

Idaho National Laboratory: Nuclear Flexibility via Multiple Products in Integrated Energy Systems

Prepared by Shannon Bragg-Sitton and Konor Frick of the Idaho National Laboratory (INL), a laboratory operated under DOE's laboratory complex.

INL is 1 of 17 DOE National Laboratories in the United States. INL, managed by Battelle Energy Alliance for the DOE Office of Nuclear Energy (DOE-NE), is the leading center for nuclear energy research and development. It is INL's vision to change the world's energy future and secure our nation's critical infrastructure. As such, the INL mission is to discover, demonstrate, and secure innovative nuclear energy solutions, other clean energy options, and critical infrastructure. INL's Integrated Energy Systems initiative, highlighted in the work presented here, is central to achieving a future in which energy demands across multiple use sectors are met by a combination of non-emitting energy sources to provide an optimized energy future. This chapter highlights work led by INL, in collaboration with other national laboratories, including Argonne National Laboratory, Oak Ridge National Laboratory, and NREL, to evaluate integrated energy system options that utilize nuclear energy in new ways. By working with key collaborators in the nuclear industry, these analytical studies are now becoming a reality in demonstration projects.

As established in the introduction to this report, nuclear energy systems can be flexible via many pathways, including operational flexibility (varying core power through various approaches) or product flexibility. This section focuses on nuclear flexibility via the production of alternative products in response to varying net demand for electricity. Recognizing that nuclear reactors have a demonstrated record of flexible power output, as described in the chapters provided by EDF and Exelon, this operational mode may not be economically desirable under all scenarios or within all electricity markets, nor does it efficiently use the capital that has been invested in these thermal generation systems.

The primary focus of the DOE-NE Program on Integrated Energy Systems, led by researchers at INL, has been to assess the potential for integrated energy systems to enhance the flexibility of the energy supplied by nuclear plants and to thereby maximize the use of the clean energy provided by these systems (Bragg-Sitton et al. 2020). This work begins with the question: "What additional product streams can be made using excess energy?" This question must be addressed within the context of a specific deployment location, which has implications relative to the electricity market structure, supply, and demand; available feedstock for industrial processes; and available product markets. Product streams, ranging from potable water to hydrogen, synthetic fuels, ammonia-based fertilizers, and various chemicals, have been considered. Each product stream has its own market and market drivers and its own geographic location that would maximize profitability. Some of these products would only require electricity to support production, while others require both thermal and electrical energy.

1.1 Modeling and Simulation Toolset

The DOE-NE Integrated Energy Systems program has developed a computational framework that leverages various modeling and simulation tools to specifically support the specialized requirements for designing, evaluating, and optimizing integrated energy systems configurations within the context of various market structures. This specialized framework is applied to assess

*This document encompasses one section of a larger report, titled *Flexible Nuclear Energy for Clean Energy Systems*. The full report can be found at <https://www.nrel.gov/docs/fy20osti/77088.pdf>. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.*

the technical and economic viability of potential system constructs for both loosely coupled (electricity-only integration) and tightly coupled system designs. These systems require the dynamic exchange of large amounts of data, process conditions, energy streams, and control commands to operate efficiently. The integrated energy system simulation framework is designed to support both steady state and dynamic system operation, ensuring that energy balances are maintained under all conditions. Subsystems are defined with sufficient fidelity to assess technical performance; once a feasible technical solution is defined, economic performance optimization can be applied within defined operational and technical performance constraints. Five key components make up the simulation ecosystem, which is continuously being enhanced to ensure that it can support an evaluation of system options (e.g., multiple reactor concepts, process options, energy markets):

1. Renewable energy profiles and energy demand, represented by stochastic time series
2. Probabilistic analysis and optimization algorithms, implemented in the INL-developed Reactor Analysis and Virtual Control Environment (RAVEN) (Cristian Rabiti et al. 2017)
3. Detailed process models for plant design and systems integration at the level of process unit operations (e.g., heat exchangers, pumps, compressors, chemical reactors)
4. Reduced order models representing dynamic physical behavior of subsystems developed from plant design models (e.g., generation technologies, power conversion, energy users), developed in the Modelica language (Modelica Association 2018)
5. Integrated energy system-specific RAVEN plugins for economic performance analysis, Tool for Economic AnaLysis (TEAL, formerly called CashFlow) (C Rabiti et al. 2017), and Heuristic Energy Resource Optimization Network (HERON) (Talbot, Gairola, et al. 2020).

This simulation approach is applied to illuminate the economic potential of using nuclear energy to support various process applications. The framework applies a probabilistic approach in conducting these analyses to allow the model to capture the inherent uncertainties in projecting project costs and revenues. The integrated energy system simulation framework supports simultaneous stochastic modeling of several markets and units, as shown in Figure 1.

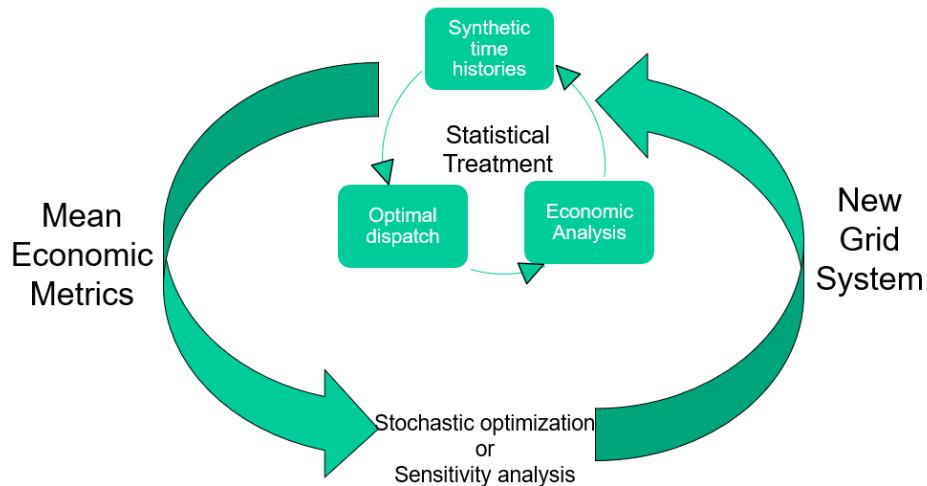


Figure 1. Stochastic technoeconomic analysis workflow

Source: INL. Used with permissions.

RAVEN acts as the workhorse of the integrated energy system framework. Its tasks include:

- Creation of exogenous market conditions (i.e., electricity demand, Variable Renewable Electricity generation) via reconstruction of trends, using:
 - Fourier decomposition
 - Stochastic behavior, using auto regressive moving averages (Talbot, Rabiti, et al. 2020).
- Parallel dispatching of the software representing the physical model on both desktop and high-performance computing machines
- Optimization of the system design and operation
- Uncertainty quantification.

To accomplish this, RAVEN relies heavily on artificial intelligence algorithms to reduce computational cost of performing uncertainty quantification, reliability analysis, and parametric studies. This is achieved by training machine learning algorithms to surrogate models of complex physical systems.

TEAL is a plugin that enables RAVEN to compute several financial indices, including net present value, internal rate of return, and profitability index. TEAL monitors the simulation, performed by RAVEN, and extracts the values of a set of prescribed cost drivers to build the financial indices. Those indices can be used as a goal function for the optimization search. TEAL also includes flexible options to deal with taxes, inflation, and discounting and offers capabilities to compute a combined cash flow for components or subsystems that have different lifetimes.

HERON is a plugin that enables RAVEN to perform stochastic technoeconomic analyses of grid-energy systems in a generic approach. The primary functions of HERON are to generate the complex RAVEN workflows necessary to optimize component capacities under stochastic systems and to perform optimal dispatch of the system resources. HERON can analyze systems with complex components transferring a variety of commodities, including production components and varied markets.

High-fidelity dynamic process models are created in the Modelica language. The Modelica language is a nonproprietary, object-oriented, equation-based language that supports the modeling of complex, physical systems; thus, it has been widely adopted across industry for commercial application. Modelica is an inherently time-dependent modeling language that allows for the rapid interconnection of independently developed models, thus supporting system interconnectivity and the development of novel control strategies, while still encompassing overall system physics. Models are used to evaluate system design options, characterize system inertia, calculate thermal losses, and determine efficiency of integrated systems. Current models in the INL library include thermal energy storage, electrical energy storage, reverse osmosis, four-loop nuclear power plants, integral pressurized water reactors (PWR) (based on the IRIS reactor), natural gas turbines, high-temperature steam electrolysis (HTSE), and switchyards. Additional dynamic models are developed as needed to support the growing suite of case studies.

Analysis of a proposed integrated energy system configuration is initiated by selecting a deployment location and technologies to be included in the study. An analysis might consider the use of existing plants (e.g., a current fleet nuclear plant with an established capacity) or may consider a greenfield build of all subsystems. The intended deployment location establishes the electricity and product markets, demand structures, and so on. RAVEN then takes the regional market data, creates an Auto Regressive Moving Averages and Fourier representation of the data, and then samples it to create synthetic time histories of the original data that preserves the underlying trend; it is statistically identical but represents different potential transient scenarios. Time-dependent electricity demand and/or prices, solar and/or wind generation data, market requirements, and other input data necessary to drive the optimization is fed into the dispatch plugin HERON. HERON uses this information to create a dispatch schedule for all the plants based upon a user defined goal function (e.g., marginal cost, maximum net present value, reliability in covering total demand). These dispatch scenarios are then used as input to the physical Modelica models to drive the simulation. Any missed demand that results from technical constraints, such as ramp rates and physical limitations for the various subsystems, is reported, leading to a change in the dispatch strategy or application of a penalty function in the analysis. The net present value is then computed using the CashFlow plugin based on demand that is met, missed demand, and ancillary product sales. This process is repeated until an optimal solution is found.

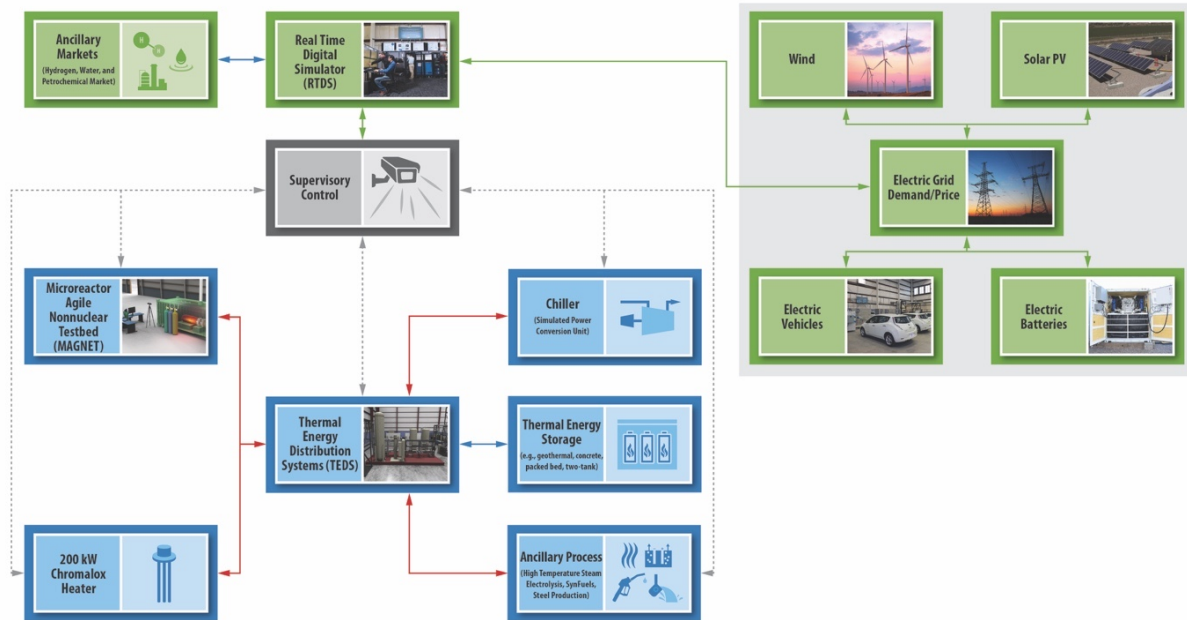
This framework has been a key tool in successfully simulating regional energy networks to provide economically optimized solutions for nuclear utilities. Results of specific case studies have led to utility plans to demonstrate integrated energy systems at existing nuclear plants in the United States, specifically hydrogen production, as reported later in this chapter.

1.2 Experimental Toolset

The laboratory research team is developing experimental systems for concept demonstrations to support the validation and verification of the physical modeling results and conclusions. The

This document encompasses one section of a larger report, titled [Flexible Nuclear Energy for Clean Energy Systems](https://www.nrel.gov/docs/fy20osti/77088.pdf). The full report can be found at <https://www.nrel.gov/docs/fy20osti/77088.pdf>. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.

demonstration will first utilize a scaled, electrically-heated integrated test facility at INL, followed by a demonstration within nuclear systems. The Dynamic Energy Transport and Integration Laboratory is currently being installed within the INL Energy Systems Laboratory to demonstrate an integrated system operation in a lab setting. The Dynamic Energy Transport and Integration Laboratory will utilize controllable electric heaters to demonstrate simultaneous, coordinated, and efficient transient distribution of electricity and heat for power generation, energy storage, and industrial end uses (Frick et al. 2019). The overall facility will provide a demonstration of real-time integration with the electrical grid, renewable energy inputs, thermal and electrical energy storage, and energy delivery to an end user, as shown in Figure 2. As such, an integrated energy network can be emulated with hardware-in-the-loop to improve our understanding of how to optimize energy flows while maintaining system stability and efficient operation of all assets in the system. Further, such a system will provide insight into the performance of new control algorithms, human factor needs, and cybersecurity requirements that will be present in integrated energy systems.



(a)



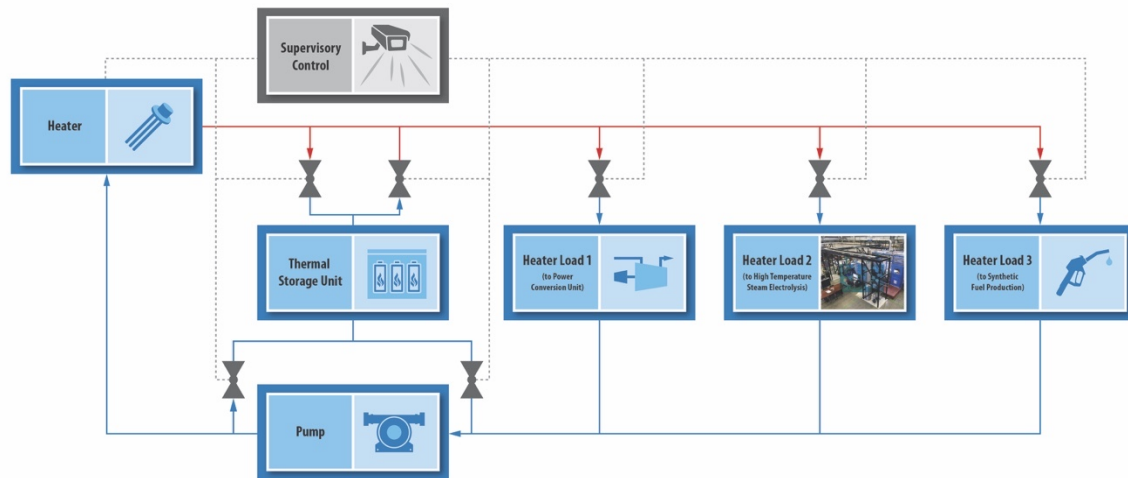
(b)

Figure 2. System configuration of the INL Dynamic Energy Transport and Integration Laboratory:
(a) Overall planned configuration of all components; and (b) Rendering of key laboratory facilities.
The Thermal Energy Distribution System (TEDS) and MAGNET facilities are currently under construction.

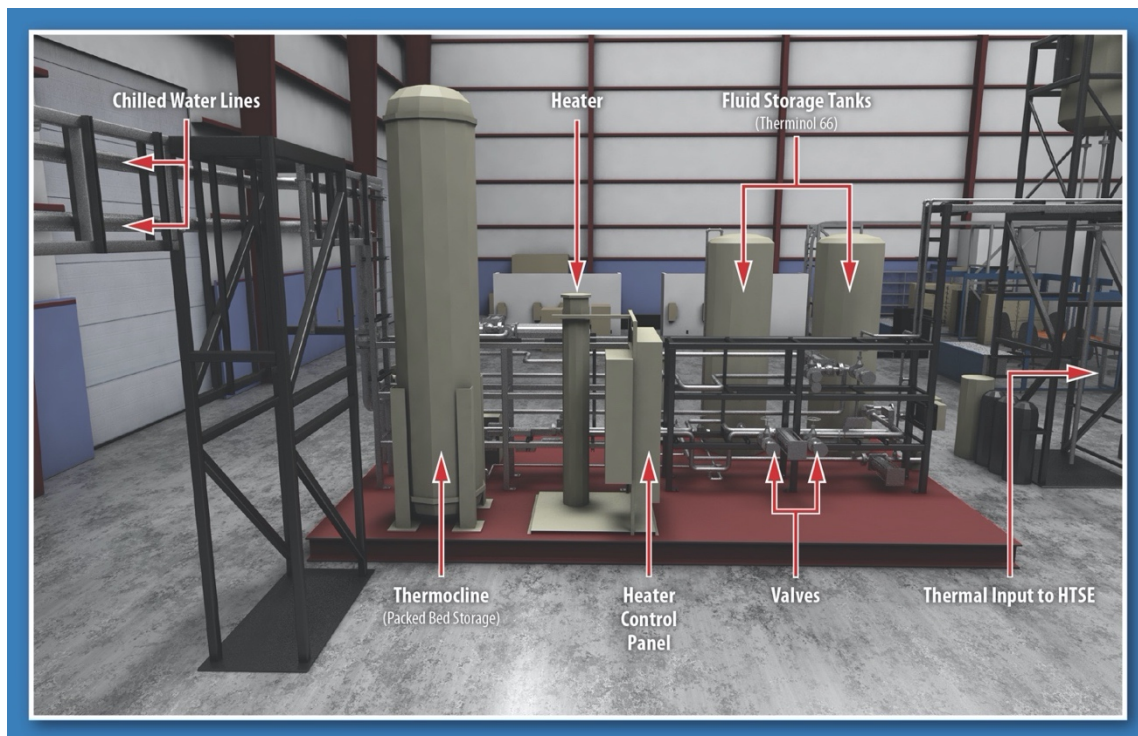
Source: INL. Used with permissions.

This document encompasses one section of a larger report, titled Flexible Nuclear Energy for Clean Energy Systems. The full report can be found at <https://www.nrel.gov/docs/fy20osti/77088.pdf>. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.

Serving as the backbone of the installation is the TEDS (Stoos et al. 2019), shown in Figure 3. This system is designed to be a “plug-and-play” network of valves, pipes, and heat exchangers that allows the mass movement of thermal energy between connected subsystems. TEDS is currently designed to utilize the commercially available heat transfer fluid Therminol-66. Therminol-66 operating conditions range from -3°C to 343°C , while vapor pressure remains low across the operating band. With this large operational band, different systems can be attached to the TEDS without the need to swap to a different fluid. The system is designed to support the emulation of energy input from nuclear or coal generators, which typically have outlet temperatures on the order of 300°C from the main system steam generators.



(a)



(b)

Figure 3. Simplified system configuration for the INL TEDS, showing: (a) Flow paths; and (b) Rendering of hardware components. TEDS hardware is currently being installed and will be operational in 2020.

Source: INL. Used with permissions.

The initial ancillary product end user is HTSE hydrogen production facility. The current facility is a 25-kWe HTSE system (O'Brien et al. 2020), but this will be replaced by a larger scale system (~150-kWe) in the near future. This coupling will enable system control to be verified, while simultaneously allowing for system dynamics and characteristic times scales of heat up and cool down to be quantified. Additional heat loads to be tested in the initial phase of TEDS operation include a single-tank packed bed thermocline and a simulated Rankine cycle power conversion unit.

The broader Dynamic Energy Transport and Integration Laboratory includes several microgrid components, such as the digital real-time simulator stations that represent power systems in the grid and facilitate real-time connections to other geographically diverse facilities, wind energy input, solar photovoltaic (PV) input, chemical flow batteries, and electric vehicle and battery charging. The digital real-time simulator enables a connection to outside wind farms, such as the National Wind Technology Center at NREL, that uses real-time wind data to offset demand curves. Virtual connection with existing test facilities that emulate the dynamics of a nuclear reactor primary, such as the NuScale Integral System Test facility at Oregon State University, is also being assessed. Additionally, there exists hardware-in-the-loop that provides realistic time delays and thermal time constants that the system must adhere to. Several additional flanges were added to TEDS to support interconnection with additional thermal energy providers and end users to increase the functionality of TEDS as a plug-and-play type of system. Electrically heated nuclear reactor emulation systems and thermal energy distribution infrastructure are expected to be installed in 2020.

1.3 Case Studies and LWR Demonstration Projects

Leveraging the vast knowledge base and simulation toolsets available from the DOE-NE Integrated Energy Systems and LWR Sustainability programs (INL n.d.), INL has been a lead partner on several cost-shared projects with nuclear utilities to evaluate the potential for nonelectric application of existing nuclear plants in the U.S. Utility partners include Arizona Public Service (APS), Exelon, Energy Harbor, and Xcel Energy. Each of the utility partners are considering implementing flexible operations at their currently-operating nuclear stations, specifically via product flexibility, to provide an alternative revenue stream for their plants (Wald 2019). In general, these utilities are exploring a phased approach to flexible operations, initially using in-front-of-the-meter electrical integration to support additional processes (e.g., water purification and hydrogen production), with the goal of eventually incorporating higher-efficiency processes through a combination of thermal and electrical integration if the economic case is strong. A summary of these activities is available in Table 1.

Table 1. U.S. LWR (Current Fleet) IES Case Study Synopsis

Utility	Product Stream	Technology	Market	Volatility Driver	Coupling
APS	Water	Reverse osmosis	Regulated	Solar and water scarcity	Electrical and physical water lines
Energy Harbor/Xcel/Arizona Public Service	Hydrogen	Low-temperature electrolysis	Regulated (Energy Harbor), Deregulated (APS, Xcel)	Wind and natural gas	Electrical
Exelon	Hydrogen	HTSE	Deregulated	Wind and natural gas	Electrical and thermal
Exelon	Hydrogen	Low-temperature electrolysis	Deregulated	Wind and natural gas	Electrical

As seen in Table 1, an emphasis has been placed on hydrogen production as an option for nuclear plant flexibility in these initial U.S. case studies. Hydrogen, as a basic feedstock for several large energy markets, could provide an additional source of revenue to enhance the value of existing nuclear plants and to further enhance their ability to respond to varying demand. To this end, utilities are implementing demonstration projects for both low temperature and high temperature electrolysis technologies. Low-temperature electrolysis takes water molecules as an input and applies a current across an electrolytic cell to split the water molecules into pure oxygen and hydrogen. HTSE follows a similar process but operates at much higher temperatures (650°C-800°C), thus achieving higher efficiencies. Both processes are currently under consideration for demonstration and pilot application within the nuclear industry. Low-temperature electrolysis is easier to configure with a nuclear power plant since it only requires electrical energy, while HTSE has the potential to produce hydrogen at a price that is more economically competitive. A detailed synopsis of the energy requirements for both is available in Table 2.

Table 2. Breakdown of Hydrogen Production Technology Energy Requirements

Hydrogen Production Technology	Electrical vs. Thermal Requirements	Electric Ramp Rate Limit	Steam ¹ Ramp Limit	Fixed demand needed for hot standby mode ²
Low-Temperature Electrolysis	100% electrical, 0% thermal	100% can be ramped instantaneously	N/A	0% assuming PEM electrolysis
HTSE	85%–95% electrical, 5%–15% thermal	80-90% can be ramped instantaneously, remainder is used as topping heat	Fixed steam flow in current designs	10%–20% electrical energy as topping heat; all thermal energy used for feedstock preheating

In addition to hydrogen production technologies, water treatment via reverse osmosis is also considered for utilities with limited regional water supply. An in-depth look at each of the four case studies is presented below.

1.3.1 APS

APS is the operating owner of the Palo Verde Generating Station in the arid southwest region of the United States that has recently seen a boom in solar installations. Palo Verde Generating Station, the largest nuclear plant in the United States, is home to three PWRs. Palo Verde Generating Station uses mechanical draft evaporative cooling towers that provide for steam cycle waste heat rejection. The Palo Verde Generating Station cooling water is provided via a contract with local municipalities to utilize reclaimed municipal wastewater. In the U.S. Southwest, water resources are limited, and the effluent is becoming increasingly more valuable to these municipalities as scarcity of the natural water resources increases concurrent with population growth in the area. As a result, there is a steep escalation in the annual cost of effluent. This results in increased plant cooling costs, leading APS to seek alternative sources of water to use for facility cooling needs.

APS has been researching this issue in cooperation with researchers at INL to evaluate the potential for using a portion of the electricity from Palo Verde Generating Station to desalinate brackish groundwater using reverse osmosis. Addition of reverse osmosis could help the plant to manage the increasing penetration of solar PV in the region while simultaneously reducing the cost of cooling water. Reverse osmosis requires only electrical integration and can be cycled on and off

¹ Flexibility in steam delivery depends on the operating power level and turbine design. Variation of steam flow to electric and nonelectric applications may be limited to less than 3% per hour at some PWR plants if the reactor is between 90% and 100% of its thermal power rating. Limitations to the rate of change in steam flow between the turbine and some ancillary process, such as HTSE, while maintaining constant reactor thermal power, needs to be investigated for the specific plant and turbine set and thus is not reported here. Maximum diversion of steam from the turbine to coupled processes without shutting down portions of the plant secondary depends on the plant and component designs.

² Hot standby is when the process is producing zero product but is capable of going to 100% product production almost instantaneously.

at will as electricity prices fluctuate. This desalinated water, devoid of harsh minerals that would foul heat exchangers, can then be used to cool the plant, with excess fresh water potentially being sold to the public. By desalinating groundwater, APS can potentially reduce the amount of reclaimed wastewater that must be purchased from local municipalities.

Utilizing the RAVEN/HERON/Modelica toolset, a regional water market was constructed for the Phoenix west valley alongside reverse osmosis and Palo Verde water train process models. Several analyses have been carried out using these tools. The conclusions were unexpected, highlighting the possibility of using discharged brine from a large reverse osmosis plant to be diluted into the cooling water and subsequently disposed using Palo Verde Generating Station evaporation ponds. This would lead to a decreased cost to generate potable water due to the decreased waste management cost at the reverse osmosis. Moreover, the analysis also showed possible benefits to Palo Verde Generating Station due to reduction in the costs of water procurement.

The technoeconomic analysis framework developed at INL allowed identification of this business opportunity with a possible differential net present value of ~\$100 million if all municipalities in the vicinity participated (Epiney et al. 2019).

1.3.2 Energy Harbor/APS/Xcel

The principle objective of the project awarded to the tri-utility consortium of Energy Harbor, APS, and Xcel Energy is to carry out the planning, design, installation, testing, demonstration, and evaluation of integrated energy technologies connected to an LWR power plant, with a focus on a scalable hydrogen generation pilot plant. The project will install a low-temperature electrolysis hydrogen generation pilot plant unit at the Davis-Besse Nuclear Power Station in Ohio (Boardman et al. 2019). The financial security of the Davis-Besse plant has recently been challenged by falling natural gas and renewable energy prices. Owing to its geographical location, large transportation network, and proximity to large industrial users in America's heartland, Davis-Besse was selected as the pilot nuclear demonstration facility for low-temperature electrolysis hydrogen production. The project, which is supported by a cost-share award from DOE, aims to install a 2-MWe low-temperature electrolysis unit to produce hydrogen by splitting water molecules into H₂ and O₂. This initial demonstration is expected to operate from January 2021 to January 2023 (Henry 2020). Energy Harbor would utilize the clean hydrogen produced as a secondary revenue stream for the nuclear facility while still supporting the grid at its maximum capacity at times of high electricity demand. Hydrogen, as a base product of many petrochemical industries, would be marketed to the surrounding refineries, fertilizer plants, and other agricultural production facilities. The expected result is to have a fully functional operating hydrogen generation skid that has been integrated into the normal operating routine of a nuclear power plant. In addition, accumulated operating data will highlight the technical feasibility and economic viability of this integrated system.

The project will also include technical and economic assessments for APS and Xcel Energy, which operate nuclear power facilities in different electricity markets in the United States. These assessments will support the technical and financial feasibility of integrated system operations for hydrogen generation. This information, along with pre-front-end engineering design input from the collaborating utilities, will support the development of an investor-grade report summarizing the business case for undertaking similar projects to implement hydrogen generation at other LWR power plants. Results from the system demonstration will ultimately be available to other nuclear

power utilities to support the large-scale commercialization of the integrated energy system technology at the 100s-MWe scale.

If the initial demonstration is successful, Energy Harbor is considering the potential for an increased investment into larger systems that may include a thermal integration component to support high-temperature electrolysis. This initial demonstration will help utilities understand the benefits, challenges, and regulatory and marketplace requirements for the multimarket operation of such systems. A larger-scale hydrogen production system could supply additional clean hydrogen to the various customers mentioned earlier at an even lower cost point.

1.3.3 Exelon

In addition to the regional cases with APS and Energy Harbor, wind resources coupled with transmission network constraints across the U.S. Midwest are causing variable pricing scenarios for nuclear generating stations operated by the Exelon Corporation. As an initial response, several Exelon plants have begun operating with “advanced nuclear dispatch,” varying power output from the plant to avoid the sale of electricity at a loss. This operational mode is limited by U.S. Nuclear Regulatory Commission regulations and turbine ramp limits. Exelon is also considering extending their flexibility via alternative products. Hydrogen production, using excess energy from Exelon plants, could support the needs of the petrochemical, steel manufacturing, and agricultural industries throughout the Midwest.

A cost-share project led by Exelon Corporation in collaboration with DOE national laboratories will demonstrate an end-to-end integrated grid-scale carbon-free H₂ production, storage, and utilization pilot plant at an Exelon-owned nuclear generating facility, providing the necessary data to further reduce the technical and financial risk associated with commercial integrated energy system deployment. Via a partnership between INL, NREL, Argonne National Laboratory, Exelon, and Fuel Cell Energy, this project was initiated by a technoeconomic analysis of the viability of retrofitting existing PWRs to produce hydrogen (H₂) via HTSE. These analyses indicate that such integration would allow nuclear facilities to support the growing hydrogen market. The use of excess or low-price electricity for hydrogen production essentially provides an economic floor to the sale of electricity by the nuclear facility, leading to a paradigm shift in the interaction between the nuclear plant and the electricity market. The nuclear plant would sell electricity to the market only when prices are sufficiently high to compensate for revenue that would be lost by halting hydrogen production. In this, many nuclear plants could effectively operate in the electricity market as a peaking plant.

To accommodate such an integration, a detailed analysis of the HTSE process operation, requirements, and flexibility was conducted. The technical analysis includes proposed nuclear system control scheme modifications to allow for the dynamic operation of the HTSE via both thermal and electrical connection to the nuclear plant. High-fidelity Modelica simulations showcase the viability of such control schemes.

From the detailed analysis of the nuclear integration and the HTSE process design, a comprehensive cost estimation was conducted in the commercially accepted Aspen Process Economic Analysis and the Hydrogen Analysis Production models to elucidate capital and operational costs associated with the production, compression, and distribution of hydrogen from a nuclear facility. Alongside this costing analysis, market analyses were conducted by NREL and

ANL on the electric and hydrogen markets, respectively, in the PJM interconnect (i.e., the Pennsylvania, Jersey, Maryland Power Pool), the regional transmission organization in which the Exelon nuclear plants operate.

Utilizing the electricity data market projections in the PJM interconnect from NREL and hydrogen demand/pricing projections from ANL, a five-variable sweep over component capacities, discount rates, and hydrogen pricing was completed using RAVEN and its resource dispatch plugin HERON. Each combination of variables was evaluated over a 17-year timespan, from 2026 to 2042 (inclusive), to determine the most economically advantageous solution.

Results suggest that positive gain is achievable at all projected hydrogen market pricing levels and at all discount rates. However, exact component sizing and net returns vary based on these values, and, if incorrect sizing is selected, major net losses could occur. Overall, the results of the Exelon study advocate that, through market diversification, existing nuclear plants have the potential to substantially increase current profit margins, increase market penetration, and ultimately solidify their place as a mainstay in energy production in the U.S. Midwest. The complete results of the study are available in the report by Frick et al. (Frick, Talbot, et al. 2019).

Exelon is now moving forward to demonstrate hydrogen production, first using an electrically integrated low-temperature electrolysis, at an Exelon-owned and operated plant via a follow-on cost-share project with the DOE. This project will install a 1-MW low-temperature electrolysis unit at an Exelon plant (specific plant to be announced) and will evaluate market opportunities and regulatory requirements related to the participation of integrated hydrogen production and nuclear plant facilities in organized power markets. This will be accomplished by demonstrating dynamic control and operation of the electrolyzer and assessing the economics of dynamic participation combined with the revenue streams from hydrogen production. The main objective of this project is to demonstrate that hydrogen can be economically produced at large scale using nuclear energy. This demonstration will also verify the proposed operating scheme by testing the response characteristics of a commercially scalable hydrogen electrolysis unit and the ability to support grid regulation while producing hydrogen for local users. This demonstration will pave the way to potential future demonstration of large-scale, thermally integrated HTSE.

1.4 Future Work: Advanced Reactor Applications

The LWR industry community was instrumental in defining the initial pilot case studies focused on the use of excess energy from currently operating LWRs to support the production of nonelectric commodities, specifically focusing on water desalination and hydrogen production, and near-term, high-value opportunities. As the LWR studies move to demonstration for hydrogen production at Exelon and Energy Harbor plants, DOE and national laboratories will continue to support that work to ensure success. In addition, the DOE-NE Integrated Energy System program is moving forward to assess the potential for integrated energy systems that utilize advanced reactor technologies to support a wide range of industrial and chemical manufacturing processes.

1.5 References

- Boardman, Richard D, Cristian Rabiti, Stephen G Hancock, Daniel S Wendt, Konor L Frick, Shannon M Bragg-Sitton, Hongqiang Hu, et al. 2019. “Evaluation of Non-Electric Market Options for a Light-Water Reactor in the Midwest.” INL/EXT-19-55090-Rev000, 1559965. Idaho Falls, ID: Idaho National Laboratory. <https://doi.org/10.2172/1559965>.
- Bragg-Sitton, Shannon M, James O’Brien, Richard Boardman, and Cristian Rabiti. 2020. “Reimagining Future Energy Systems: Overview of the US Program to Maximize Energy Utilization via Integrated Nuclear-renewable Energy Systems.” *Int J Energy Res*, February, 1–14. <https://doi.org/10.1002/er.5207>.
- Epiney, Aaron S., James D. Richards, Jason K. Hansen, Paul W. Talbot, Pralhad Hanumant Burli, Cristian Rabiti, and Shannon M. Bragg-Sitton. 2019. “Case Study: Integrate Nuclear Water Desalination—Regional Potable Water in Arizona.” INL/EXT-20-55736-Rev001. Idaho Falls, ID: Idaho National Laboratory. <https://doi.org/10.2172/1597896>.
- Frick, Konor, Alexander Duenas, Piyush Sabharwall, JunSoo Yoo, Su-Jong Yoon, James E O’Brien, and Thomas E O’Brien. 2019. “Thermal Energy Delivery System Operational Characteristics and Control Strategies.” In *Proceedings of the 11th Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC & HMIT)*, 12. Orlando, FL. <https://www.osti.gov/biblio/1498251/>.
- Henry, T. 2020. “Davis-Besse Chosen as Pilot Site for Hydrogen Production Research.” Toledo Blade. January 14, 2020. <https://www.toledoblade.com/business/energy/2020/01/14/davis-besse-chosen-as-pilot-site-hydrogen-production-research/stories/20200114139>.
- INL. n.d. “Home.” Light Water Reactor Sustainability Program. Accessed June 21, 2020. <https://lwrs.inl.gov/SitePages/Home.aspx>.
- Modelica Association. 2018. “Modelica Standard Library.” May 22, 2018. <https://github.com/modelica/ModelicaStandardLibrary>.
- O’Brien, J. E., J. L. Hartvigsen, R. D. Boardman, J. J. Hartvigsen, D. Larsen, and S. Elangovan. 2020. “A 25 KW High Temperature Electrolysis Facility for Flexible Hydrogen Production and System Integration Studies.” *Int J Hydrog Energy* 45 (32): 15796–804. <https://doi.org/10.1016/j.ijhydene.2020.04.074>.
- Rabiti, C, A Epiney, P. Talbot, J.S. Kim, S. Bragg-Sitton, and A. Alfonsi. 2017. “Status Report on Modelling and Simulation Capabilities for Nuclear-Renewable Hybrid Energy Systems.” Technical Report INL/EXT-17-43441. Idaho Falls, ID: Idaho National Laboratory. <https://www.osti.gov/biblio/1408526/>.
- Rabiti, Cristian, Andrea Alfonsi, Joshua Cogliati, Diego Mandelli, Robert Knoshita, and Sen Sonat. 2017. “RAVEN User Manual.” Technical Report INL/EXT-15-34123 (Revision 3). Idaho Falls, ID: Idaho National Laboratory. <https://www.osti.gov/biblio/1235208>.
- Stoots, C., A. Duenas, P. Sabharwall, J. O’Brien, J.S. Yoo, J.E. O’Brien, T. O’Brien, and T. O’Brien. 2019. “Thermal Energy Delivery System Design Basis Report.” INL/EXT-18-51351 (Revision 00). Idaho Falls, ID: Idaho National Laboratory.
- Talbot, Paul W., Abhinav Gairola, Prerna Prateek, Andrea Alfonsi, Cristian Rabiti, and Richard D. Boardman. 2020. “HERON as a Tool for LWR Market Interaction in a Deregulated Market.” Technical Report INL/EXT-19-56933-Rev000. Idaho Falls, ID: Idaho National Laboratory. <https://doi.org/10.2172/1581179>.
- Talbot, Paul W., Cristian Rabiti, Andrea Alfonsi, Cameron Krome, M. Ross Kunz, Aaron Epiney, Congjian Wang, and Diego Mandelli. 2020. “Correlated Synthetic Time Series

- Generation for Energy System Simulations Using Fourier and ARMA Signal Processing.” In *Proceedings of the 6th International Conference on Nuclear and Renewable Energy Resources (NURER2018)*. Jeju, Korea: Int J Energy Res: Special Issue. <https://doi.org/10.1002/er.5115>.
- Wald, Matt. 2019. “Inventive Nuclear Plants Think Beyond Electricity to Hydrogen.” *Nuclear Energy Institute* (blog). November 14, 2019. <https://www.nei.org/news/2019/nuclear-plants-beyond-electricity-hydrogen>.