveries in advanced nuclear energy to carbon-free energy options and to protecting the United States' most critical infrastructure assets, the talented team at INL is constantly pushing the limits to redefine what's possible.

"Transitioning to a low-carbon energy system is critically important for global sustainability, and integrated energy systems can harness the benefits of clean energy sources working together, including nuclear and renewables. Idaho National Laboratory is pleased to engage with labs around the world to discuss how to achieve this ambitious goal. Our research for the U.S. Department of Energy's Office of Nuclear Energy enables us to play a key role in meeting our growing energy needs while also reducing carbon emissions."

Dr Marianne Walck
Chief Research Officer for Idaho National Laboratory

NATIONAL RENEWABLE ENERGY LABORATORY (US)

www.nrel.gov/esif

At the National Renewable Energy Laboratory (NREL), we focus on creative answers to today's energy challenges. From breakthroughs in fundamental science to new clean technologies to integrated energy systems that power our lives, NREL researchers are transforming the way the nation and the world use energy.

"Building off many years of our domestic collaborations focused on low-carbon integrated energy systems, we are excited to participate in this international collaboration among national laboratories."

Doug Arent
Executive Director of Strategic Public Private Partnerships at NREL

2022 INAUGURAL SUMMIT

In January 2022, the eight national laboratories held their first Summit to progress a global integrated energy system approach to mitigating climate change.

The aim of the event was to build a long-term legacy for COP26, the United Nations Climate Change Conference, in the year of the UK's presidency. It signifies the importance of integrated energy systems for deep decarbonisation worldwide, and the particular role that national laboratories play to drive science, innovation and research and development (R&D) for a net zero energy economy.

Hosted by the UK's National Nuclear Laboratory (NNL), the Summit saw senior delegates from the eight national laboratories across Canada, France, Japan, the UK and USA express their intention to collaborate around an international approach in progressing a holistic understanding of what future integrated energy systems will look like in order to evolve technologies to be fit and ready to deliver.

Speaking at the Summit, **Sir Patrick Vallance, the UK Government's Chief Scientific Adviser,** said:

"The climate challenge that we all face is a huge one for societies across the world to come to terms with and to think about what response we need to make – urgently – in order to get on top of it. In November 2021, COP26 laid out very clearly what the challenges are in terms of the changing climate and, importantly, the role of innovation in how we solve this.

"It is very clear that this is an international issue and therefore requires international collaboration. Nations are going to have to harness all the resources they have and, particularly in respect of this Summit, to think about the role of national laboratories, which have been absolutely crucial to support translation, adoption and deployment of technologies that will make a difference.

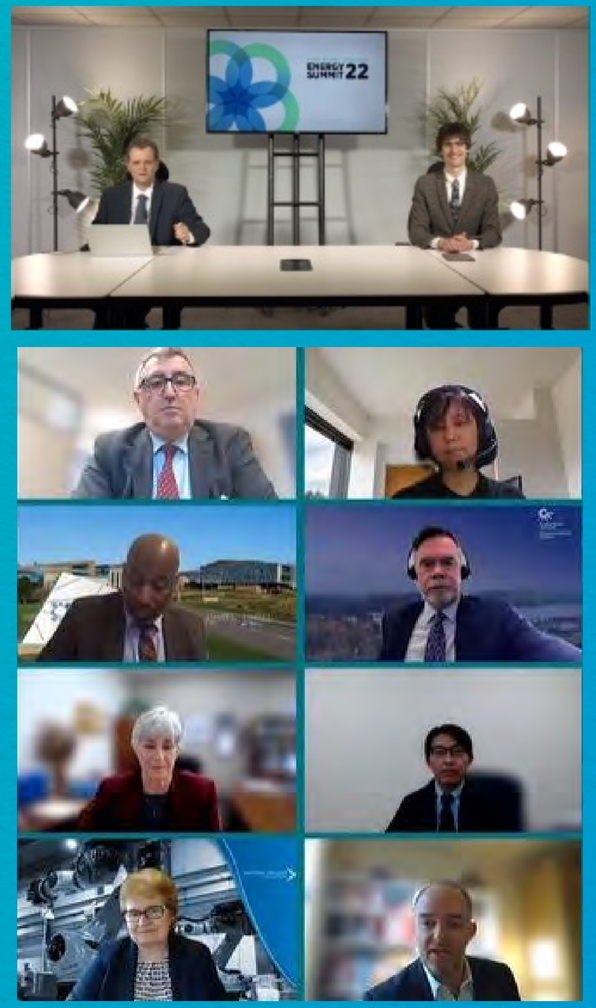
"So with this meeting, it's important that it is international in scope, it's important that it is national laboratories coming together with all the resources and insights they can bring and it's important that it reflects the urgency of the work ahead."

UK Energy Minister the Rt Hon Greg Hands MP also said:

"Visiting NNL a few weeks after I became Energy Minister, I was hugely impressed by the passion and the innovation that I saw. I am therefore very excited about this Summit and the opportunity to bring together national laboratories and the wider energy sector with the aim of accelerating crucial science and innovation towards a net zero future.

This kind of long-term, global collaboration – not just between countries, but between nuclear and renewables, and other low-carbon sources – will contribute to making the energy system fit for the future."

Encompassing nuclear, renewables and other low-carbon energy vectors, the Summit reflected a turning point in the global energy debate – recognising the importance of collaboration not just internationally but across traditional siloes in the energy community as part of the urgent transition to low-carbon sources.



Inaugural Energy Summit: (top) Keith Franklin and Tim Gregory; (bottom, clockwise from top-right) Tomoko Murakami, IEEJ; Jeff Griffin, CNL; Kentaro Funaki, JAEA; Guy Newey, ESC; Fiona Rayment, NNL; Marianne Walck, INL; Peter Green, NREL; Stephane Sarrade, CEA.

SUMMIT OUTCOMES:

The Summit concluded with a statement of intent for joint working over the coming years, which could include sharing each national laboratory's vision of integrated energy systems, and best practice in research and innovation. Further discussion led to the identification of four initial collaboration areas:

- Engaging End Users: Working collaboratively to engage with and understand the needs of energy end users across various markets, and assessing the potential of integrated energy systems to meet these needs.
- Energy System Modelling: Sharing learning, technology datasets, and scenarios from studies to model future integrated energy systems. Sharing results and guiding future studies, considering aspects such as the circular economy and life cycle assessment, economics, technological readiness, and deployment timeframes. Investing in ways to make modelling open to benchmarking and review, including sharing models as open source where possible.
- Hydrogen: All parties recognise that the use of hydrogen as an energy vector will be important in a net zero world, whether used directly as a fuel or as a feedstock for other synthetic fuels, chemicals, fertilizer, etc. Developing research relating to the generation (including using high-temperature heat), storage and use of low-carbon hydrogen, and sharing advances made in this area.
- Sustainability in operations: Applying and sharing best practices in sustainability in our own operations, and maximising where we can use our influence to promote a sustainable future. This includes environmental, economic, and social impacts.

The concluding statement also set out a variety of methods for collaboration, including but not limited to: exchange visits, workshops, exchange of correspondence, and joint papers and presentations to conferences and other meetings. The labs committed to explore shared communication and outreach, showcasing our collaborative approach across the globe to inspire further partnerships that advance knowledge around integrated energy systems in the fight against climate change. Finally, the labs shared a commitment to meet annually, to review progress and set the agenda for the future.

COP27 PANEL SESSION AND IMPACT PAPER

COP27 panel session (from right to left): (chair) James Murphy, NNL Chief Strategy Officer; Paul Kearns, Director of the US Argonne National Laboratory; Paul Nevitt, NNL's Director of Science and Technology; Martin Keller, Director of the US National Renewable Energy Laboratory (NREL); Jonathan Cobb, Senior Communications Manager at the World Nuclear Association.

At the COP27 Conference in Egypt in November 2022, delegates gathered to make progress on climate action amid a growing energy crisis. Previous UNFCCC commitments to climate action established the need to move away from fossil fuels, requiring a massive scale up in clean energy sources including nuclear and renewables, along with energy storage and other smart solutions.

In that context, the labs hosted a **panel session** at the Conference, which included the presentation of an **impact paper** co-authored by the eight laboratories describing our collaboration (summarised below). The panel session was chaired by James Murphy, NNL Chief Strategy Officer, with a guest keynote from Paul Kearns, director of the US Argonne National Laboratory and past chair of the US Department of Energy National Lab Directors' Council. Joining the panel were: Martin Keller, director of the US National Renewable Energy Laboratory (NREL); Jonathan Cobb, Senior Communications Manager at the World Nuclear Association; and Paul Nevitt, NNL's Director of Science and Technology, who also presented the impact paper.

The impact paper offered a summary of IES activity across the three collaboration areas of engaging end users, energy systems modelling, and hydrogen, with further highlights of activity within each country. The paper made a series of recommendations on advancing RD&D in integrated energy systems, namely:

- A focus on nuclear-renewable hybrid systems, with storage and flexibility, supports the decarbonisation of an increasingly electrified energy system
- Beyond electricity, broaden the consideration of energy vectors to include heat, hydrogen and synthetic fuel
- Deepen engagement with end users to optimize the outputs from integrated energy solutions
- Take an integrated approach at multiple spatial scales and ensure consistency between national strategies and local energy planning
- Take an integrated approach at each stage of system deployment, from long term planning to operational control
- Ensure the integration readiness of physical system components through development and demonstration
- Facilitate the economic assessment of integrated energy systems to inform business planning by future owner/operators

2023 SUMMIT, LONDON

Members of the global national laboratories steering committee met in London in January 2023 to develop and agree on a plan to deepen our collaboration. This was the first time that the committee met in person and enabled in-depth sharing of challenges and opportunities common across the nations.

The workshop focussed on three key areas for collaboration: end users, models and data, and hydrogen, with the labs sharing their experience and aspirations in each area. Across these topics, the importance of policy, market dynamics, human behaviour, and international energy markets was also raised.

To gain insight from outside the sector, the workshop also featured talks from **Weinerberger** on their low carbon energy needs, from **DNV** on conversion of gas networks to hydrogen, and from **ITM Power** on their electrolyser development. This allowed a greater understanding of the needs, challenges and capabilities of the industries that the labs include in their models, which will hopefully lead to improved model accuracy and improved determination of the optimal path to net zero.

As a result of the meeting, members of the steering committee have agreed to establish cross-organisation working groups. Early activities for these groups have already been identified:

End users working group

- Build a heat map of common markets of interest across the labs, to be used to coordinate and prioritise engagement

Models and data working group

- Share model coverage and roadmaps
- Identify opportunities to share existing models and datasets
- Identify data gaps for collaborative development of new open datasets
- Agree a use case for model benchmarking

Additionally, the members will explore the feasibility and practicalities of facility-sharing. This could deliver great cost savings: instead of each country needing to build and operate one of each type of facility, national resources can be shared in a mutually beneficial manner.

Communication is also key to ensure our work makes a difference. Some areas, or international industries, may benefit from a joint communications plan. This will be explored further after the end users working group has made its recommendations. The group also has ambition to build on its appearance at COP27 with presentations at COP28 and the Clean Energy Ministerial. Most importantly, engagement needs to go beyond the energy sector echo chamber: the group needs to engage with a range of users and vendors.

Overall, at the event an essential foundation was laid for the coming years of collaborative activity. Through the working groups, subject matter experts can be brought together from across the labs with a clear goal in mind, and the international community of national labs can speak with one voice about how to calculate the best path to net zero.

Representatives from the collaborating labs at the Energy Summit in London, January 2023

LAB HIGHLIGHTS

Canadian Nuclear Laboratories

CANADA - CANADIAN NUCLEAR LABORATORIES (CNL)

Canadian Nuclear Laboratories (CNL) integrated energy systems activities are coordinated through the Clean Energy Demonstration, Innovation, and Research (CEDIR) Initiative. This initiative is divided into two phases:

- Phase 1 - CEDIR Labs, focuses on modelling and lab-scale R&D underway immediately.
- Phase 2 - CEDIR Park, takes a longer-term view with a focus on technology demonstration as part of a small modular reactor (SMR) enabled hybrid energy system.

The flagship of CEDIR Labs is a proprietary multi-objective optimization tool, Hybrid Energy System Optimization (HESO), which has been developed to better understand and inform how hybrid energy systems can support Canada's clean energy transition in a cost effective, reliable, and sustainable way. In addition, as part of CEDIR Labs, CNL has developed a number of other model and simulation tools to explore various aspects of IES. Ongoing research covers a wide range of topics including system optimization, CFD and thermalhydraulics, energy storage, clean hydrogen production, clean fuel production, and cyber security/ remote operation. These are supported by experiments in energy storage, microgrid, and synthetic gas, to deepen our understanding of these enabling technologies and inform future model development. In addition CNL has performed several case studies to better understand the potential of IES; including:

- A nuclear-enabled green mine site
- Direct heat and electricity to support Department of Defence operations in Canada
- Electrification of residential heat
- Oil sands extracting and upgrading
- Remote communities.

In 2023, CNL is expected to begin a new study in partnership on the suitability of SMRs to support commercial greenhouse operations in Canada, and is actively seeking other collaborations as well.

Phase 2 of the CEDIR Initiative focuses on the development of CEDIR Park; a physical demonstration park to support the development, validation, and deployment of nuclear-enabled IES. The CEDIR Park concept is still in development and progress is being made towards a conceptual design for the main building which is to include several indoor and outdoor demonstration bays capable of accommodating a wide variety of clean energy technology demonstrations. CEDIR Park is expected to be deployed in parallel with a SMR, which will enable the demonstration and licensibility of a reactor closely coupled with other clean energy systems or industrial process.

Journal papers:

1. A.M. Bayomy and M. Moore, "Nuclear renewable hybrid energy system assessment through thermal storage system", Int. Journal of Energy Research, 2020. https://onlinelibrary.wiley.com/doi/abs/10.1002/er.5514
2. A. M. Bayomy, T. Pettigrew, M. Moore, and R. Lumsden, "Small Modular Reactors for Green Remote Mining: A Multi-Objective Optimization from a Sustainability Perspective", under review in Energy Conversion and Management.
3. P. Sanongboon and T. Pettigrew, "Hybrid energy system optimization model: Electrification of Ontario's residential space and water heating case study", Energy and Climate Change, 2022. https://doi.org/10.1016/j.egycc.2021.100070
4. P. Sanongboon, T. Pettigrew, and M. Moore, "Techno-Economic Analysis of Small Modular Reactor for Oil Sands Extraction and Upgrading in Canada", to be published.
5. P. Sanongboon and T. Pettigrew, "Economic Feasibility of Near-Zero Emission Configuration for a Canadian Remote Mine", to be published.

Conference papers:

1. A. Mahmoud and M. Moore, "Assessment of Nuclear Renewable Hybrid Energy System (NR-HES): Technical-Economic Approach", 2020 May, 4th International Conference on Generation IV and Small Reactors (G4SR-4), Toronto, Canada.
2. A. Mahmoud, P. Sanongboon and L. Mosscrop, "Business Model for a Nuclear Hybrid Energy System", 2022, 4th International Conference on Generation IV and Small Reactors (G4SR-4), Toronto, Canada.
3. P. Sanongboon, "Feasibility and Benefits of Nuclear Reactor Hybrid Energy Systems: A Remote Community Case Study" 2022, 4th International Conference on Generation IV and Small Reactors (G4SR4), Toronto, Canada.
4. P. Sanongboon, and M. Moore, "Supporting the Fight Against Climate Change with Hybrid Energy System Optimization, HESO", 2022, Annual Canadian Women in Nuclear Conference, Niagara Falls, Canada.
5. P. Sanongboon, "Technological Learning and Nuclear Small Modular Reactor for Hydrogen Production", 2022, IAEA Energy Optimization Tool Workshop, Stockholm, Sweden.

Webinars:

1. A. Mahmoud, 2021, "Nuclear Renewable Hybrid Energy System (NR-HES)", G2SR4-2 Technical Webinar, March 18, 2021.
2. M. Moore, "Net Zero Needs Nuclear", 2023, Organization of Canadian Industries, (Panel speaker).
3. M. Moore, "Hybrid Energy Systems: CNL;s Clean Energy Demonstration, Innovation, and Research (CEDIR) Initiative", 2023, North American Young Generation in Nuclear.

LAB HIGHLIGHTS

FRANCE - ALTERNATIVE ENERGIES AND ATOMIC ENERGY COMMISSION (CEA)

To meet both the current and future stakes of the energy transition which is indispensable to fight climate change, the CEA has been leading research on low-carbon power systems combining nuclear and renewable energies. This research covers low-carbon power production methods, the systems used for energy storage, control and conversion, and resource management within a circular economy strategy. This wealth of expertise serves the interests of the French public authorities and industry players.

A way to deal with the challenges associated with the energy transition is to integrate the use and production of nuclear energy in local hubs (small power grids, isolated sites).

Hydrogen as an Energy Vector

With physical and chemical properties that enable it to produce and store large amounts of energy, green hydrogen has the capacity to support electricity grids. Hydrogen is becoming the key energy vector for long-range clean mobility and is supporting the emergence of low-carbon-emission industrial processes.

CEA teams at LITEN (located in Grenoble) are conducting research on hydrogen as an energy vector developing key components for hydrogen production, storage, and conversion. These technologies are now mature enough to respond to the demands of today's market and environmental imperatives.

SMR: an hybrid system beyond power generation

Situated in the 50 to 300 MW range, the small modular reactors (SMR) provides a solution for regions off the grid without local power sources, as well as for countries looking to decarbonise their electricity by using power plants equivalent in size to those of coal-powered plants (about 300 MW).

In France, the CEA is investigating this technology through the NuwardTM project led by EDF in collaboration with Framatome, TechnicAtome et NavalGroup. It is based on two 170 MW reactors, with the target of delivering the first of a kind around 2030. The French state once again stressed the importance it gives to deploying the SMRs by making it the top priority of the 'France 2030' plan. This plan provides a clear orientation for French research, setting aside €8 billion over five years to meet the five objectives set for the energy sector and the energy transition in particular. In the much longer term, the CEA foresees the possibility of exploiting these small reactors to decarbonise other parts of energy systems. Under the IDNES project, researchers are assessing the capacity of SMRs to generate not only electricity but also to provide hot water and decarbonised hydrogen to meet local needs. In the latter cases, the SMRs will be connected to high-temperature electrolysis units, an innovation developed by the CEA-Liten.

In addition, the CEA has participated in various events to present the French Nuclear Policy for Carbon Neutrality and Energy Security.

Links

https://www.cea.fr/cea-tech/liten/english/Pages/Medias/News/Hydrogen-Vector/New-insights-into-what-makes-solid-oxide-electrolyzer-cells-mechanically-robust.aspx

https://mix-energy.com/en/home/

https://www.youtube.com/watch?v=NWyFRSRu10o

LAB HIGHLIGHTS

JAPAN – JAPAN ATOMIC ENERGY AGENCY (JAEA)

Nuclear and Renewable Hybrid Energy System (NR-HES)

JAEA is carrying out R&D called Nuclear and Renewable Hybrid Energy System (NR-HES). This system is an integration of renewable energy (RE) and nuclear such as large and small modular light water reactors, small modular sodium-cooled fast reactors, high temperature gas-cooled reactors, and it focuses on attaining power grid resilience, nuclear fuel cycle sustainability and net zero.

In this system, development of integrated simulation tools is being carried out in a national project in collaboration with the University of Tokyo, Institute of Energy Economics Japan (IEEJ) and industries to assess 1) electricity grids resilience, 2) energy supply (electricity, hydrogen, heat, fuel) best mix scenarios and 3) fuel cycle sustainability and operation flexibility of advanced nuclear reactors at local and national levels to underscore nuclear energy roles in a net zero society.

In 2022, preliminary simulations were conducted using an electricity supply-demand model with detailed geographical and temporal resolution to evaluate the best mix of electricity generation options including point-by-point deployment scenario of SMRs. Similarly, preliminary calculations were carried out with an integrated energy supply-demand model to clarify the role and economic value of various reactor types based on the latest domestic and international trends in energy policy. Required to input to these analytic models, the performance parameters such as nuclear fuel cycle balance, safety and economic effects of distributed reactor siting, and load-following capabilities have been updated reflecting the latest progress on advanced reactor designs.

In another national project, an out-of-pile test facility to demonstrate the platform of reliability, operability and resilience is also planned. This platform simulates an integrated system, such as nuclear power, heat storage, hydrogen, and renewable energy systems. In this platform, a nuclear reactor simulator can demonstrate its operation safety and flexibility. An Internet of Things (IoT) system will monitor, forecast, and optimize energy production of the total system.

In 2022, the basic design works of this facility has been implemented and the trial operation of the IoT system computing program has been achieved.

LAB HIGHLIGHTS

UK - ENERGY SYSTEMS CATAPULT (ESC)

WWU - Regional Decarbonisation Pathways – Future of the Gas Grid

Energy Systems Catapult worked with Wales & West Utilities to explore the implications of decarbonisation on their natural gas distribution network. The Catapult delivered a strategic plan and decarbonisation roadmap for WWU, utilising whole system modelling to develop three future scenarios with different levels of hydrogen adoption across a variety of regional, sub-regional and temporal scales.

The regional aspects of the strategic plan utilised the Catapult's internationally peer-reviewed Energy System Modelling Environment (ESME). This is a least-cost, techno-economic whole system model, widely regarded as one of the most mature and credible models of its kind.

The sub-regional aspects leveraged the Catapult's new ESME Network tool to provide insights at a more granular level. The outcomes were a range of potential net zero pathways and insights about how the wider energy system and networks within it could develop over time.

Scottish Energy scenarios - Development of Whole System Energy Scenarios for The Scottish Government

Energy Systems Catapult delivered three Scotland-specific whole energy system scenarios consistent with the wider UK transition. These scenarios demonstrate three different routes for Scotland's to meet its annual, interim (2030) and net zero (2045) net zero targets, through different combinations of technology innovation and societal change:

- The Technology (TEC) scenario is able to remove significant amounts of CO2 by direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) used to produce hydrogen and electricity. This reduced the level of societal change necessary to meet targets thus minimising the impact on people's lifestyles.
- The lower energy demands assumed in the Societal Change (SOC) scenario meant targets were achievable with far lower amounts of biomass and engineered removals of CO2. In addition, shifts in diet from red meat and dairy, combined with ambitious programmes of peatland restoration and afforestation, meant land use became a net GHG sink.
- Balanced Options (BOP) combined some technology innovation with some degree of societal change to meet GHG targets in a more balanced way than TEC or SOC.

Future Energy Grids for Wales (FEW) - Welsh Gov - Whole systems analysis for Wales with electricity and gas network implications.

The Welsh Government aims to establish the country as a global leader in technologies that will power a net zero future, which required a re-examination of the infrastructure needed to deliver rapid and effective change.

Energy Systems Catapult used their ESME modelling suite and engagement with network operators, Ofgem, and the Welsh Government to develop pathways to net zero by 2050. The project identified the key implications for electricity and gas network operators and energy governance recommendations for the Welsh Government.

Two baseline whole energy system scenarios focus respectively on greater success in technology innovation or improved consumer awareness and engagement.

Hydrogen Innovation Initiative (HII) - Making Hydrogen work for the UK.

The emergence of new global markets for zero carbon hydrogen presents a major economic opportunity for UK businesses in line with the UK Government's Ten Point Plan for a Green Industrial Revolution.

To realise this opportunity, we cannot continue to innovate in traditional sector driven silos and must develop new connectivity across sectors, organisations, places and nations. This led to the creation of the Hydrogen Innovation Initiative (HII) - a collaborative initiative between the Catapult Network (including ESC), National Physical Laboratory, Net Zero Technology Centre, the Aerospace Technology Institute and Advanced Propulsion Centre supported by Innovate UK.

The Hydrogen Innovation Initiative's mission is to help maximise the UK share of the global hydrogen market by helping the nation's businesses to innovate new products and services. Over the course of this year HII will be working with UK clusters, industry, investors, innovators and government, to build the strategic case for UK investment into hydrogen innovation, making the case for a national Hydrogen Innovation programme.

The work of HII will accelerate translational research to grow the Hydrogen Economy and the critical role it will play in delivering Net Zero.

LAB HIGHLIGHTS

NATIONAL NUCLEAR LABORATORY

UK - NATIONAL NUCLEAR LABORATORY (NNL)

Unlocking UK Nuclear Hydrogen

As part of a **UK Nuclear Hydrogen Roundtable**, leaders from across the government, financial, energy and hydrogen sectors gathered with the shared aim of unlocking the nuclear hydrogen economy. This was a pivotal cross-sector meeting that sought to identify the challenges that must be overcome to enable nuclear-derived hydrogen to contribute to a net zero energy system and a resilient green recovery. The Roundtable and subsequent report are delivered as part of the Nuclear Sector Deal, which is a commitment by the sector to work collectively, with support from government, to drive clean growth throughout the economy and make civil nuclear power an integral part of the UK's energy future. This document details the action plan required by both industry and government to realise the potential for nuclear-enabled hydrogen to contribute to a future net zero energy system through delivery of cost competitive, zero carbon hydrogen at scale. Successful and rapid delivery of this plan, which can be implemented through the Nuclear Sector Deal, will enable nuclear energy to make a significant contribution to a world-leading hydrogen economy.

Nuclear Enabled Hydrogen to the Gas Networks

Under the government funded Advanced Nuclear Skills and Innovation Campus (ANSIC) NNL and DNV, a leading authority in the UK on a gas network transition, collaborated to deliver a first-of-a-kind project to bring the nuclear and gas network sectors together, exploring the potential for hydrogen produced from nuclear energy to be transported and distributed to end users through a converted hydrogen gas network.

The project concluded there are no showstoppers to nuclear-enabled hydrogen being injected to the gas network. The findings of the report can provide policymakers and energy system stakeholders, including National Grid and the Gas Distribution Networks (GDNs), with a heightened level of confidence that nuclear could be deployed to support transition of the gas networks to hydrogen. This is anticipated to lead to spin-off projects that can build the momentum on nuclear to support a gas network transition (decision making on the gas network transition scheduled by 2026) and assist in understanding options and opportunities for providing low cost, secure and resilient hydrogen to consumers in the medium and longer terms, reducing reliance on natural gas and fluctuating international energy markets. As part of the project, NNL and DNV engaged with 34 organisations, held three in person workshops (including attendance at a nuclear licensed site), delivered five seminars and presented at seven conferences. Read the **World Nuclear News article.**

Bay Hydrogen Hub

Funded as part of the Department for Energy Security and Net Zero (DESNZ) Industrial Hydrogen Accelerator Programme, the Bay Hydrogen Hub - Hydrogen4Hanson project demonstrates the decarbonisation of energy intensive cement and asphalt production with hydrogen produced using nuclear derived heat and electricity and Solid Oxide Electrolysis Cell technology (SOEC).

The feasibility study stage was led by EDF R&D and comprised of EDF Energy (operator of Heysham nuclear station), EDF R&D, Ceres (electrolyser developer), NPROXX (hydrogen transport technology provider) Hanson (asphalt and cement producer) and NNL.

This project positions the UK as leaders globally and demonstration would mean the UK would be amongst the world's first demonstration of nuclear derived hydrogen production via Solid Oxide Electrolysis and end use. NNL led on the feasibly of future developments beyond demonstration, establishing that future siting, economics and scalability are all favourable for development of nuclear enabled hydrogen generation. This work, like the above hydrogen to gas networks project, unlocks the understanding for a range of stakeholders on the part nuclear energy can play in supporting net zero through the production of hydrogen as well as enabling a broader education and engagement around nuclear energy and how it benefits society beyond electricity generation. Read the **Feasibility Study**.

LAB HIGHLIGHTS

NATIONAL NUCLEAR LABORATORY

Preliminary Economic Assessment of GW Scale Nuclear Enabled Hydrogen Production

NNL carried out **preliminary economic assessments** for the potential levelized cost of producing hydrogen from GW scale new build nuclear reactors at multiple financing rates that could be consistent with a Regulated Asset Base (RAB) financing model. Exclusively using government published data as inputs, and remaining consistent with government published economic calculation methods, the costs for nuclear driving PEM, Alkali and solid oxide electrolysers were assessed and were shown to be potentially cost competitive with other forms of low carbon hydrogen production. The work adds to the 2021 Hydrogen Production Costs modelling by BEIS, which did not fully assess the economics of nuclear enabled hydrogen and therefore highlights a potential opportunity for the hydrogen sector to draw on an additional source of low carbon hydrogen.

HyTN - Development of Thermochemical Hydrogen Production from Nuclear

Nuclear power is already a high capacity source of zero carbon electricity generation in the UK, making up 40% of our existing clean electricity supply. The next generation of nuclear reactors, Advanced Modular Reactors (AMRs), could play a similarly significant role in the wider energy system, not just electricity, through the generation of large quantities of hydrogen at a scale and cost that enables it to be used as a primary energy vector. AMRs operate at higher temperatures of up to 950°C and have the potential to unlock high temperature thermochemical processes for the production of hydrogen, with subsequent conversion of this hydrogen into suitable energy vectors such as ammonium and synthetic hydrocarbons.

Worldwide studies have shown these thermochemical technologies have significant potential to generate low cost hydrogen at scale. The UK has limited knowledge and understanding of these technologies to date. Therefore, this **feasibility report** proposes a programme of work to unlock a technology combination through demonstration, that can deliver large scale, low cost hydrogen production to enable a greater rollout of hydrogen solutions, to contribute to the wider net zero energy system.

Advanced Modular Reactor high temperature heat for industrial processes

NNL are working with Energy Systems Catapult (ESC) to extend their UK whole energy system model (ESME) to test high temperature heat from AMRs being delivered directly to support industrial processes. NNL are providing the economic and technical performance assumptions for the reactor, while ESC will incorporate this into their model and test whether the new technology offering is taken up as part of a cost-optimal system design. The project will focus on clustered industries only (Iron & Steel, Chemicals, Cement, Refineries) with the potential to serve high and low temperature process heat, as well as drying and separating processes, for a total potential market of approximately 100TWh in 2050.

UK Integrated Energy Systems Collaboration Centre

As set out among NNL's commitments during the 2022 inaugural summit, work progresses on initiating a UK collaboration centre for Integrated Energy Systems, which NNL will initially fund over a five year period.

LAB HIGHLIGHTS

US - IDAHO NATIONAL LABORATORY (INL)

Integrated Energy Systems Research

The DOE Office of Nuclear Energy (DOE-NE) program on Integrated Energy Systems (IES) is led by researchers at Idaho National Laboratory (INL), and work is conducted in partnership with an array of other DOE laboratories, industry, and academia. IES research and development activities are additionally complemented by the DOE-NE Light Water Reactor Sustainability (LWRS) program, where work under the Flexible Plant Operations & Generation pathway supports analysis of opportunities for non-electric applications of current fleet nuclear plants and collaborates with multiple plants on near-term hydrogen production demonstration opportunities. The DOE-NE programs additionally partner with the Hydrogen and Fuel Cell Technologies Office under the DOE Office of Energy Efficiency and Renewable Energy to jointly fund the development of analysis tools, technologies, and nuclear-integrated hydrogen demonstration projects.

The primary focus of DOE-NE IES research is to assess the technical and economic potential of nuclear-driven IES to enhance the flexibility and utilization of nuclear reactors working alongside renewable generators to meet an array of energy demands—thereby maximizing the utilization of clean energy resources across all energy sectors. Various energy applications and product streams beyond electricity are being evaluated, ranging from generation of potable water to production of hydrogen, fertilizers, synthetic fuels, and various chemicals.

Advances in IES Modeling, Simulation, and Optimization

INL, working in partnership with other U.S. national laboratories and universities, has developed the Framework for Optimization of ResourCes and Economics (FORCE) for energy system design and optimization. FORCE supports analysis of the technical and economic feasibility of candidate energy systems operating within specific energy markets and supporting multiple product markets (for more information and to access training modules see https://ies.inl.gov/SitePages/FORCE.aspx). FORCE and its various plug-ins support evaluation of the integrated operation of multiple reactor types, renewable technologies, and energy users across the electricity, industry, and transportation sectors. Input data are required for the intended energy market and how that market might fluctuate over time: time-dependent data for renewable energy sources based on historical datasets, and financing details such as capital costs, interest rates, and rate of return. The models employed by FORCE represent detailed dynamic operations of the various interconnected subsystems, determining optimal subsystem capacities and real-time dispatch. Dynamic models currently include multiple rector technologies, thermal and electrical energy storage, desalination, hydrogen production, balance of plant options, and other necessary components and subsystems. The FORCE tool suite is available as open source via github.

INL has led numerous feasibility studies, many in partnership with other national laboratories and private industry, some of which are now leading to operational systems. Analysis reports associated with enhanced utilization of currently operating light water nuclear plants are primarily issued via the LWRS Flexible Plant Operation & Generation Pathway. Reports covering simulation tool development and enhancements and application of FORCE to advanced reactors are generally issued via the IES program (https://ies.inl.gov/SitePages/Reports.aspx).

LAB HIGHLIGHTS

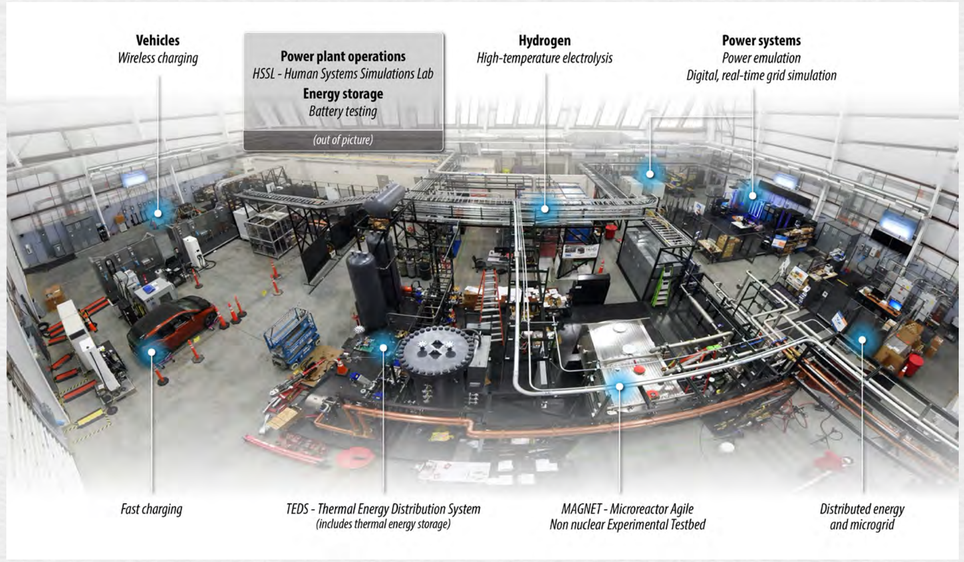
Idaho National Laboratory

Experimental Demonstration

INL has established a nonnuclear facility to test novel systems integration. It provides the opportunity to conduct lab-scale testing and demonstration of individual or coupled technologies in order to demonstrate performance characteristics, integration approaches, and system control options. The facility uses electric heating to represent the heat that would be provided by a nuclear reactor. The test facility includes a microreactor testbed, thermal energy distribution, high-temperature electrolysis components and systems, power systems emulation, and microgrid infrastructure.

Detailed studies on the utilization of the existing fleet of nuclear plants for hydrogen production via low temperature or high temperature electrolysis (LTE or HTE) are now resulting in cost-shared (public/private funding) demonstrations at three U.S. nuclear plants. In March 2023 the Constellation Nine Mile Point Nuclear Plant in New York began onsite production of hydrogen using nuclear power coupled to LTE. This demonstration will be followed by hydrogen production at the Energy Harbor Davis-Besse Nuclear Power Station, also using LTE, and the Xcel Energy Prairie Island Nuclear Generating Plant using higher-efficiency HTE.

These early LWR-based demonstrations provide a strong foundation for thermal and electrical integration of non-grid energy users (e.g., hydrogen production, among others) with greenfield projects. Advanced reactors are designed to operate at higher temperatures, run more efficiently, and provide greater flexibility than LWRs, making them ideally suited to many industrial heat users. These systems are available at a range of capacities, allowing them too work in concert with renewables power microgrids in isolated communities, supply heat and electricity to remote mining operations, provide dedicated energy for large hydrogen markets and so much more.



INL is the U.S. DOE lead laboratory for nuclear energy and also leads development and demonstration of HTE for hydrogen production. INL partners with multiple steam electrolysis companies to demonstrate performance of individual solid oxide electrolysis stacks and complete systems as private industry seeks to advance their technologies to achieve to commercial-scale hydrogen production. From 2022 to 2023, in collaboration with Bloom Energy, INL has operated a 100-kWe Bloom HTE system for over 4000 hours under both steady state and transient conditions. INL is now preparing to receive a 250-kWe HTE system from FuelCell Energy for testing and is finalizing construction of an “open architecture” system that will support advancement of HTE systems from other vendors.

Engaging an International Audience

INL and NREL jointly support the **Nuclear Innovation: Clean Energy Future (NICE Future)** initiative under the Clean Energy Ministerial. Two **key publications** were issued by NICE Future in 2022. “The Nuclear Hydrogen Digest: The Role of Nuclear Energy in the Hydrogen Economy” showcases examples of leading nuclear energy based hydrogen initiatives around the world which can be used to power hard-to-electrify sectors such as transport and heavy industry. Additionally, the Research Impacts on Social Equity and Economic Empowerment (RISE3) initiative was launched under NICE Future. The first action for RISE3 was to develop the case study series. They include submissions from participating countries and partner organizations that demonstrate how advanced and innovative nuclear energy technologies, such as small modular reactors, will support the clean energy transition in a variety of community contexts.

LAB HIGHLIGHTS

US - NATIONAL RENEWABLE ENERGY LABORATORY (NREL)

Integrated Energy System Research

The Advanced Research on Integrated Energy Systems (ARIES) Platform

The National Renewable Energy Laboratory (NREL), in partnership with the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, developed the Advanced Research on Integrated Energy System (ARIES) platform. ARIES supports development and demonstration at the system level and is designed to mimic the complexity and scale of real-world energy systems. The ARIES platform is highly adaptable to different technologies and helps researchers address key energy challenges through advanced research equipment, hardware and software that can mirror renewable energy configurations, interconnected grid-scale devices and energy resources for experimentation, high-performance computing capabilities, and a team of laboratory experts.

NREL researchers establish communication pathways between lab devices and a virtual world. For example, the cyber range makes it possible to analyze energy systems subjected to energy disruption scenarios. Researchers can investigate vulnerabilities in a virtual world, such as in photovoltaic arrays or wind turbines.

Another example, the Hybrid Energy Real-Time Emulation Hub (HERTH), will be developed for connectivity between various hardware-in-the-loop and controller-hardware-in-the-loop devices and emulated devices in real-time environments to demonstrate the dynamic and transient interaction of hybrid energy systems.

The NREL and Idaho National Laboratory (INL) SuperLab

In January 2023, researchers demonstrated a virtual hybrid power plant, connecting energy assets across NREL and INL. This "SuperLab" showed that renewable and nuclear energy can work together to support the grid.

Through the SuperLab, NREL's ARIES provided a solar array, battery storage system, hydrogen fuel electrolyzer, and a controllable grid interface linked with simulations of a small modular nuclear reactor and high-temperature electrolysis in the Human Systems Simulation Laboratory at INL. The demonstration showcased the ability of nuclear power and renewables to work in combination to power the grid. An upcoming demonstration scheduled for late 2023 will simulate a nationwide disaster across eight national laboratories.

Integrated Buildings Distributed Energy Resources and Integrated E-mobility

Grid-buildings integrated energy systems are critical to our energy future and for realizing electrification and demand-side sustainability. NREL's building and grid interface modeling and simulation allow researchers to examine building control and automation, future market structures, and cybersecurity or cloud-connected appliances.

At the Energy Systems Integration Facility and the Thermal Testing Facility, NREL performs thermal and electrical characterization of home appliances and distributed energy resources. High-performance computing allows NREL researchers to examine large data sets and perform simulations with millions of buildings in a grid. This work extends to electric vehicles (EVs) grid integration research, drawing on crosscutting grid modernization and power system design capabilities. NREL uses modeling with tools like the Electric Vehicle Research Infrastructure (EVRI) evaluation platform, which enables researchers as well as industry and utility partners to study and develop optimal strategies for coordinating EVs with buildings, the grid, and other energy systems. Partners can bring in actual devices (charging hardware, vehicles, etc.) for performance evaluations under varying conditions.

Supporting Hydrogen at Scale: A key connection between power, fuels, industry, and chemicals

Hydrogen and fuel cell research at NREL seeks cost-efficient production, storage, transport, and use of hydrogen throughout energy systems. Hard-to-decarbonize sectors may benefit from clean fuel in the form of hydrogen. NREL research supports the vision and goals of the H2@Scale Initiative, which was created to advance the utilization of hydrogen across energy sectors and to complement the electric grid. Through the initiative, NREL analysts, in partnership with researchers from Argonne National Laboratory, Idaho National Laboratory, Lawrence Livermore National Laboratory, and industry experts, investigated new uses for hydrogen—think steelmaking and synthetic fuels—and their report characterized the economic potential of hydrogen consumption throughout energy sectors. Analysts predicted a 2- to 4-fold increase in potential hydrogen demand throughout the U.S. NREL recently partnered with Fortescue Future Industries (FFI) to power research projects in the sector. Such partnerships may help propel NREL's green technologies to commercial markets.

NREL leads the low-temperature electrolysis efforts under the H2NEW consortium. The consortium's objective involves overcoming technical barriers to affordable, reliable, and efficient water electrolyzers and the R&D includes determining how electrolyzers can optimally operate with variable generation and performance requirements to do so.

Innovative Analysis of Integrated Energy Systems

NREL supports research in broader analyses of integrated energy systems. The Nuclear Innovation: Clean Energy Future (NICE Future) initiative reported on evidence of the effectiveness of combined nuclear and renewable energies in future energy systems. This report cited international expertise in noting that flexibility of nuclear systems and innovation can help propel nuclear and renewable energies.

NREL produced a paper in Joule reporting on the potential of a novel hybrid energy system combining renewable, nuclear, and fossil (with carbon capture) energies that outlines a path toward an energy system that leverages various energy systems to optimize each one. A report from the Tri-Laboratory Materials Workshop, which included INL, National Energy Technology Laboratory (NETL), and NREL, further outlined necessary considerations in the development of integrated hybrid energy systems and identified technology gaps and research needs. NREL's broad work in integrated energy systems seeks solutions to today's energy grid challenges.

GLOBAL NATIONAL LABORATORIES

INTEGRATED ENERGY SYSTEMS