Global National Laboratories

INTEGRATED ENERGY SYSTEMS COLLABORATION

Recommendations for Advancing Research, Development and Demonstration (RD&D)

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SUMMARY

Integrated Energy Systems will be essential to the delivery of net zero, enabling renewables, nuclear and energy storage technologies to work together to provide clean electricity, heat, hydrogen and more. A group of eight national laboratories across five countries are collaborating on this important topic and here we share highlights of our work and recommendations for advancing RD&D in Integrated Energy Systems.

SUMMARY OF RECOMMENDATIONS

- **A focus on nuclear-renewable hybrid systems, with storage and flexibility, supports the decarbonization 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.**

INTRODUCTION

Delegates are gathering at COP27 to make progress on climate action amid a growing energy crisis. Previous 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.

To enable this transition, energy systems must become more integrated, drawing on the diverse characteristics of multiple generators to deliver clean, affordable, and reliable energy services to meet the evolving needs of society across multiple energy use sectors. Such integrated energy systems will be critical in enabling the displacement of unabated fossil fuels in transport, buildings and industry, by supporting an expansion of clean energy vectors like electricity, hydrogen and heat.

GLOBAL NATIONAL LABORATORIES COLLABORATION

To help prepare for this, a group of national laboratories have established a global collaboration on Integrated Energy Systems.[1]

This includes eight partners across five countries:

- **Canada:** Canadian Nuclear Laboratories (CNL)
- **France:** The French Alternative Energies and Atomic Energy Commission (CEA)
- **Japan:** Japan Atomic Energy Agency (JAEA), the Institute of Energy Economics Japan (IEEJ)
- **UK:** National Nuclear Laboratory (NNL), Energy Systems Catapult (ESC)
- **US:** Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL)

Each of the labs is working on aspects of the Integrated Energy Systems challenge, including development of modelling frameworks, conceptual designs, experimental laboratories and demonstration projects. Together, these labs have identified several areas of common interest where international collaboration is being focused: market assessment and end user engagement; hydrogen production; country specific models and case studies.

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[1] https://www.nnl.co.uk/innovation-science-and-technology/collaborations/energy-summit-2022/

END USER ENGAGEMENT

Integrated energy systems can make a critical contribution to decarbonizing buildings, transport and industry, as well as emerging energy applications such as production of synthetic fuels, desalination and direct air carbon capture. However, designing and optimizing these systems requires a robust understanding of the various energy users' needs, and consideration of different clean energy technology and integration options for satisfying these.

As such, the global national laboratories team has developed a consensus that integrated systems thinking must start with a clear focus on understanding energy user requirements. Early and ongoing engagement with these energy customers is essential.

In October 2022, the Non-Electric Applications of Nuclear Heat (NEANH) Task Force of the Generation IV International Forum (GIF),[2] under the leadership of INL, organized a workshop that included collaborating laboratories from all five countries represented in the current collaboration. This workshop brought together industrial energy users, integrated energy systems researchers and advanced nuclear reactor vendors.

Reactor vendors provided a showcase of what nuclear energy can offer from the supply side, while researchers from the different labs highlighted modelling tools and frameworks for the design and optimization of systems that can integrate these reactors with renewables and storage, providing affordable, reliable, low carbon energy to the user.

A group of industry representatives, energy end users, provided critical input on their own energy needs and the unique challenges of operating in their various industries and geographies, with subsequent discussion on the opportunities and challenges of integration. These industries included chemical production, refineries, oil sands, ammonia production and district energy (to include both heating and cooling).

The energy intensity of many industrial activities, and the tendency for these to be clustered together, makes these applications an ideal starting point for integrated energy system planning, with potential to integrate additional customers in the surrounding area, such as public, commercial and residential buildings and transport infrastructure. In these cases, by seeking out synergies among co-located energy users, integrated energy systems can be fine-tuned to optimize delivery of electricity, hydrogen and direct heat at different temperatures, improving supply reliability and minimizing costs.

In other cases, the industrial activities in question are situated in remote locations, isolated from centralized grids and often supported by significant quantities of fossil fuels transported to the site. The challenges and opportunities here are different, but the potential to integrate local energy sources and minimize reliance on delivery of fossil fuels is similarly attractive.

By having integrated energy systems as a convening theme, it was possible to initiate direct conversations between energy technology vendors and industrial energy users. Several key points emerged from the discussion:

- **Cross-sector communication:** Participants from across the spectrum commented on the importance of listening and communicating across traditional silos.
- **Regulation(s):** Co-locating energy technologies such as nuclear alongside heavy industries will require integrated solutions that can navigate multiple sets of regulation, which vary by sector and jurisdiction.
- **Data:** A recurring theme was the need for transparent data from both sides, on which to plan and test different integrated energy system solutions.
- **Public Engagement:** Whether it be for remote industrial applications or those adjacent to densely populated areas, integrated energy system solutions will depend on buy in and participation from local communities.
- **Cost:** Integrated energy system solutions must demonstrate that they can provide an affordable solution to the energy needs of a given set of users.
- **Demonstration:** For many industries, it will be necessary to first 'see' the proven benefits of integrated solutions in the form of real demonstration facilities, providing confidence for investment decisions.

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[2] Non-Electric Applications of Nuclear Heat Task Force, GIF https://www.gen-4.org/gif/jcms/c_203298/chapter-5-neanh-tf

HYDROGEN PRODUCTION

Hydrogen production has been proposed as a key route to decarbonization of hard-to-abate sectors across the world. Whether used in its pure form, or as a feedstock to another energy vector such as ammonia or synthetic hydrocarbons, many challenges exist in the scale up of global low carbon hydrogen production.

Electrolysis powered by renewable energy has emerged as a primary option for hydrogen production in the near term, given the rapid and ongoing deployment of renewables around the world. Many countries are also investing in the development of carbon capture and storage (CCS) enabled hydrogen, making use of a natural gas feedstock while diverting carbon emissions to suitable long-term storage.

In some parts of the world, land and resources may constrain the scale up of renewables, and geological factors may prohibit the storage of captured carbon. In these cases, an integrated approach incorporating complementary technologies can overcome these constraints. This may include solutions using the electricity and heat from nuclear energy to drive more efficient production processes.

Integrating nuclear as a heat source can drive both high temperature electrolytic and thermochemical technologies, which provides further diversity to the future production routes and scale up. Additionally, the availability of low carbon heat alongside hydrogen production could allow for onward production of derivative fuels, such as ammonia or synthetic hydrocarbons, which provide valuable buffer storage mechanisms in the energy system.

When considered as part of an Integrated Energy System, hydrogen provides increased flexibility and allows for multiple viable routes to decarbonization, reducing risk. Translating analysis into reality requires significant developments in incentivization, business models and technology innovation to deliver the scale up required as part of a net zero energy system.

COUNTRY SPECIFIC MODELS

Across the collaborating laboratories, expert teams of researchers are building and deploying models to support integrated energy systems analysis at different scales. Modeling activities range from national scale net zero pathways to individual sites designed to integrate grid renewables with nearby nuclear reactors, providing electricity, heat and hydrogen to industry and other users. As part of our commitment to collaborate and share best practices, the labs are sharing knowledge on modeling methods, data management and individual case studies. Highlights from each country are provided below.

Canada

Canadian Nuclear Laboratories (CNL) has developed the Hybrid Energy System Optimization (HESO) tool, which is a proprietary mixed integer linear programming optimization model that can be used to evaluate different clean energy pathways. The HESO tool has been used for a variety of case studies,[3] working with key stakeholders to understand their energy requirements and assessing pathways to reduce total emissions from the process. Recent case studies include:

- A collaborative project[4, 5] with Ontario Power Generation (OPG), Mirarco Mining Innovation, and an industry partner to complete an economic feasibility and cost-benefit study to assess to potential to use a small modular reactor (SMR) to reduce carbon emissions related to electricity and heat production at a mining site in the Canadian North.

- A feasibility study conducted for the Department of National Defence, on how a SMR could be used to provide both electricity and thermal energy to reduce a Canadian Military Base's reliance on and use of diesel fuel.

HESO and supporting model development continues under CNLs Clean Energy Demonstration, Innovation, and Research (CEDIR) Initiative.[6] This includes more detailed economic and thermalhydraulic models, which are used to better understand specific phenomenon to inform the HESO model.[7]

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[3] Electrification of Ontario's residential space and water heating case study, Energy and Climate Change, https://doi.org/10.1016/j.egycc.2021.100070

[4] Remote mining in the far north (OPG, MIRARCO, CNL), https://www.opg.com/documents/smr-economic-feasibility-and-cost-benefit-study-for-remote-mining/

[5] Benchmarking Approach for Decision Analysis of Small Modular Reactors (SMRs) in Mining (OPG, MIRARCO, CNL), Energy Policy (in-review)

[6] https://www.cnl.ca/clean-energy/clean-energy-demonstration-innovation-and-research-cedir-park/

[7] Nuclear renewable hybrid energy system assessment through the thermal storage system, Energy Research, https://doi.org/10.1002/er.5514

France

To achieve our carbon-neutral objectives by 2050, the CEA is working on various building blocks of low-carbon energy production systems; i.e. supporting the current and future nuclear fleet through the development of small modular reactors (SMR), and conducting R&D on PV solar power and hydrogen.

CEA is investigating tools that offer flexibility and energy storage methods, along with smart-load grid management and power conversion possibilities. It is specifically focusing on the performance and energy efficiency of complex energy systems.

To meet the challenges of the energy transition and the goal of carbon neutrality by 2050, and to cope with the efficient integration of renewable energies into the energy mix and the growth of new uses, energy networks (heat, electricity, gas) must be rethought. From their architecture to their management, from components to systems, CEA teams are working alongside their industrial partners to design smarter, more resilient, more efficient and more economical networks.

Japan

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, sodium-cooled fast reactors, high temperature gas 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 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 IoT system will monitor, forecast, and optimize energy production of the total system.

UK

Energy Systems Catapult maintains a collection of modelling tools to help identify market opportunities, policy/regulatory choices and innovation priorities for the journey to net zero.

At the national scale, the Energy System Modelling Environment (ESME) identifies cost-optimized decarbonization pathways across the whole UK system, independent of sector interests. This includes the complex interactions of power, gas, heat and transport, and the different ways in which energy might be supplied, managed and consumed in the future. Constraints include net zero targets, resource and technology limitations, and operational factors that ensure adequate system capacity and flexibility.

ESME underpinned the Innovating to Net Zero[8] report, which modelled hundreds of potential pathways to 2050 – ramping up or down different technologies and behaviours – to understand the combinations, interactions and trade-offs of competing decarbonisation approaches. A further study, Nuclear for Net Zero[9], provided a deep dive into the role of nuclear technologies in achieving the UK targets.

ESME sits within a wider integrated modelling suite with further granularity in specific areas, including: regional/local infrastructure, individual building physics, multi-vector storage and flexibility, transport integration and energy system simulation. ESC deploy these and other tools to provide a technology agnostic, whole systems approach to decarbonizing industrial sites, business parks and campuses[10].

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[8] ESC (2020) Innovating to Net Zero https://es.catapult.org.uk/case-study/innovating-to-net-zero/

[9] ESC (2020) Nuclear for Net Zero https://es.catapult.org.uk/report/nuclear-for-net-zero/

[10] https://es.catapult.org.uk/what-we-do/future-energy-system/decarbonising-campuses-business-parks-and-industrial-sites/

US

The U.S. Department of Energy (DOE) has been researching the role of nuclear and renewable energy in integrated, clean energy systems for nearly a decade. These systems consider the potential electric and non-electric applications for both current fleet nuclear power plants and for emerging advanced reactor technologies expected to be ready for deployment within the next decade, as well as the role of these generation technologies alongside a growing amount of renewable generators on the grid and application of fossil resources with integrated carbon capture technologies. Design of increasingly complex, multidimensional energy systems is a significant challenge, requiring innovation in how they are modeled and optimized. As such, the U.S. DOE national laboratories for applied energy systems (including nuclear, renewable, and fossil energy sources) have partnered to develop a new modeling framework for engineering-based modeling and analysis for complex optimization of energy generation, transmission, services, processes and products, and market interactions.[11]

As an example, the U.S. DOE Office of Nuclear Energy Integrated Energy System program,[12,13] led by Idaho National Laboratory, has established a computational framework that leverages advanced modeling and simulation tools developed through the support of multiple programs and laboratories while incorporating specialized tools necessary for the economic optimization of integrated systems. The overall framework, called Framework for Optimization of ResourCes and Economics (FORCE), is applied to conduct analysis of the technical and economic viability of a range of possible IES configurations and, ultimately, to optimize those configurations within a specific deployment region.

The flexible FORCE platform supports coupling of diverse generation technologies, can be used to evaluate dynamic delivery of energy to multiple energy use sectors, and provides an interface to access several code repositories that individually address a portion of the problem. The tools within FORCE are available as opensource, allowing stakeholders to directly access and utilize these tools; more details are available at the IES program website.[14]

The FORCE tool suite, applied in conjunction with other energy modelling tools developed and utilized by NREL, such as the Regional Energy Deployment System (ReEDS) capacity expansion model and the PLEXOS production cost model, has allowed early evaluation of IES that would utilize nuclear energy for hydrogen production in multiple regions of the U.S. This has led to multiple nuclear-hydrogen demonstration projects, as summarized in the recently published *Nuclear-Hydrogen Digest*.[15] Numerous analysis reports can be found at the U.S. DOE IES program website.[16] Work is also being conducted to link these tools to the Institute for the Design of Advanced Energy Systems (IDAES), developed by the U.S. DOE National Energy Technology Laboratory.

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[11] Arent, D.J., Bragg-Sitton, S.M., Miller, D.C., et al., Multi-input, multi-output Hybrid Energy Systems, *Joule*, 5, 1-12, January 20, 2021.

[12] Bragg-Sitton S., et al. Integrated Energy Systems: 2020 Roadmap, INL/EXT-20-57708 Rev. 1, https://www.osti.gov/biblio/1670434, September 2020.

[13] The 2022 IES modelling and simulation roadmap is currently in final review and will be available at https://ies.inl.gov/SitePages/Reports%20-%20System%20Simulation.aspx upon approval.

[14] U.S. DOE IES program website, FORCE tool suite, https://ies.inl.gov/SitePages/FORCE.aspx. Training resources can be viewed at https://ies.inl.gov/SitePages/FORCE_2022.aspx.

[15] *Nuclear-Hydrogen Digest: Nuclear Energy in the Hydrogen Economy*, a publication supported by the Clean Energy Ministerial's Hydrogen Initiative and Nuclear Innovation: Clean Energy Future initiative, available at https://www.nice-future.org/assets/pdfs/nuclear-hydrogen-digest.pdf.

[16] U.S. DOE IES analysis reports are available at https://ies.inl.gov/SitePages/Reports%20-%20System%20Simulation.aspx; integrated system related reports from the U.S. DOE Light Water Reactor Sustainability Program are available at https://lwrs.inl.gov/SitePages/GroupedReports-sorted.aspx?ReportCategory=Flexible%20Plant%20Operation%20and%20Generation.

RECOMMENDATIONS

A focus on nuclear-renewable hybrid systems, with energy storage and flexibility, supports the decarbonization of an increasingly electrified energy system. Despite the rapid deployment of renewables, over 60% of global electricity generation still relies on unabated fossil fuels.[17] Further substantial deployment of renewables and nuclear can help displace these; however, this requires an integrated approach to overall energy system design that ensures adequate energy storage and other smart, flexible solutions.

Beyond electricity, broaden the consideration of energy vectors to include heat, hydrogen and synthetic fuel. Electricity itself only makes up around 20% of global final consumption of energy.[18] This share will expand as more energy applications, such as light duty vehicles, are electrified. However, many more applications – district heat networks, high temperature industry processes, heavy duty road vehicles, shipping and aviation – may be better served through provision of direct heat, hydrogen or synthetic fuel. The deployment of integrated energy systems incorporating nuclear cogeneration can ensure a ready supply of high-grade heat and electricity for direct use by customers, or for production of hydrogen and synthetic fuels.

Deepen engagement with end users to optimize the outputs from integrated energy solutions. Ensuring the affordability and reliability of clean energy provision requires a robust understanding of the needs of energy customers across buildings, industry and transport. The mix of users in each locality can vary significantly, from remote mining operations to dense urban areas. Participation of the various groups will be key to ensuring optimal design as well as community buy-in for any proposed solutions.

Take an integrated approach at multiple spatial scales and ensure consistency between national strategies and local energy planning. Across the world, countries are increasingly taking a national whole systems approach to the energy transition. At the same time, our labs are deploying tools to support integrated energy system planning on the scale of individual energy parks to serve local customers. It is important to maintain awareness, communication and alignment where appropriate, between researchers and decision makers across these spatial scales.

Take an integrated approach at each stage of system deployment, from long term planning to operational control. As is evidenced by the participating laboratories' case studies, the applications of integrated energy systems thinking range from multi-decadal system planning tools and concept designs for integrated energy parks, down to simulation tools linked with physical equipment in experimental labs. The continuity of an integrated systems approach across these different stages helps to identify potential barriers and accelerate the deployment of clean energy solutions. In the future, digital twins may assist in the day-to-day control and operation of integrated energy system solutions.

Ensure the integration readiness of physical system components through development and demonstration. As work progresses from modelling and simulation to operation and control of real systems, the technology readiness of individual components such as heat exchangers and thermal energy storage systems comes to the forefront.[19] Design concepts for integrated energy systems may rely on currently available components, which may have been deployed previously on a different scale or in a different context. Work may therefore be required to demonstrate the suitability of these components for integration in the proposed system.

Facilitate the economic assessment of integrated energy systems to inform business planning by future owner/operators. Consideration must be given to the institutional arrangements and business models appropriate for the operation of an integrated energy system drawing on multiple energy sources, producing and handling multiple vectors, and delivering these to multiple customers. These arrangements will vary according to local norms and business practices, and particularly when incorporating nuclear reactors, by regulatory jurisdiction. Current integrated energy system tools can be modified and supplemented to enable assessment of appropriate business models and simulate revenue flow.

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[17] https://www.iea.org/fuels-and-technologies/electricity

[18] IEA (2020), Key World Energy Statistics 2020, IEA, Paris https://www.iea.org/reports/key-world-energy-statistics-2020, License: CC BY 4.0

[19] INL (2020) Integrated Energy Systems: 2020 Roadmap https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_26755.pdf

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