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Light Water Reactor Sustainability Program

FPOG Technical Program Plan for FY 2023

September 2022

U.S. Department of Energy
Office of Nuclear Energy

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ABSTRACT

This report presents the Technical Program Plan for Fiscal Years (FY) 2023–2027 for the U.S. Department of Energy (DOE) Light Water Reactor Sustainability Program—Flexible Plant Operation and Generation (FPOG) Research Pathway. The objective of this Pathway is to carry out the research needed to help nuclear power plants achieve positive revenue generation for the life of these plants. Research activities include 1) technical and economic assessments of realistic market opportunities for producing secondary energy products near nuclear power plants, 2) developing and demonstrating engineering systems and control concepts to dispatch thermal and electrical power to an industrial user, 3) developing guidance on relevant safety and environmental operating license reviews, amendments, and renewals. The purpose and activities of a Hydrogen Regulatory Research and Review Group is discussed. An overview is also provided on the potential benefits of the Infrastructure Investment and Jobs Act Bill that will support the commencement of Regional Clean Hydrogen Hubs, and the Inflation Reduction Act that provides compelling production tax credits for nuclear electricity and clean hydrogen using nuclear energy.

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ACRONYMS

A&E	Architecture and Engineering
AC	alternating current/direct current
ANL	Argonne National Laboratory
APS	Arizona Public Service
ATC	around-the-clock
BIL	Bipartisan Infrastructure Law
BWR	Boiling Water Reactor
CDF	core damage frequency
CFR	codes of federal regulations
CI	carbon intensity
CRADA	Cooperative Research and Development Agreements
DBA	design basis accidents
DOE	Department of Energy
DOE-NE	DOE-Office of Nuclear Energy
DSL	delivery steam line
EPA	Environmental Protection Agency
EPC	engineering and plant construction
EPRI	Electric Power Research Institute
ETS	energy transfer system
FEED	Front-End Engineering and Design
FERC	Federal Energy Regulatory Commission
FOA	funding opportunities announcements
FOAK	first-of-a-kind
FORCE	Framework for Optimization of ResourCes and Economics
FPO	Flexible Plant Operations
FPOG	Flexible Plant Operation and Generation Pathway
FT	Fischer-Tropsch
FY	fiscal year
GHG	greenhouse gas
GPWR	generic pressurized water reactor
GREET	greenhouse gases, regulated emissions, and energy use in transportation
GW	guided wave
H3RG	Hydrogen Regulatory Research and Review Group
HERON	Holistic Energy Resources Options Network
HFTO	Hydrogen and Fuel Cell Technologies Office
HIL	hardware-in-the-loop
HMI	human-machine interfaces
HSI	human-system interface
HSSL	Human Systems Simulation Laboratory

HTE	high-temperature steam electrolysis
HTSE	high-temperature electrolysis (HTSE)
HYSYS	Hyprotech Systems (processing modeling software)
I&C	instrumentation and control
IES	integrated energy system
INL	Idaho National Laboratory
IRR	internal rate of return
ISO	independent system operator
LAR	license amendment review
LCA	life-cycle analysis
LCFS	low-carbon fuel standard
LCOH	levelized cost of heat
LCRI	Low-Carbon Research Initiative
LERF	large early release frequency
LMP	locational marginal price
LTE	low-temperature electrolysis
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
MCR	main control room
MRS	moisture separator reheater
MWh	mega-watt hours
NBE	Nuclear Beyond Electricity
NEET	Nuclear Energy Enabling Technologies
NERC	North American Electric Reliability Corporation
NG	natural gas
NPP	nuclear power plant
NPV	net present value
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
P&ID	process and instrumentation design
PEM	polymer-electrolyte membrane
PJM	A regional transmission organization in the eastern United States
PM	preventative maintenance
PNNL	Pacific Northwest National Laboratory
PRA	Probabilistic Risk Assessment
PV	photovoltaic
PWR	pressurized water reactor
R&D	research and development
RAVEN	Risk Analysis Virtual Environment
ReED	Regional Energy Development Environment
REGEN	Regional Economy, Greenhouse Gas Energy (Model)

RELAP	Reactor Excursion and Leak Analysis Program
RTDS	real-time grid simulation
SCRAM	safety control rod axe man (or similar, meaning emergency shutdown)
SMR	steam-methane reforming
SOEC	Solid oxide electrolysis cell
TEA	Techno-economic Assessment
TEAL	Tool for Economic Analysis
TPD	thermal power delivery
TPE	thermal power extraction
TRL	technology readiness levels
UFSAR	Updated Final Safety Analysis Report
XSL	extraction steam line
ZEC	zero-emissions credits
ZEV	zero-emissions vehicle

FLEXIBLE PLANT OPERATION AND GENERATION TECHNICAL PROGRAM PLAN FOR FY 2023

1. GOALS AND STRATEGY

The emerging gap between the growth of non-dispatchable renewable energy generation and lagging clean energy storage continues to contribute to the unproductive expansion of time-of-day excess clean generation. The overlapping impact of the dominant clean generating sources (intermittent renewables and baseload nuclear power) exacerbates this challenge during daily supply-and-demand cycles. A contributing factor is that both intermittent renewables and baseload nuclear have inherent flexibility constraints in their operational models. Nuclear power has significant near-term potential to change its longstanding operational model by shifting generation output away from electrical generation when there is no additional grid demand for clean energy. During these times, in lieu of performing flexible plant operations by turning down reactor power, nuclear plants can flexibly produce real-time usable or storable clean energy to decarbonizing functions across the power, industrial, and transportation sectors. Specifically, hydrogen by electrolysis as a flexible energy stream from the existing nuclear fleet has the potential to favorably influence all sectors as a storage medium and energy carrier for excess intermittent carbon-free generation.

The Flexible Plant Operation and Generation (FPOG) Pathway conducts research and development (R&D) to address nuclear power plant (NPP) economic viability in current and future energy markets through market economic analysis, systems engineering and process development, development of new operating procedures, and testing and demonstration. This work is based on two strategic goals that are consistent with the Light Water Reactor Sustainability (LWRS) Program [1]:

1. Conduct research needed to inform decisions, demonstrate technical solutions, and provide methods needed for the long-term management and continued operation of NPP systems within a new utilization paradigm that would ensure their profitability.
2. Engage key stakeholders to effectively implement FPOG in a manner consistent with utility, state, and national energy security; economic strength; and environmental sustainability aspirations in the 21st century.

FPOG is an approach to using the full capacity of any given nuclear reactor while producing electricity that is transmitted to the electricity grid or by directing the thermal power and/or electricity produced by the NPP to an industrial customer either full time or variably as electricity is dispatched to the grid as shown in . This has two highly important effects:

- Maintains full utilization of the asset (nuclear plant) and thereby continues the highest possible level of return on the capital investment.
- Avoids most of the operational and plant support issues with flexible plant operations (FPO), which mainly involve the reactor side.

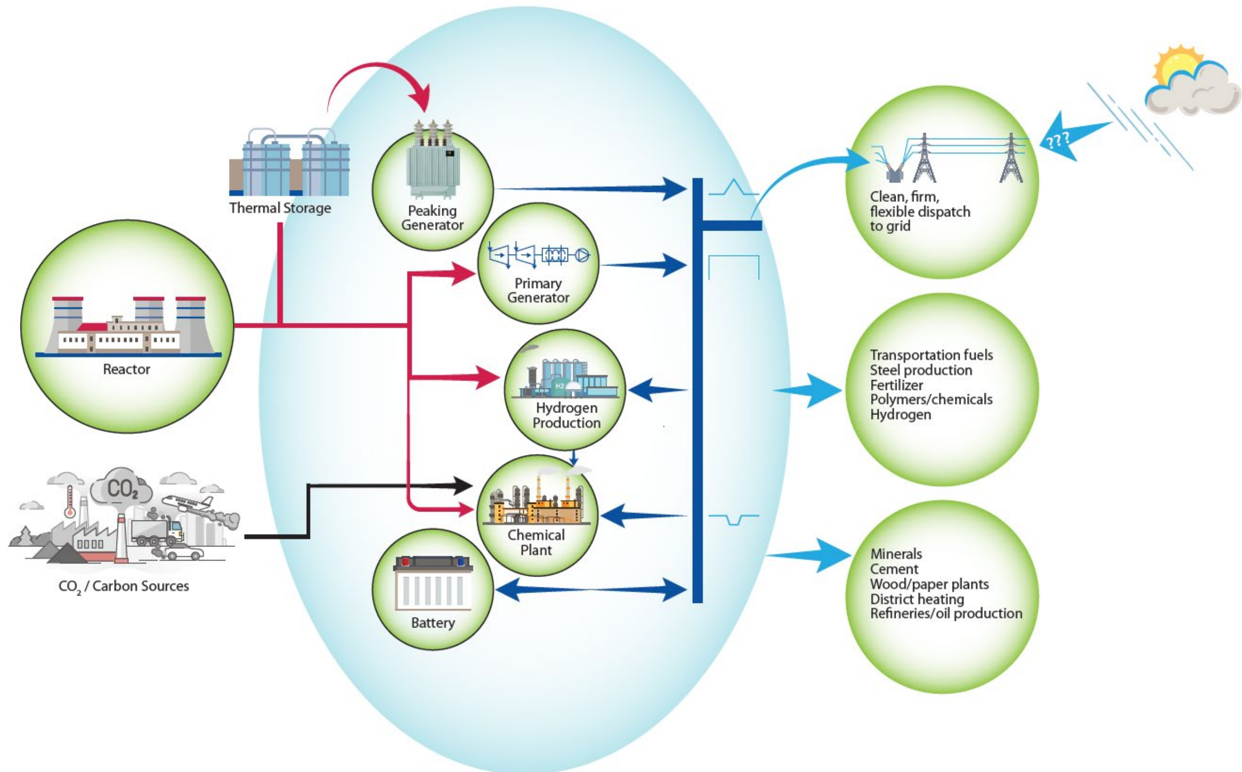

Figure 1. Flexible plant operation and generation paradigm for nuclear power plants.

Load-following, whether by price signals or Independent System Operator (ISO) order, is currently driving many nuclear plants to non-optimum asset investment recovery and certainly lower revenue in two ways: (1) the obvious loss of MWh sales and (2) operating at a less-efficient power level. It also entails additional operation and maintenance expenses on the reactor side as they constantly adjust reactor power levels (by borating and then diluting the coolant in the case of a pressurized water reactor) as well as supporting engineering costs to constantly refigure the core life based on power maneuvers.

A deeper description of FPOG drivers and options is given in Appendix A. Flexible Plant Operation and Generation. The balance of this plan focuses on the progress made, and the specific research activities that will be executed over the next 5 years (fiscal year [FY] 2023–2027).

2. FPOG R&D APPROACH

The first test of FPOG as a new paradigm for NPPs is proving the technical feasibility and business case through techno-economic assessments (TEAs) of options. With the value of FPOG being established in FY 2019 through FY 2022 for hydrogen production, energy arbitrage, and production of other secondary products, the Pathway began designing and evaluating thermal-hydraulic and controls systems connections to dynamically apportion and deliver thermal and electrical power to one or more customers. The purpose of these R&D activities is two-fold: (1) to reduce the technical, economic, and safety risks of implementing FPOG applications and (2) to provide guidance on relevant safety and environmental operating license reviews, amendments, and renewals. In FY 2022, the additional impetus for flexible operations was garnered from the evaluation of energy storage and electricity arbitrage as well as the assessment of hydrogen offtake markets such as steel manufacturing, petroleum refining, fertilizer plants, and low-emissions transportation fuels produced with clean H_2 and CO_2.

The FPOG R&D plan needs are organized into four activities with the following goals:

Design and Economics: The purpose of this activity is to complete TEAs to evaluate market opportunities for light water reactors (LWR) that will supply electricity and steam or heat to produce non-electricity products. The goal is to produce investor-grade reports that will help introduce LWR owners to industries that can exploit the clean, affordable energy supplied by nuclear plants. It also considers large energy storage systems that can help LWRs shift electricity production to periods when demand exceeds the net generation capacity of baseload nuclear, renewable wind, solar, and hydrogen power and non-spinning-reserve capacity. Accordingly, this activity addresses trends in the industry and transportation markets relative to opportunities for LWRs to provide electricity and thermal energy to reduce manufacturing costs and pollutant emissions. It specifically considers energy markets that are growing and those that are trending to reduce pollutant emissions, especially GHG pollutants. Additionally, because FPOG allows nuclear plants to maximize revenue by dispatching electricity to the grid during periods of peak demand, this activity applies analytic tools and systems simulation models to evaluate the technical feasibility of dynamically dispatching electricity to the grid by ramping up and ramping down closely coupled process industries. These analyses need to be performed for both regulated and non-regulated markets to achieve the benefits of applications on a region-specific basis.

Thermal/Electrical Energy Dispatch: The purpose of this activity is to address operational challenges associated with FPOG, including hardware implementation and control systems R&D as well as a reactor operator and other human factors that are needed to dynamically extract and deliver thermal energy from an NPP for use by an industrial process. This research is needed to ensure thermal energy extraction can be performed smoothly and efficiently without impacting anticipated operating conditions. It reduces the technical and safety risks that could impact scaling hydrogen production and the buildout of other industries looking to tap into thermal energy produced by nuclear reactors. The methods and relative percentage of thermal energy removal will differ, depending on the design of the NPP's generation configuration and the thermal energy needs of a closely coupled system and user. This research will enable LWR owners, system integrators, and technology vendors to understand and implement appropriate control interfaces that ensure reactor operators and other users that operations will be responsive to plant conditions and interactions, which will be more complex than standard power generation. This activity particularly focuses on hardware interactions, such as mass flow and thermal energy balances as mechanical control valves are opened and closed to ensure consistent, optimal operation is maintained while accounting for thermal energy inertia with heat delivery systems and system feedback. It helps address licensing and possible amendments to safety bases necessary to deliver thermal energy to an independent user. Direct coupling to the electrical switchyard of a nuclear plant also requires systems engineering and controls development. Apportioning electricity between the grid and a direct industry customer requires modifications or additions to transformer and load dispatch power equipment and lines.

Safety Assessments: The goal of this effort is to ensure the FPOG systems remain within the operating basis of LWRs or to otherwise inform plant owners on license modifications for relatively large percentages of LWR thermal energy delivery to an industrial user. Research includes completing hazard and safety assessments for probabilistic risk assessment (PRA) evaluation of electricity connections and thermal energy extraction and coupling to chemical plants, commencing with a high-temperature electrolysis hydrogen production facility tied to an LWR. These activities inform the PRA for LWR power plants for use in determining a licensing pathway. One objective is to provide guidance on the separation distance needed to avoid relicensing due to the production of hydrogen and chemicals in proximity to LWR plants. Chemical and hydrogen plant siting, operating conditions, and engineering measures are being evaluated to satisfy the existing Nuclear Regulatory Commission (NRC) operating license based on an updated PRA analysis. Additionally, a thermohydraulic analysis of the heat extraction system used to supply an industrial plant with process heat is being completed.

Stakeholder Engagement: It is imperative to ensure the pathway R&D is relevant to the needs of the LWR community. Meetings with stakeholders are used to present the outcomes of the ongoing research and to obtain recommendations that help set future priorities. Beginning in Fiscal Year 2022, A Hydrogen Research Regulatory Review Group (H3RG) was formed to begin to identify the technical and safety risks that may need to be added to follow the 10 Code of Federal Regulations (CFR) 50.59 requirements [2]. The H3RG consists of a broad group of experienced nuclear utility design and licensing lead personnel, Department of Energy (DOE) laboratory research leads, contracted architect engineering companies, nuclear plant operators, and licensing experts. The H3RG is divided into the committees shown in .

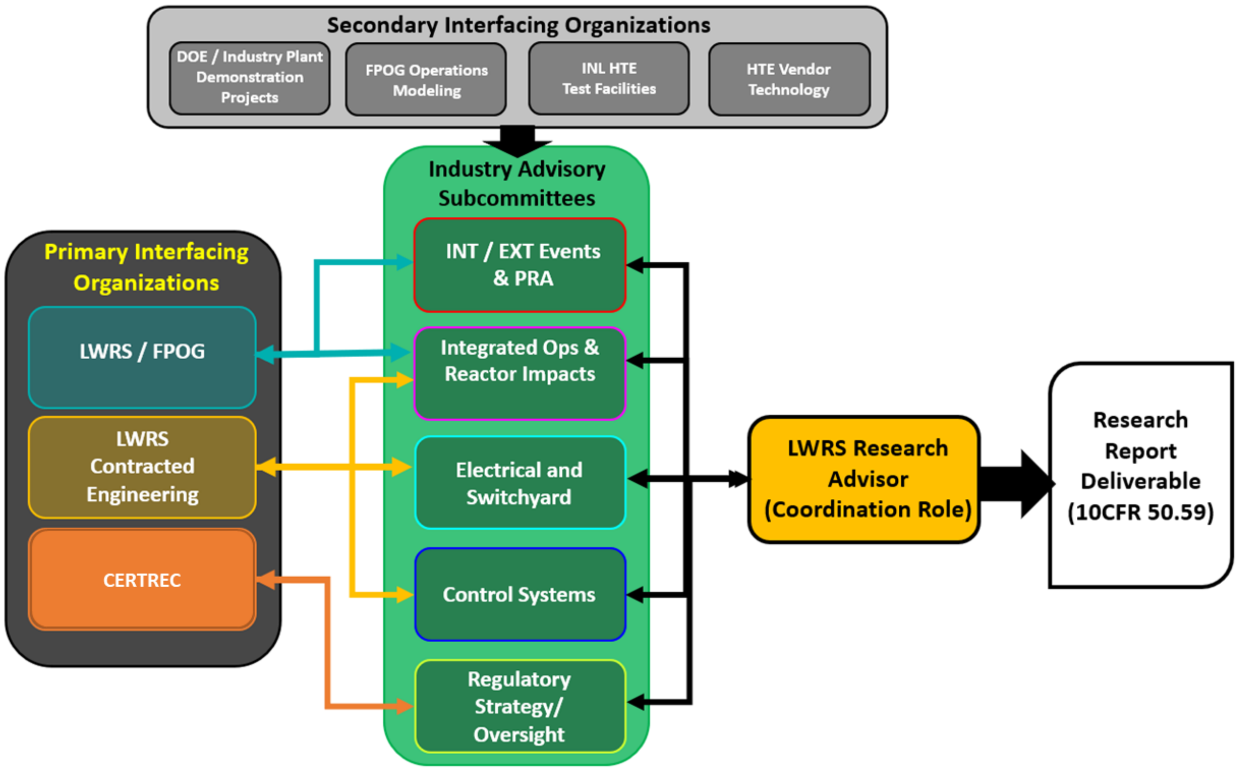

Figure 2. H3RG organizational structure.

2.1 Technical and Economic Assessments

The objective of this work is to show how FPOG can increase the revenue of NPPs and keep them operating by:

- Establishing thermal and electrical power connections to new dispatchable loads, such as hydrogen plants, refineries, chemical plants, or combinations of those assets.
- Dispatching varying amounts of NPP energy to the electricity grid and industrial users. This generally requires energy or product storage. The overall revenue of combined users must pay for the plant modifications and the capital over an acceptable term for the project, and this usually requires a high-capital utilization factor.
- Storing energy to produce power when demand on the grid exceeds the installed generation capacity. We referred to this as energy arbitrage. Arbitrage makes sense in a place like the Southwest where solar energy is projected to dominate the total grid market. Wind energy is having the same consequence in other markets. As the trend to build more solar and wind power continues, base load

plants will be required to throttle their output, if they lack other applications that can utilize power that cannot be sold to the grid.

Evaluating the value proposition for LWR FPOG applications follows a graded approach. The potential for new projects is evaluated using the process illustrated in where a progressive approach is used to identify the ultimate market potential.

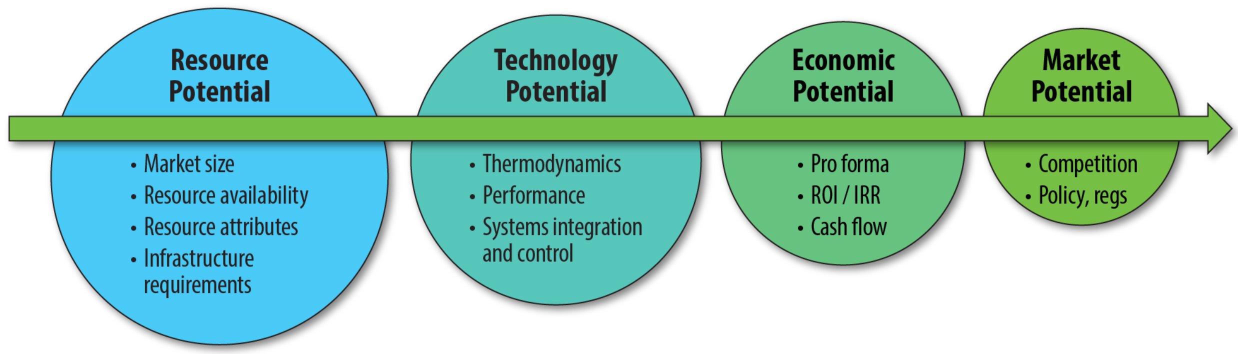

Figure 3. Four tests for developing FPOG non-electrical product markets.

The classical approach to plant design and economics is to complete a Front-End Engineering and Design (FEED) study that determines the capital expenses and operations expenses of the plant and calculates the return on investment that can be realized through a discounted cash investment and revenue analysis. This TEA is generally presented in terms of the return on investment in terms of the Net Present Value (NPV) of the investment with a specified debt and equity rates. The Internal Rate of Return (IRR) that leads to a NPV of zero at a set period (e.g., 20 years from the start of operation) is another measure used by investors when deciding the value of an investment. An IRR of at least 10% is typically the threshold required by capital investors, while returns of 20% and higher are often expected when a project is first-of-a-kind and considered at moderate to high risk of meeting production targets and market pricing. If a capital investment is being made by an existing energy company or utility, corporate strategy, company financial holdings, and tax considerations are other factors that are taken into consideration. The fraction of debt financing as a second source of capital is also critical since debt can generally be secured at lower interest rates based on public bonds and loan guarantees that are typically available to public utilities and public-private cost-shared projects.

An example of the estimated levelized cost of hydrogen (LCOH) for a high-temperature electrolysis plant that is coupled directly to a generic 1-GWe NPP is plotted in as a function of the price of electricity and other variables that determine the capital expenses and operations expenses of the hydrogen plant. The cost of steam is presumed to be proportional to the cost of electricity [3].

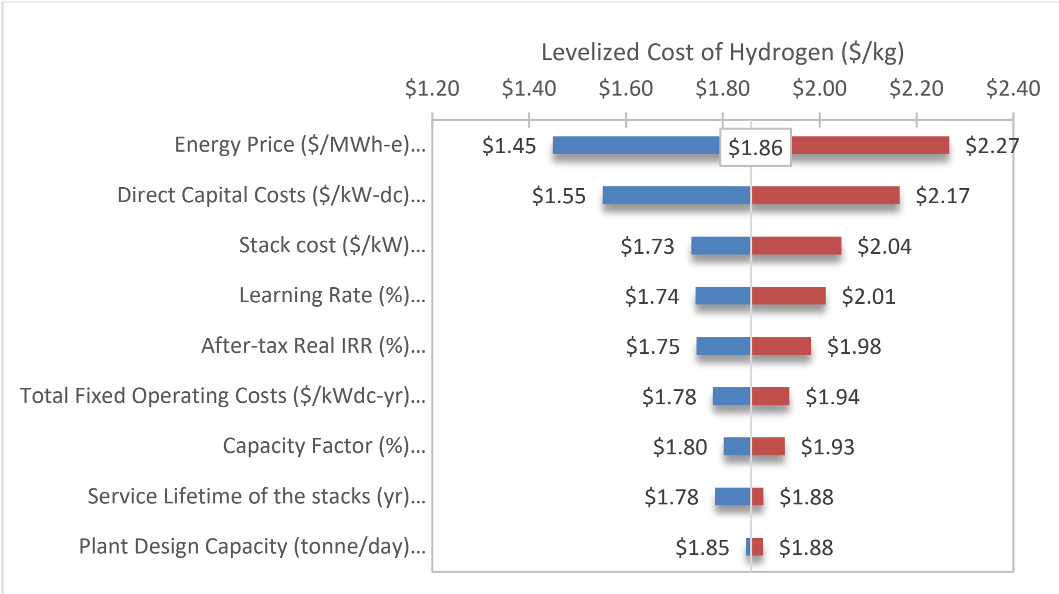

Figure 4. Sensitivity of LCOH to selected constant hydrogen production case input parameters.

It can be useful to project grid non-electricity market prices using tools that forecast the cost of natural resources, electricity and commodity market shifts, and power generation buildout. These models can help evaluate strategies to dispatch electricity between the grid, energy storage, or secondary users that are not connected to the grid. At the same time, thermal energy may be dispatched to the non-grid energy user.

The Department of Energy Office of Nuclear Energy (DOE-NE) Integrated Energy Systems (IES) program has been developing a computational framework to solve time-dependent energy cash-flow problems relevant to optimizing the scale and operating schedule of tightly integrated energy generation and services production. A description of the modeling and simulation foundation for IES can be found in the Roadmap for the Integrated Energy Systems [4]. The approach to optimizing complex time codependent systems draws on the algorithms applied in the Idaho National Laboratory (INL) code Risk Analysis Virtual Environment (RAVEN) to predict hourly grid prices looking ahead for the life of a project which is generally 15, 20, or 30 years.

The modeling and simulations software suite are now packaged in a model framework called FORCE[a] (Framework for Optimization of ResourCes and Economics). LWRS benefits from all prior and ongoing efforts to develop computation tools that enable technical/economic analysis of tightly coordinated energy systems.

Two subroutines were developed in FY 2021–2022; (1) Holistic Energy Resource Optimization Network (HERON) and (2) Tool for Economic Analysis (TEAL).[b] HERON controls the computation workflow using an inner and outer loop of economic analyses as shown in . To determine the ability of a particular integrated NPP and industrial user to respond to temporal response requirements, either a multi-physics-based model of transient operations or a suitable physical prototype of the system must be developed to accurately characterize the dynamic operating feasibility of the unit operations. For the NPP, this includes the rate that thermal energy and electrical power can be transferred to the industrial user. For the industrial user, the response rates of all thermal-hydraulic systems and chemical reactor operations must be determined.

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[a] For more background on FORCE, visit the IES website: https;//ies.inl.gov/SitePages/System Simulation.aspx

[b] HERON development was supported by the LWRS Program. TEAL was developed under the IES program.

FORCE accesses a collection of transient process models developed in the Modelica™ language or other models that can be translated to reduced-order models through functional mockup integration as a functional mockup unit. The library of transient codes is referred to as HYBRID. In addition, system control interactions are governed and limited by a subroutine named Feasible Actuator Range Modifier (FARM) that ensures practical control limits are maintained.

The final step of modeling and simulation of hybrid cases is to wrap the physics models of the hybrid plant with the plant design and scaling models and cash-flow models to demonstrate the technical feasibility of the combined operations and to evaluate the economic viability of the system. A factorial assessment and sensitivity study of the systems design and operating variable requires a code that can efficiently execute a search of the governing physics of the systems and economic parameters.

also shows the computation flow and outputs that help evaluate FPOG options based on the NPV of the optimized system (HERON) consistent with the operating schedule that is bound by the physical limitations of ramp rates determined by the subroutines in HYBRID.

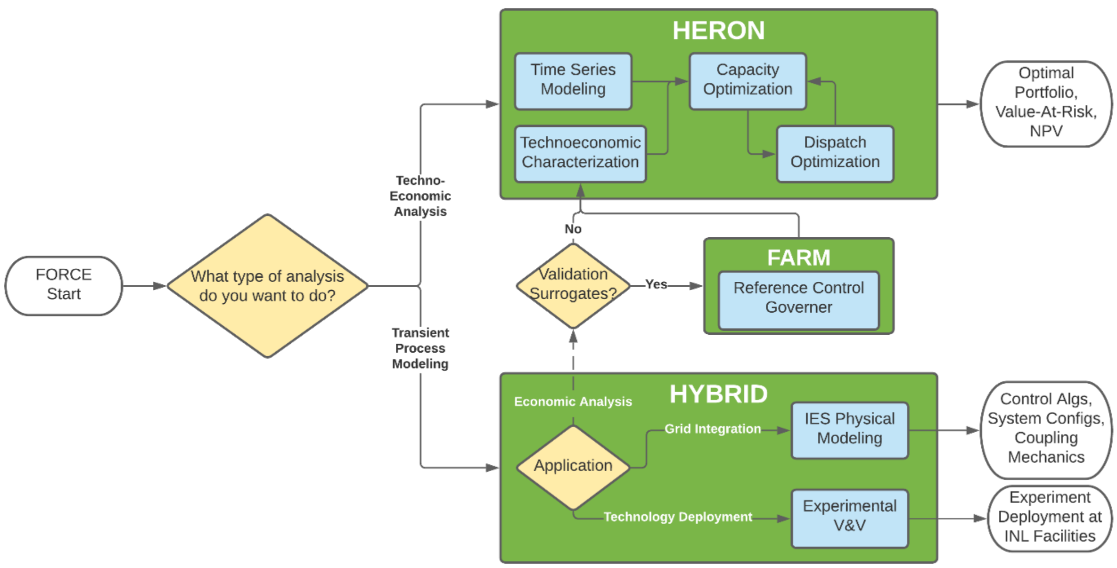

Figure 5. HERON workflow analysis [5].

An illustrative example showing a response schedule that optimizes profit for an NPP dispatching to a grid that has an appreciable amount of non-dispatchable solar energy is shown in . In this case, the capacity of hydrogen storage was determined in parallel with the optimization of electricity dispatch between the grid and the hydrogen plant.

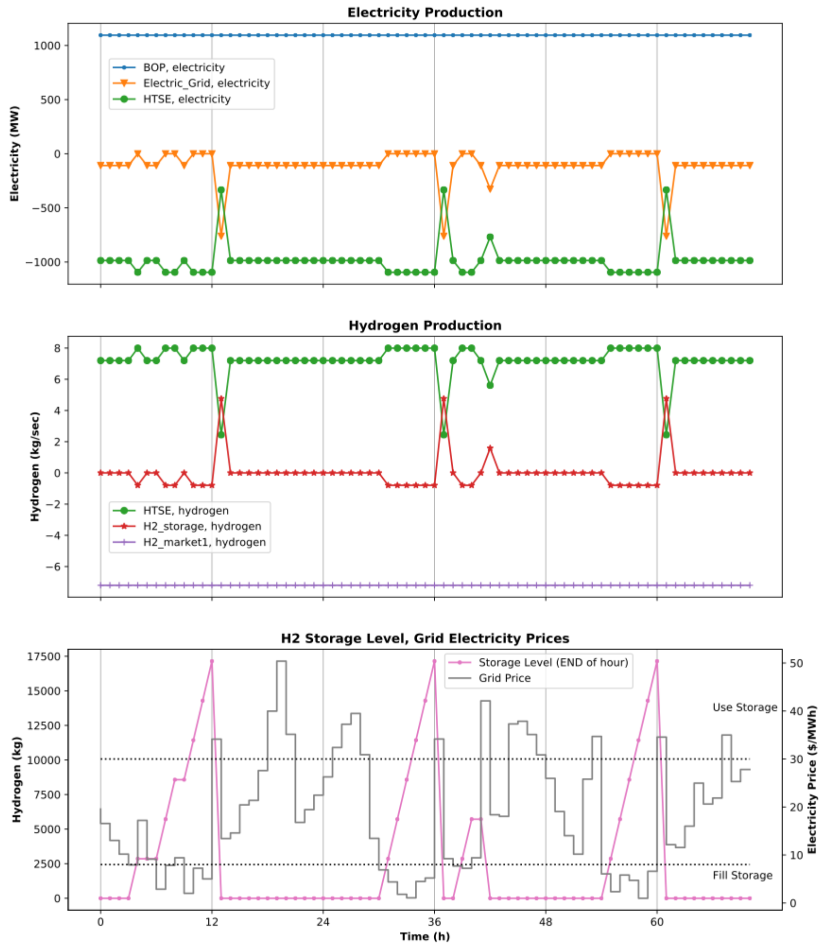

Figure 6. Optimized FORCE solution for hybrid operation of a nuclear plant in the electricity and hydrogen markets [6].

Finally, beginning in FY 2021, the benefits of nuclear energy for producing zero-emissions products are being determined using the GREET Model (Greenhouse Gases, Regulated Emissions, and Energy use in Transportation).[c] This model was developed and is updated by Argonne National Laboratory (ANL) for the purpose of calculating the evaluating the life-cycle emissions associated with the production and application of an energy sources, together with the production of specific energy services or products. GREET provides a standard for comparing the environmental emissions options.

Table 1 provides a summary of the approaches and tools used to address the identified research needs along with the typical input requirements for the analysis.

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[c] The GREET model is a one-of-a-kind analytical tool that simulates the energy use and emissions output of various vehicle and fuel combinations and industrial manufacturing industries. Visit- https://greet.es.anl.gov/.

Table 1. Computational tools used to assess FPOG benefits.

Research Needs	Information Required	Approach and Tools Applied
Nuclear plant operating costs and revenue model	• Revenue targets, plant operating schedule, or plan • Relevant plant maintenance and operating costs, re-fueling schedules • Location-specific grid market and regulatory and pricing structures • Electricity future market demand profiles and ancillary service needs, including energy storage	• Data sheets/survey for individual utilities and reactor owners • Location-specific grid market and regulatory and pricing structure and financial transaction rules • Regional capacity expansion models (e.g., Regional Energy Development Environment [ReEDs][ε]), US-REGEN[μ], RESOLVE[£] • Electricity price models (e.g., 10-minute interval), e.g., Plexos[ω] • National grid models; Energy balancing market forecasts (development in progress by DOE national laboratories, Electric Power Research Institute (EPRI), private companies)
New markets for nuclear power plants	• Utility and nuclear plant owner strategy • Regional non-electricity energy market opportunity identification and assessments • Corporate investment criteria • Clean energy market value (e.g., Zero-Emissions Credits; Clean Fuels Obligations)	• Survey and projection of industry and transportation energy needs and consumer trends • Aspen/Hyprotech Systems (HYSYS[α]) industrial process computer models and plant economic pro-forma worksheet calculations • Energy storage cost and response models • GREET[γ] model life-cycle assessments • Biomass/waste resources utilization and feedstock logistics and price models
Dynamic supply of electricity or thermal energy	• Thermal and electrical energy delivery systems design • Impact on NPP operations and stability • Concept of hybrid plant operations • Transient operating limits of energy delivery and industrial users	• Transient full-scope or reduced-order nuclear plant thermal energy management simulators (e.g., GPWR[λ], Rancor Microworld[ζ] PEPSE[ξ]) • Transient thermal-hydraulic energy delivery systems models • Real-time digital grid simulators • Grid dispatch models • Human factors and control environment
NPP operation safety	• Impact on reactor core heat rate • Impact on plant maintenance and operating schedules and costs	• Operating license review and update • Safety and hazards analyses and revised PRA

Research Needs	Information Required	Approach and Tools Applied
Hybrid plant operations revenue optimization	• Scale of industrial plant • Electricity and thermal energy dispatch schedule • Scale of energy storage	• FORCE[η] • RAVEN[δ] and Plugins HERON[τ] and TEAL[ϕ] • Hybrid model repository[π]

ε. ReEDS – Regional Energy Deployment System, National Renewable Energy Laboratory [7]

μ. US-REGEN – U.S. Regional Economic, Greenhouse Gas, and Energy Model [8]

£. RESOLVE – developed by E3, identifies long-term generation and transmission investments in electric systems, subject to the reliability, technical, and policy constraints [9]

ω. PLEXOS™ – Commercial electricity production simulation- or equivalent codes

α. Aspen Plus™/HYSYS™ – Commercial process simulators and process evaluator- or equivalent process design codes

γ. GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, Argonne National Laboratory

λ. GPWR – Generic Pressurized Water Reactor Simulator; or other LWR plant-specific LWR full-scope simulators

ζ. Low-fidelity nuclear plant simulator providing a simplified representation of a PWR and used for evaluation of nuclear human factor involving attention and situation awareness

ξ. PEPSE® – Performance Evaluation of Power System Efficiencies; Models plant operating data for all major power cycle operating parameters

η. FORCE – Framework for Optimization of Resources and Economics

δ. RAVEN – Rick Analysis Virtual Environment

τ. HERON – Holistic Energy Resource Optimization Network

ϕ. TEAL – Tool for Economic Analysis, Idaho National Laboratory

π. Hybrid repository – set of models in Modelica™ to build representation of FPOG systems

2.2 System Design and Testing

Close coupling of an NPP to an industrial user necessitates engineering design changes to the NPP to deliver thermal energy and/or electricity to the industrial user in a new manner. Every NPP is unique beginning at the reactor core and continuing through the thermal-hydraulic, power generation, and cooling systems. Each electricity transmission switch yard line up with the grid is also unique. Consequently, plant design modifications will be required to tap any substantial amount of electricity or steam for FPOG applications.

Interfaces with the industrial user are broken into (1) electrical coupling, (2) thermal coupling, and (3) control systems coupling. To modify an existing NPP, all changes will need to be evaluated and tested in a manner that is consistent with the NRC requirements of the facility operating license. As a minimum, this will require accurate modeling of the physical hardware and control systems using computer models. In some cases, the computer models may require verification and validation with physical testing on a scale that provides an accurate representation of the heat and mass transport of the modified system. However, small-scale demonstration projects may not require a priori modeling when the interface with the existing plant is within the authorized operational limits of the plant. Small pilot plant operations can help transition operations to full-scale FPOG conditions by providing data pertinent to scaling up the process interfaces with the NPP.

For purposes of discussion, shows a hybrid FPOG applications where thermal energy and electricity are dispatched to a high-temperature steam electrolysis plant. In this case, a slip stream of steam is extracted from the main steam lines ahead of the turbine generator. Condensate is returned to the plant condenser in a such manner that has the least impact on the thermal hydraulics of the power generation block and cooling water recirculation systems. However, both the NPP and the grid will likely be directly coupled to the operations of the steam electrolysis plant, even though the systems can be viewed as independent systems that can proportionally couple and decouple with the grid as a load-following plant. This will allow the nuclear plant to provide load-following power to the grid.

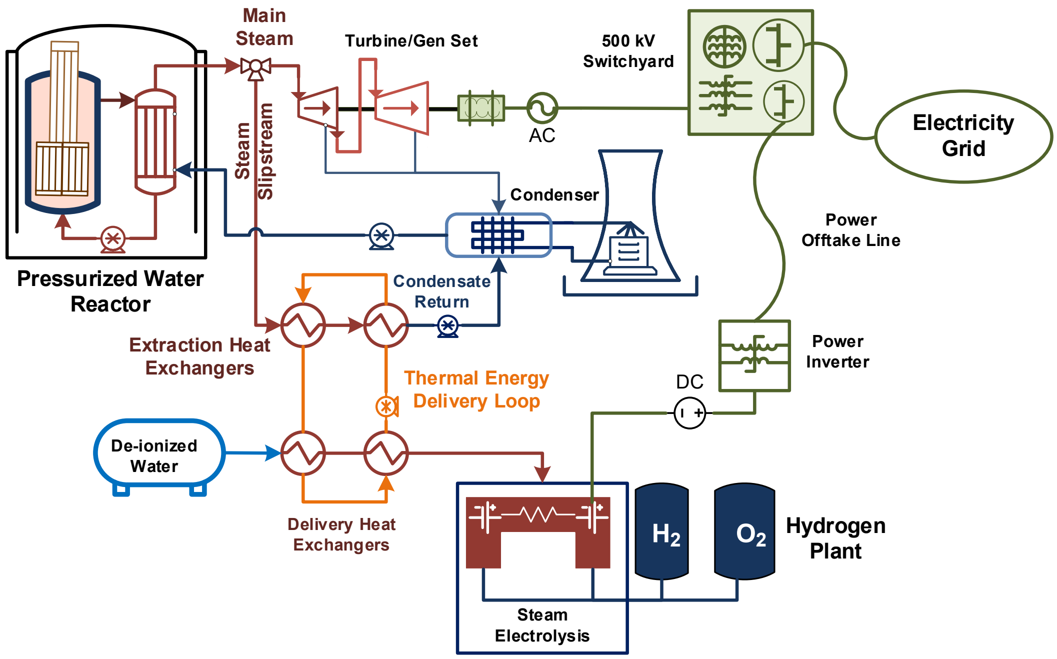

Figure 7. Conceptual design of a hybrid FPOG plant producing hydrogen and grid electricity.

2.2.1 Thermal Coupling

Thermal energy dispatch to an external plant will require significant modifications to the existing thermal-hydraulic systems. The physical systems must not disrupt normal plant operations or result in a deviation of core heat rates outside of the operating license requirements. Ideally, the concept of thermal energy extraction will allow the plant to maintain the core heat rate near the name plate capacity of the plant. Small variations are considered part of the normal operations, and these will be experienced with FPOG operations that modulate the power output of the plant. Nonetheless, it is in the best interest of the plant to maximize the energy output of the plant to generate the most income possible.

The mode of thermal energy extraction can take on a variety of forms, including the location where the thermal energy is tapped and the manner the thermal energy is transferred to the industrial user. At this time, any system that would independently extract heat from the reactor core is not being considered since this would require major changes to the reactor core and primary steam generation systems. It does seem feasible, however, to utilize the existing steam bypass system to transfer thermal energy to a new heat delivery system. One option for thermal power extraction is to use an existing steam bypass or install a new steam bypass system to the main steam line in the power generation deck. Tapping into the main steam line outside the reactor core and downstream of the main steam stop valves will greatly reduce the time and permits that will be required to modify the plant thermal energy distribution systems.

A second location where heat could be safely extracted from the power cycle is before or after an intermediate turbine at the point of steam extraction and re-heat tanks (see). The heat taken from any of the inter-stage reheater lines, through either a steam bypass line or an in-line heat exchanger, would only reduce the temperature (viz., enthalpy) of the reheated steam. In either situation, steam extracted from the NPP is only used to deliver heat to the steam generator located within the electrolysis unit. This serves two purposes: (1) it avoids potential contamination of the electrolysis plant, and (2) high-purity steam is generated from a demineralized water supply. The steam from the nuclear plant will be returned to either a feed water heater or the main condenser.

A cost-benefit engineering study is needed to determine the optimum location of thermal energy extraction with the associated impact on power generation efficiency, turbine operations, thermal flows, and condenser operations. All impacts on core operations must be evaluated to understand how transient energy extraction may impact the heat rate of the reactor. The impacts of any potential disruption in the steam bypass or extraction heat exchangers must be considered relative to potential core damage initiating events.

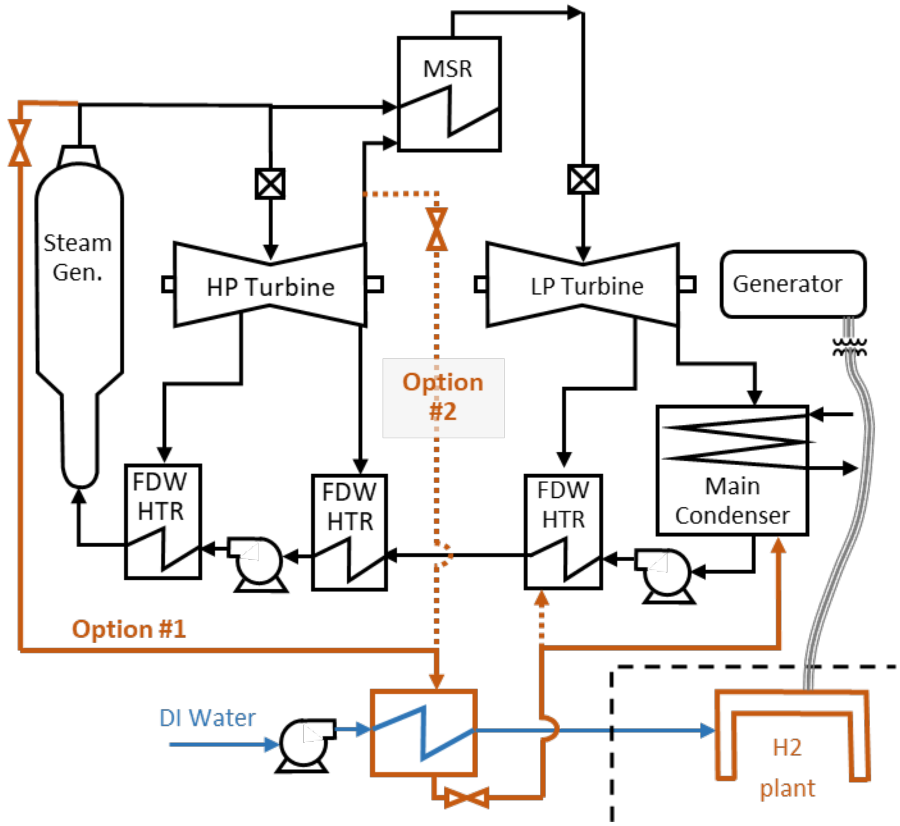

Figure 8. Two options for extracting steam for high-temperature electrolysis steam generation. (MSR-Moisture Separator Reheater; HP- High-Pressure; LP- Low Pressure; FDW HTR- Feed Water Heater; DI-Demineralized Water).

Heat delivery to the industrial user can be accomplished with a variety of heat transport systems. Common systems of industrial heat transport that could be used include intermediate-pressure steam lines or lines filled with synthetic oils (that are non-flammable at the expected operating temperature). The quality of heat produced by LWRs eliminates the choice of molten salts, which have melting points greater than 350°C (662°F), as well as most liquid metals, which have melting points above 400°C (752°F). Circulation of hot gases is a possibility and may be appropriate for specific heat applications.

In summary, the mode of heat extraction and heat delivery to the industrial user will require a comprehensive evaluation of the industrial user needs and the nuclear plant design configuration and impact on power generation and reactor core operations. A thermal hydraulics model of the candidate heat delivery systems will be necessary to reduce the risk of actual systems design and deployment. A subscale test system may be useful to demonstrate the proposed concept before an actual modification of the plant is completed.

2.2.2 Electrical Coupling

In designing a separate electricity connection to FPOG customers, changes to the existing NPP switchgear and transmission system connections and operating procedures will be necessary. Potential load rejection by the electricity grid as well as the FPOG customer must be taken into consideration. Measures to control droop in grid frequency currently include automatically or manually changing output by speed governors on the power plant generating unit, and disconnecting selected loads (for example, customers) from the grid (this is also known as "load shedding"). However, NPPs typically cannot respond with power output increases in this manner when they are operated at their limit of 100% licensed power. FPOG operations may increase the flexibility of managing grid power conditions by providing a closely coupled large load that can be adjusted more readily than the power generation turbines.

The most basic FPOG options will involve withdrawing electricity from the plant either before or after electricity transmission to the grid. It is common practice to withdraw electricity for certain "house loads" that include plant lighting and heating, water treatment and cooling tower units, and power for pumps, steam circulators, and core management. Such house loads are only a small percentage of the total plant power production. However, to make a substantial impact on plant revenues, a direct connection to a large FPOG industrial user is anticipated. Therefore, it will be necessary to divert the power to the secondary non-grid user from the power plant transmissions station.

shows an example of electrical coupling to the alternating current/direct current (AC/DC) rectifier for an electrolyzer where the power is drawn from the switchyard before the main grid circuit breaker and step-up transformer that feeds the power to a high-voltage grid transmission line shown here to be 230 kV. The connection to the electrolyzer requires an independent circuit breaker followed by a step-down transformer to reduce the power voltage feed to the rectifier to 3.3 kV. A Unit Auxiliary Transformer up to 40–60 MWe is likely feasible from this offtake in the transmission station. Larger electrical coupling will likely need to come from the high-voltage side of the step-up transformer where a loss of load would be absorbed by the bulk power grid.

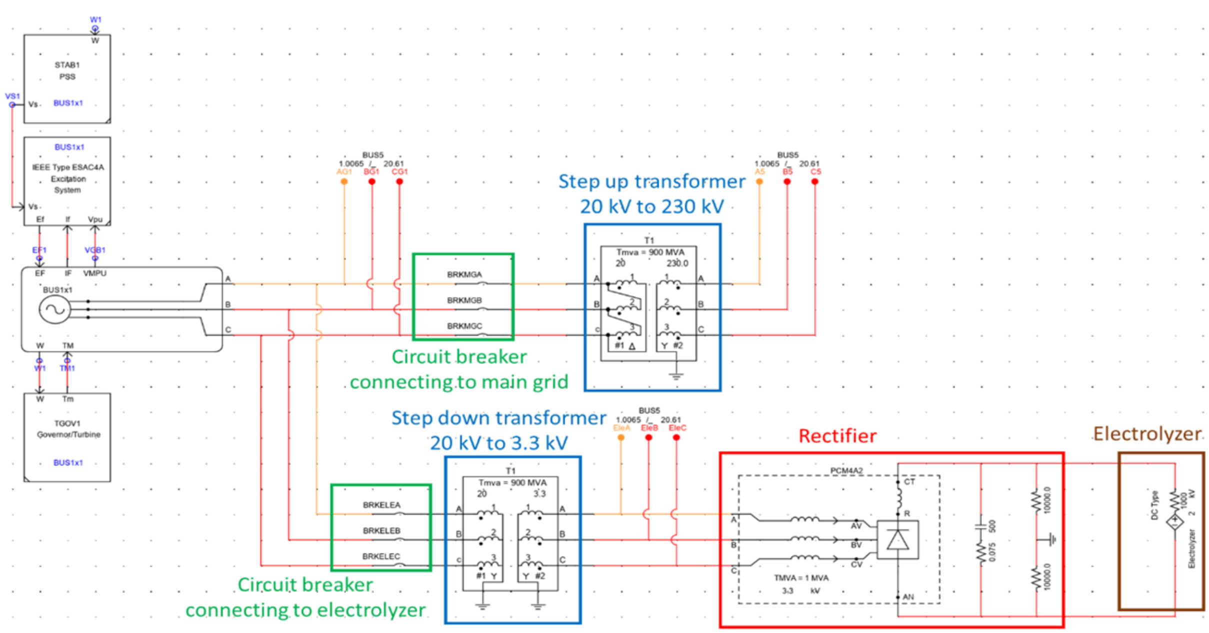

Figure 9. Electrical power coupling example before power transformer step-up to grid transmission line.

Likely, an agreement with the grid regulatory agencies, such as the North American Electric Reliability Corporation (NERC) subject to oversight by the Federal Energy Regulatory Commission (FERC), will be required to ensure the electricity market is not vulnerable to manipulation.

It is imperative to perform FPOG electric power system dispatch simulations to study the effects of the system under both normal operating conditions as well as single faults (sudden losses of key transmission circuits or generating units). The simulations can confirm time-dependent power system response in terms of voltage and frequency, physical limitations to prevent overloading transmission circuits, and automatic load shedding and emergency disconnects. It may be necessary to demonstrate the physically separate electricity and FPOG user transmission circuits are independent and proper prevention is in place to ensure the NPP can provide long-term core decay heat removal under any loss of load scenario.

2.2.3 Controls Systems Coupling

The key to any mode of FPOG application will be implementing a new concept of operations. This will likely entail new nuclear plant control procedures, new (digital) instrumentation, and controls to divert thermal energy and electricity to FPOG hybrid users. As a minimum, increased operator cognizance will be required. However, the nuclear plant operators will likely be responsible for apportioning heat and electricity to an FPOG hybrid plant. The NRC requires that the licensed operators maintain sovereign control of all nuclear plant operations that could impact core heating.[d] Hence, the implementation of new human-machine interfaces (HMIs) (i.e., human factors) may be needed to maintain the safety of the plant efficiently and reliably during normal and off-normal FPOG conditions.

Technical guidance for the FPOG applications data collection, analysis, and decision systems and associated monitoring and control systems will be developed under this Pathway. These systems will be based on a high-temperature electrolysis (HTE) hydrogen production plant that is sized to utilize all the power generated by a typical NPP. The control systems and human factors developed for this case can then be readily applied to other FPOG cases. It is important to address nuclear plant startup and shutdowns for planned and off-normal initiating event associated with the hydrogen plant.

Pre-eminent among design principles is that integration with a hydrogen plant or energy storage unit will not translate adverse control effects back to the nuclear reactor. It follows that this is also a fundamental premise to be demonstrated in regulatory evaluation performed under the 10 CFR 50.59 or license amendment review (LAR) processes for any modification to an operating nuclear facility. The Institute of Nuclear Power Operations IER 17-5 coined the concept of maintaining a "Line-of-Sight to The Reactor Core" with respect to managing reactivity through operational crew performance, teamwork, and fundamental operator behaviors and knowledge. This principle is also aligned with licensing approval requirements that apply to modifications to the nuclear plant. Modifications in support of nuclear integrated HTE must be designed from first principles to not result in normal, upset, or transient conditions, which could challenge the operating crew's ability to control the reactor as required by 10 CFR 50.59.

The full potential of a nuclear-hydrogen hybrid operation is to garner the highest revenue possible when participating in the grid reserve capacity market. This will allow the hydrogen plant to operate at nearly full capacity with minimal storage while also supporting grid needs, such as enabling firming the grid when renewables production is low. This is more predictable with solar photovoltaic (PV) than with significantly random wind energy. One consideration is that wind energy generally has its highest capacity during the spring and fall when power demand is typically at a minimum. For these cases, it is desirable for nuclear plants to provide Regional Transmission Operators and Independent Systems

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d USNRC 10 CFR 50.54(i) Conditions of Licenses specifies "except as provided in 55.13 of this chapter, the licensee may not permit the manipulation of the controls of any facility by anyone who is not a licensed operator or senior operator as provided in part 55 of the chapter."

Operators with fast-response capacity. Achieving this goal sets a technical objective for the hybrid operations and requires enhanced or new communications between the grid and the NPP in coordination with the hydrogen plant operators.

The hydrogen plant only requires electricity and steam to operate. To keep controls as simple as possible, only a few items are needed for the main control room operator. For the electrical inputs to the plant, controls are included that are typical for operating switches/disconnects/breakers to initiate the flow of electricity, such as control switches and position indicating lights. Typical alarm indications would be included. The overall control scheme is assumed to be comprised of only controls within the main control room (MCR) to initiate the flow of electricity and steam to the hydrogen plant. With a larger scale (greater than approximately 100 MW_e) hydrogen plant, it is assumed that the plant is operated by personnel that are different from those operating the nuclear plant. Therefore, controls for the hydrogen plant itself are not part of this nuclear energy dispatch scheme. It is assumed that an intermediate heat exchanger (reboiler) is used to separate the nuclear steam from the hydrogen plant. Doing so eliminates the need for any type of radiation monitoring. Condensate from this heat exchanger is returned to the plant.

As for the steam inputs, controls that are typical for the valve operation are assumed. Control switches and position indication for an air-operated valve are included. Typical alarm indications would be included. Pressure indication is needed to feed the hydrogen plant but should also be sent to the MCR for awareness by the operators. The steam inlet valve(s) are assumed to be Air-Operated Valves that can modulate flow in the system and close on automatic signals as needed. The reboiler outlet valves can be manual valves for the purpose of maintenance/isolation.

All items in the MCR can be left as analog controls or can be fed into a digital control system. The status of the hydrogen plant can be fed to a plant process computer or can be monitored remotely. It is only needed for business purposes (trending and monitoring) and is not critical to the operators in the MCR of the nuclear plant.

Finally, the concept of providing rapid reserve capacity on the order of minutes, and commensurate with the ramp rates needed to match renewable energy turndown requires a fundamentally new relationship to transact with the grid operators and the hydrogen plant. Communications among the three entities is critical, even using digital signals and controls that inform the nuclear plant operators to execute an energy dispatch between the grid and the hydrogen plant. Additionally, the status of the hydrogen plant should always be apparent to the nuclear plant operators, and possibly the power transmission station operators when they exist.

The activities of this Pathway are being coordinated with the Plant Modernization Pathway Technical Program Plan. Within the research objectives of the latter, three areas have been identified that enable capabilities needed for long-term sustainable plant operation: instrumentation and control (I&C) architecture; online monitoring and plant automation; and advanced applications and process automation. These areas provide the hardware needed to address the aging of existing I&C technologies, the information necessary to provide state awareness, and software that will enable power plant staff to perform their jobs more efficiently. These research thrusts can and should incorporate FPOG unit operation.

The Human Systems Simulation Laboratory (HSSL) at INL is used to develop and evaluate advanced control room concepts. The HSSL supports advanced control room design and evaluation for existing LWR and future advanced reactors. Advanced control room concept research for existing LWRs includes control room modernization to support hybrid control rooms, integrating of existing analog and digital HMIs, traditional and machine-learning augmented integration of control room systems to support intuitive diagnostic data visualizations, development and piloting of human-centered design activities with operating crews to advance human factors best practices industry guidance, and planning and visualization of different end-state operational concepts. This advanced facility supports human factors research for operating nuclear plant control rooms, including human-in-the-loop performance and human-system interfaces (HSIs), and can incorporate mixtures of analog and digital hybrid displays and controls. It is applicable to the development and evaluation of control systems and displays of NPP control rooms, and other command and control systems.

The HSSL at INL is a full-scale virtual NPP control room simulation environment with glasstop instrumentation panels that supports the safe application of advanced simulation and modeling techniques for the development, evaluation, and validation of new and improved human-system interface designs to enhance the existing concept of operations. The HSSL glass top panels underwent an upgrade in the spring of 2021 to provide flexible operator control with exceptional performance. The laboratory was redesigned to move the observation gallery from the side to the rear for enhanced observation and greater MCR emulation flexibility (Figure 10). These changes provide a larger and more open space to accommodate larger control rooms. Furthermore, instrumentation panels with higher 4K resolution touch screen monitors were installed in bay stands with adjustable, motorized adjustments to height and angle. The high-resolution monitors provide greater flexibility for integrated prototypes overlaid on the virtual bay panel representation since there are more pixels and therefore a larger design surface to use while maintaining a clear and readable display. The motorized bay stands support greater flexibility in control room design to accommodate both vertical and curved control panels with aprons.

Briefly, the simulator contains virtual equipment representations identical to the high-fidelity and certified training simulators used in NPPs. The participating operators can view instrumentation and controls (I&Cs) and analog instrumentation on touchscreen displays that mimic the control boards of actual NPP control rooms. Because the control boards are virtual, new digital HSIs (e.g., one with a thermal power dispatch system) can be rapidly introduced and reconfigured.

Figure 10. Upgraded HSSL at INL.

For the FPOG Pathway, the HSSL is being used to develop, and most importantly, evaluate human performance in application-specific operational concepts for hybrid FPOG operations to ensure the design aligns or positively extends the existing concept of operations to bolster safety and efficiency. NPP operators execute hybrid FPOG operations with prototype HMIs to identify human factors issues and develop solutions to ensure a usable and effective design. New digital systems and operator interfaces are being developed in software and depicted in the context of the current plant control room, enabling comparative studies of the potential operator needs benefits of operator performance to the overall system safety and efficiency. It is essential to test and evaluate the performance of the system and the human operators' use of the system in a realistic setting. In control room research simulators, changes to existing plants control panels can be integrated into a realistic representation of the actual system and validated against defined performance criteria. These may be undertaken alongside plant modernization activities.

2.3 Regulatory and Licensing

Coupling an NPP to a flexible industrial process will involve changes to the physical hardware and operating systems of the plant. It is expected, as a minimum, that a safety review will be needed to identify and evaluate FPOG implementation events that could require an update to the PRA as will the operating license for the plant. However, the first goal of any FPOG application will be to avoid the need to modify the reactor license and to implement costly systems to mitigate the safety hazards that may be introduced.

The NRC develops various regulatory guides to assist license applicants' implementation of NRC regulations by providing evaluation techniques and data used by the NRC staff. Two distinct pathways through guides and CFR are identified for use in the proposed LWR plant configuration change approval. One pathway utilizes 10 CFR 50.59, Changes, Tests, and Experiments to review the effects on frequencies of design basis accidents (DBA), amendment of the Updated Final Safety Analysis Report (UFSAR), and determination of whether a LAR is required. The risk-informed support of 10 CFR 50.59 is Regulatory Guide (RG) RG 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis." The alternate pathway is the actual LAR process, which would utilize PRA results as well; however, the process utilizes 10 CFR 50.90 and should be avoided if possible due to lengthy review and monetary burden.

To meet 10 CFR 50.59 criteria, the increase in the initiating event frequencies of DBA shall be "minimal," this is generally accepted to be less than a 15% increase for each DBA. RG 1.174 comes into play as support for the regulatory decision when other events are considered, such as external events created by the presence of the hydrogen plant close to the LWR.

To meet RG 1.174 criteria, the probability of core damage frequency (CDF) should be below 1E-5 overall and the change in overall CDF should be below a magnitude of 1E-5. Any plant that starts at a 1E-4 or more CDF requires less than 1E-6 increase in CDF to be considered. The generic PWR being considered for this study has a 5.16E-5 CDF. If these metrics are met, the NRC considers this a small change which is consistent with the intent of the Commission's Safety Goal Policy Statement, and a detailed quantitative assessment of the base values of CDF is not necessary for the license review.

A Large Early Release Frequency (LERF) should be below 1E-6 overall and the change in overall LERF should be below a magnitude of 1E-6. If these metrics are met, the NRC most likely considers this a small change, which is consistent with the intent of the Commission's Safety Goal Policy Statement, and a detailed quantitative assessment of the base values of CDF is not necessary for the license review. If the criteria are not met, then a LAR must be submitted to the NRC for review and approval. An effort to evaluate bounding FPOG risks will provide a better understanding of the potential accident scenarios that may require deeper analysis or can provide an understanding of the process that may be taken to address the additive risks of FPOG to the baseline PRA of a nuclear plant. In addition, guidance on possible approaches to modify a plant operating license may reveal research activities that can be completed that would help avoid a slowdown of any FPOG installation project.

Two generic preliminary PRAs have been completed for a Mark 1 boiling water reactor (BWR) and a two-loop PWR tied to a full-scale HTE plant (ca. 1,000 MWe, 200 MWth). Several new internal and external safety initiating events were identified and evaluated using a rigorous, SAPHIRE-based, Failure Modes and Effects Analysis approach that identifies the impact on existing and new safety initiating events such as a sudden leak in the new steam extraction system, loss of offsite power, hydrogen flames, or explosions at the nearby hydrogen plant. All key PRA parameters, such as Core Frequency Damage and LERF, and Maximum Credible Accident are for a hydrogen production plant located no further than 1 km from the NPPs. The preliminary PRA was encouraging and suggested that all risks could likely be covered under CRF 50.50 and RG 1.174.

2.4 Coordination with DOE Programs

Planning, execution, and implementation of the LWRS Program are done in coordination with the nuclear industry, NRC, universities, and related DOE R&D programs (e.g., Nuclear Energy Advanced Modeling and Simulation [NEAMS], Consortium for Advanced Simulation of LWRs [CASL], Nuclear Energy Enabling Technologies [NEET], and IES Programs to assure relevance, efficiency, and effective management of the work). This work is also coordinated with the Nuclear Energy crosscutting program activities and leverages the tools and test facilities that are supported by this program.

Because FPOG applications involve electricity and non-electricity markets, it is also important that the FPOG Pathway leverage and coordinate with DOE-Energy Efficiency/Renewable Energy programs charged with technology development and advanced manufacturing (e.g., Advanced Manufacturing, Hydrogen and Fuel Cell Technologies, and the Wind, Water, Solar Power programs, respectively). In addition, FPOG applications may also converge with the goals and mission of the DOE-Fossil Energy programs and the Advanced Research Projects Agency-Energy.

It is the responsibility of the FPOG platform lead to ensure that DOE crosscutting efforts are communicated with the LWRS National Technology Director and the federal program manager.

2.5 Stakeholder Engagement

In consideration of the urgency by which some nuclear plants need to diversify their revenue stream, the goal of FPOG is to help stakeholders execute commercial deployment of the most promising options within 3–5 years. This includes FPOG cases that wholly support grid markets when consistent with the business strategy of individual utilities. This program will continue to develop FPOG energy parks as industry and utilities understand markets that extend beyond electricity markets.

The approach being applied to FPOG R&D is consistent with other LWRS Pathways that engage stakeholders to help focus the research activities and delivery outcomes on time. A key to success is addressing specific technical needs and helping power plant owners prepare for demonstration projects in partnerships with enabling technology providers and industry customers. Program success will ultimately be measured by the successful commercial deployment of FPOG. The role of LWRS is to reduce the risk of these projects by conducting R&D that raises technology readiness levels (TRL) from low to medium and then hands off the outcomes for large pilot plant demonstration and commercial deployment that may involve large private investments. This is supported by engaging stakeholders and partners with investment interest in FPOG operations, applying tools to analyze the technical and economic benefits, and demonstrating operations in appropriate scale operations.

The goals of FPOG interactions with stakeholders are reflected in the following statements (and graphically presented in):

- Engage: Collaborate with stakeholders to identify the economic challenges faced by the nuclear industry and to develop and review FPOG targeted research plans to address those challenges
- Develop: Develop tools to analyze and optimize FPOG options and complete FEED of systems to safely and efficiently conduct FPOG. (Low TRL)
- Demonstrate: Demonstrate FPOG interfaces and operating control strategies to reduce the risk of commercial demonstrations. (Medium TRL)
- Deploy: Enable broad deployment FPOG by stakeholders (High TRL).

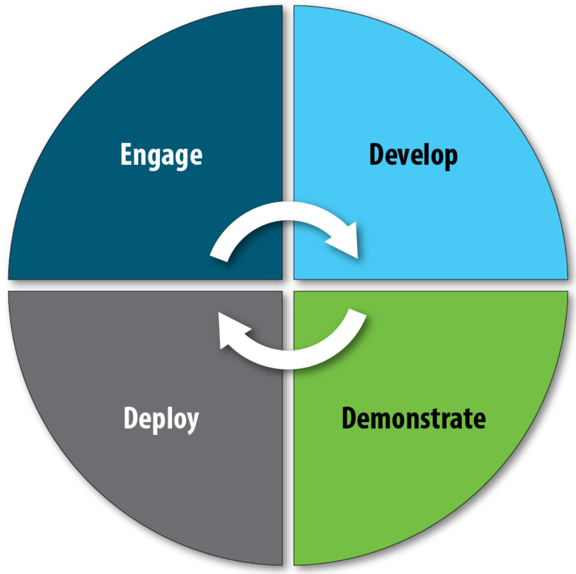

Figure 11. FPOG progressive interaction with stakeholders.

The success of this Pathway can be quantified by outcomes that help LWRs facing current or future revenue-adequacy concerns remain viable. This goal can be realized from the following outcomes:

- LWR vitality: FPOG is technically feasible for most varieties of PWRs and BWRs; the business case for hybrid markets is understood for most grid conditions and industrial markets.
- Physical interfaces: Design specifications, engineering, and system-upgrade components for electrical and thermal energy FPOG coupling to leading industrial processes are established and can be implemented.
- Controls systems and human systems interfaces: Human factors and cybersecurity operating systems have been addressed and can be readily implemented by LWR operators.
- Grid reliability and resiliency: Single plant and concerted fleet operations are valued assets in the U.S. grid and are considered viable to firm renewable power generation.

The LWRS Program works with industry on nuclear-energy-supply technology-R&D needs of common interest. The interactions with industry are broad and include cooperation, coordination, and direct cost-sharing. The guiding concepts for working with industry are leveraging limited resources through cost-shared R&D, direct work on issues related to the long-term operation of NPPs, the need to develop state-of-the-art technology to ensure safe and efficient operation, and the need to focus government-sponsored R&D on the higher-risk and/or longer-term projects, incorporating scientific and qualitative solutions that use the unique expertise and facilities at the DOE laboratories. These concepts are included in memoranda of understanding, nondisclosure agreements, and cooperative R&D agreements (CRADAs). Cost-shared activities are planned and executed on a partnership basis and include significant joint management and funding. Periodic coordination meetings are held at the program and technical-pathway levels to facilitate communication.

The R&D activities for FPOG necessarily and appropriately require close collaboration with LWR owners and industrial users of the energy that will be provided. It is also important that grid balancing authorities be aware and possibly contribute to the TEA to accurately capture the value proposition of FPOG operations that propose to provide grid services. Technology providers are also important to the success of dedicated and hybrid FPOG applications. In some cases, technology may need to be adapted to LWR energy forms. In other cases, technology innovation is important to the implementation of processes that can also operate flexibly, turning on and off as the system responds to market signals that will optimize revenues for each of the cooperating partners. Additionally, this Pathway benefits from leveraging program efforts under the DOE-NE Integrated Energy Systems Program and the DOE-EERE Fuel Cell Technology Office, and other offices responsible for renewable energy and those taking lead for grid modernization R&D. This Pathway involves analysis leads at INL, ANL, National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL) to support the technical/economical assessments and demonstration projects.

A key research area required to validate the feasibility of integrated hydrogen production at NPPs is related to how supporting design changes would conform to the licensing regulatory framework required by the NRC. Design changes are routinely performed at operating U.S. nuclear power reactors through a process where the licensee confirms that the proposed design change remains within the intent of the approved operating license. This process is controlled under the Code of Federal Regulations, Section 10 CFR 50.59. When a change is determined not to be within the limits described by the approved operating license or licensing bases, a formal license amendment process is required with specific NRC approval.

2.5.1 Hydrogen Regulatory Research and Review Group

The H3RG was formed to begin to identify the technical and safety risks that may need to be addressed to follow 10 CFR 50.59 requirements. The H3RG includes a broad collaboration with primary participants from DOE-supported national laboratory research leads, contracted architect engineering participants, and nuclear utility licensing and design personnel.

Although the goal of the H3RG is to explore success paths for using the 10 CFR 50.59 process, it may also identify potential "dividing lines" between the use of 10 CFR 50.59 evaluation and LAR processes or other licensing basis changes. If research points to specific design or operational issues that fall outside successful evaluation under 10 CFR 50.59, those areas will be identified and considered for additional research that could toggle the change back to implementation under 10 CFR 50.59. Any design or licensing consideration area that has been selectively screened out of this initial research project scope will be documented for future R&D and end-user detailed development.

2.5.2 Other Stakeholder Engagement

An important stakeholder engagement activity of the FPOG Pathway is to educate and work with public utility commissions and grid operators to both raise awareness of the benefits to grid markets and state energy policy makers. The ability of nuclear plants to provide load-following power generation is relatively new and will require an interface with grid operators to understand how a new paradigm for dispatching NPPs can be achieved. State and federal regulatory agencies will also need to clarify existing regulations or grant new operating conditions and permits that will enable hybrid FPOG operations that provide the various forms of grid reserve capacity.

Table 2 provides a list of stakeholders and industrial roles that are being promoted or coordinated by the FPOG Pathway. Some CRADAs are being undertaken under the Pathway R&D activities; however, it is expected that demonstration projects led by the NPP owners and industrial partners will fall under either DOE cost-shared competitive awards or will be executed as purely private-funded ventures. The role of the national laboratories is to help accelerate technology deployment by reducing technology and commercialization risks.

Table 2. FPOG Pathway stakeholder roles and responsibilities.

Industry	Roles and Responsibilities	Form of Engagement
Nuclear plant owners and operators	Participate in FPOG Pathway R&D activities reviews Inform and participate in plant-specific TEA Support identification and development of human factors for FPOG controls implementation[α] Complete due diligence of technology providers and industrial energy offtake customers Support pilot project demonstrations	Stakeholder engagement meetings Review FPOG R&D reports SPPs[β] CRADAs[γ] MOUs[δ] Cost-share private/public demonstration projects
Grid operators and balancing authorities	Determine grid market conditions for current and future transactions that involve NPPs (NERC and FERC requirements) Provide grid balancing and technical services market planning projections Provide power generation dispatch plans and technical specifications for communications links and relays to for NPP operators to initiate hybrid FPOG power dispatch requests[α]	MOUs[δ] Crosscut between DOE Nuclear Energy and Federal Energy Management Agency Utility Company Communications with responsible Grid Operators
Technology providers of heat delivery systems, controls interfaces, and manufacturing process unit operations	Co-develop technology for Dedicated or Hybrid FPOG operations Support TEA License technology to FPOG project developer/owner Lead or participate in pilot plant and commercial demonstration projects	Stakeholder engagement meetings SPPs[β] CRADAs[γ] MOUs[δ] Cost-share private/public demonstration projects
Industrial energy users/manufacturing companies	Support technical and economic assessment Provide market pricing and demand projections and planning Support technical integration engineering and design Support plant integration engineering and design Lead of participate in pilot plant and commercial demonstration projects	Stakeholder engagement meetings SPPs[β] CRADAs[γ] MOUs[δ] Cost-share private/public demonstration projects
Regulatory agencies: PUCs, NRC, FERC, NERC	Determine regulatory conditions for Hybrid FPOG operations and markets Ascertain licensing basis, cybersecurity requirements, operator primacy, and	Stakeholder engagement meetings MOUs[δ]

Industry	Roles and Responsibilities	Form of Engagement
	communication link protocols and certifications Ascertain credits for clean energy provisions	

α. Control of plant operating parameters ensuring nuclear safety and core stability are the responsibility of the reactor operators

β. Strategic Partnership Projects (DOE work funding by the supporting industry)

γ. Cooperative Research and Development Agreement (research jointly funding by DOE and supporting industries)

δ. Memorandum of Understanding (DOE agreement to exchange information between parties with relevant protection of proprietary data and protected information).

2.5.3 Voluntary Utility/Industry Interactions

Outside of the formal meetings of the H3RG with dozens of utilities, no formal utility/industry working meeting was scheduled for FY 2022. CRADAs with individual utilities are stemming from monthly, bi-weekly, and often weekly meetings. The FPOG Pathway was represented again at the American Nuclear Society Annual Utility Working meeting in August 2022 and the EPRI Nuclear Power Advisory Council in September 2022. The Pathway was also well represented at the annual PWR Owners Group which precipitated regular meetings with four separate nuclear plant operating companies.

The Pathway coordinated and led nuclear utility participation in national workshops related to hydrogen production demonstration projects and the Infrastructure Investment and Jobs Act (IIJA) hydrogen hubs. At the request of several nuclear plant operators, a plan for scaling up hydrogen production with NPPs was developed [10].

This report outlines the opportunity for NPPs to participate in a first-of-a-kind (FOAK) commercial nuclear H_2 project intended to bring industry partners together to create regional clean H_2 hubs. The Bipartisan Infrastructure Law (BIL) will fund at least one hub up to $1.25 billion as federal cost-share no less than 50% to execute a nuclear H_2 project. The report discusses the set of activities that are now underway or that are planned for completion by the FPOG Pathway to reduce the economic, technical, regulatory, and safety risks of these projects. DOE cross-program activities are being coordinated to ensure success in the timeframe allowed by the BIL. shows the approximate schedule of coordinated R&D and pilot demonstration projects leading up to the first commercial nuclear H_2 production project. Execution of this plan requires DOE and industry collaboration. DOE research accomplishments are being provided to the electric utilities or industries looking to participate in the H_2 hub proposal and project execution process.

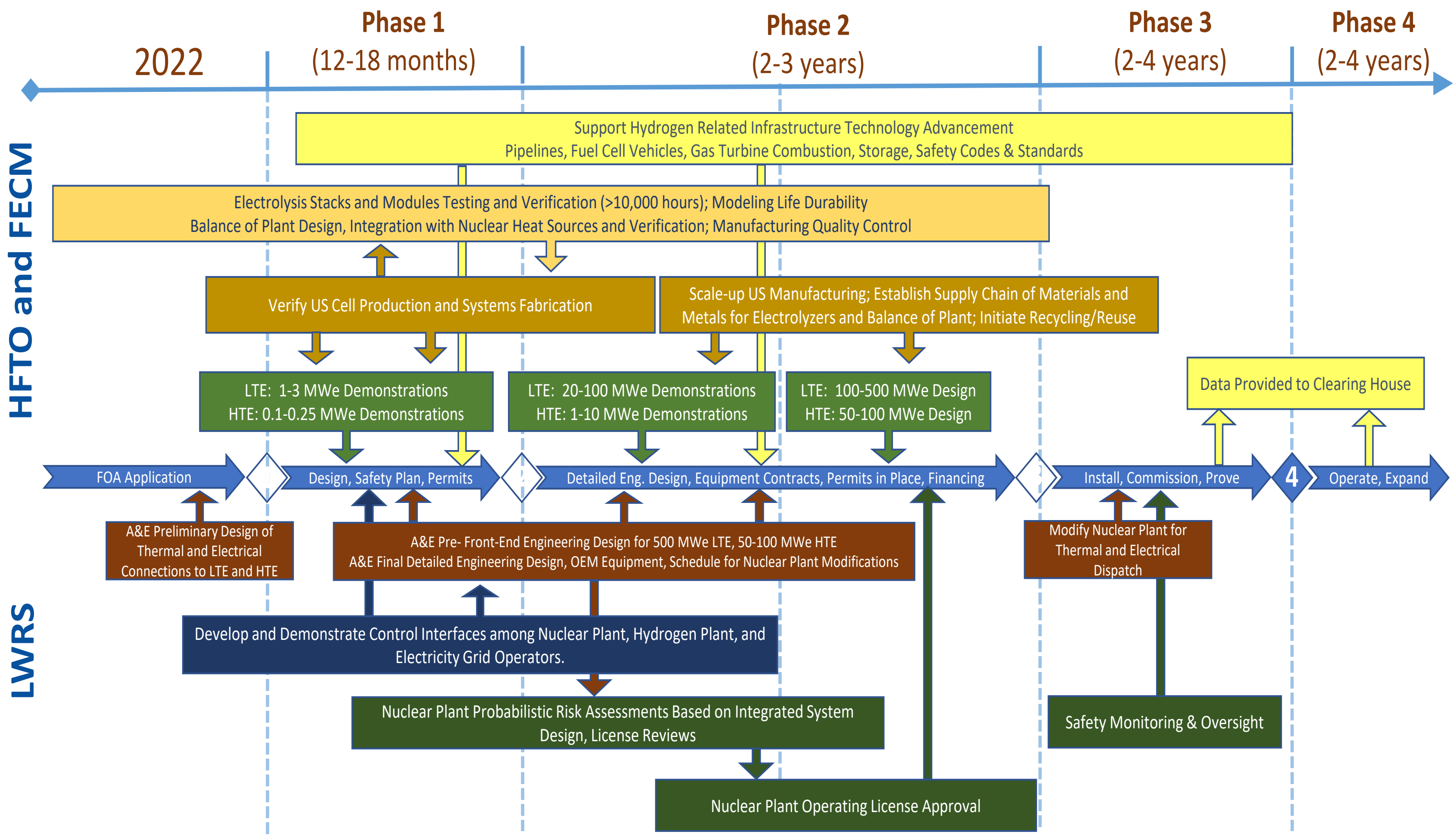

Figure 12. Approximate schedule for R&D and pilot demonstration projects leading up to the first commercial project

The 2022 BIL, officially known as the IIJA[e], provides up to $8 billion to help establish Regional Clean Hydrogen Hubs over the next 5-6 years. This Bill is key to addressing several barriers that must be addressed for many nuclear reactors to implement hydrogen production.

To qualify as clean H_2, the life-cycle emissions of carbon dioxide (CO_2) of the H_2 produced must be less than 2 kg-CO^2e[f] per kg-H_2. At least one of these hubs must use nuclear energy for some fraction of the H_2 produced in a given region. The federal cost-share of up to 50% of the total project costs up to $1.25 billion should make it possible to realize a favorable return on investment for FOAK demonstration projects.

Technical and economic assessments of H_2 production by NPPs indicate that light water reactors (LWR) will be able to feasibly produce clean H_2 through water-splitting electrolysis for an nth-of-a-kind nuclear H_2 plant. This is based on, a H_2 plant that is built and integrated into an existing NPP when the price of electrolysis units is consistent with an established supply chain of materials and fabrication year-over-year. The BIL also intentionally includes $1 billion to help raise the technology and commercial-scale manufacturing readiness of electrolysis. The assumption is that several large-scale demonstration projects and the required manufacturing industries will make it possible to expand the leading projects at nth-of-a-kind economics.

Based on the preponderance of positive technology evaluations and preliminary safety assessments in an LWR, it should be possible by 2026 to support a commercial H_2 plant ranging from 100–500 Mwe for low-temperature electrolysis and approximately 100 Mwe for HTE. In the case of HTE, the NPP would also involve a heat transfer loop that would extract and deliver approximately 25 megawatts thermal (MWth) power via a secondary steam-to-steam heat exchange design or other exchange transfer media capable of producing dry steam for an HTE electrolysis plant.

For H_2, the BIL aligns with the Hydrogen Shot priorities by directing work to reduce the cost of clean H_2 to $2/kg by 2026. It requires developing a national strategy and roadmap and includes $9.5 B in funding for clean H_2 in the following thrusts:

- $1B over 5 years for electrolysis RD&D.[g]
- $0.5B over 5 years for clean H_2 technology manufacturing and recycling R&D.[h]
- $8B over 5 years for at least four regional clean H_2 hubs.[i]
- Includes working with the U.S. Environmental Protection Agency to develop an initial clean H_2 production standard that provides ≤ kg CO_{2e} per kg H_2.[j]

A Notice of Intent to finance H_2 hubs was formally issued on June 6, 2022, by the DOE-Office of Clean Energy Demonstrations in collaboration with the Hydrogen and Fuel Cell Technologies Office (HFTO).[k] The general plan was presented at the HFTO Annual Merit Review and summarized in . The official Funding Opportunity Announcement (FOA) is anticipated around October 2022. It likely will request applications within 60–90 days. The following assumptions provide a general understanding for creating this Plan for scaling up nuclear H_2 projects:

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e H.R.3684 - 117th Congress (2021–2022): Infrastructure Investment and Jobs Act | Congress.gov | Library of Congress.

f CO_{2e} refers to a unit of greenhouse gas reductions equivalent to the impact of CO^2. As a reference, the conventional process of producing hydrogen by steam methane reforming emits 7–10 kg CO_2 per kg H_2 produced depending on the process design and accounting for life-cycle emissions associated with NG production.

g Sec. 40314 (EPACT Sec 816).

h Sec. 40314 (EPACT Sec 815).

i Sec. 40314 (EPACT Sec 813).

j Sec. 40314 (EPACT Sec 814).

k NOI (DE-FOA-0002768), visit: https://oced-exchange.energy.gov/.

- October 2022 – December 2022. Phase 1: Proposals development and submission.
- January 2023 – December 2023. Phase 1: Detailed plans for H_2 hubs, including preliminary engineering and design and project plans.
- January 2024 – December 2025. Phase 2. Detailed engineering design, permits, and financing.
- January 2026 – December 2028. Phase 3. Construction and project startup and commissioning.
- January 2029 – December 2030. Phase 4. Project ramp up and operations.

☆ Initial Application

◇ Go/No-Go Decisions

	Application	Phase 1: Detailed Plan	Phase 2: Develop, Permit, Finance	Phase 3: Install, Integrate, Construct	Phase 4: Ramp-Up & Operate
	Pre - DOE funding	**Up to $10M DOE Funding , Non-Federal Cost Share ≥ 50%, 12-18 Months**	**TBD DOE Funding, Non-Federal Cost Share ≥ 50%, 2-3 Years**	**TBD DOE Funding, Non-Federal Cost Share ≥ 50%, 2-4 Years**	**TBD DOE Funding, Non-Federal Cost Share ≥ 50%, 2-4 Years**
Engineering, Procurement, Construction, Operations	• Conceptual Design • Technical Readiness • Project Schedule • Total Project Cost Estimate	• Engineering & Design Documents • Technical Maturation Plans • Integrated Project Schedules	• Mature Engineering & Design • Technical Risk Management • Execution ready schedule & cost estimate, PM Tools • Operations Plan	• Ongoing execution reporting • Interim Go/No-Go reviews	• Ongoing performance Reporting • Technical risk updates, tracking • Final TPC accounting
Business Development & Management	• Business Strategy • Team Description • Workforce Plan • Finance Plan • Market potential analysis	• Project Management Plan • Risk Management Plan • Financial modelling • Site selection	• Finalized project structure, management, financing • Ongoing risk management • Final legal, workforce, procurement agreements • Feedstock & Offtake Plans	• Ongoing execution reporting • Ongoing risk management	• Updated financial analyses • Revised growth plans • Updated Risk Management
Permitting & Safety	• Safety history/culture description • Regulatory approval timeline overview	• Initial Hydrogen Safety Plan (HSP) & Site Safety Plan • Physical, Information, Cyber Security Plans • Environmental & Regulatory preparations	• Execution ready HSP and security plans • Permits & approvals in place for construction	• Ongoing permit, environmental, safety reporting • Permits & approvals in place for operations	• Ongoing permit, safety, and security reporting
Community Engagement & Impacts	• Initial Equity Plan addressing community engagement, Justice40, community consent or benefits agreements, job quality, workers rights, etc.	• Stakeholder engagement and Community Consent or Benefits Agreement drafts	• Finalized Equity Plan, Agreements • Community development targets identified, tracking plans	• Ongoing reporting on Equity Plan activities	• Revised community engagement plans for operations • Ongoing reporting and evaluation
Technical Data & Analysis	• Lifecycle Analysis • Techno-economic Analyses	• Project Production Model • Updated Lifecycle and Technoeconomic Analysis	• Final Lifecycle & Technoeconomic Analyses • V&V and Project Completion Testing Plans	• Periodic analyses updates • V&V data collection • Project completion testing and performance ramp V&V	• Validated performance model • Finalize lifecycle and technoeconomic analyses • Dissemination of analyses, lessons learned

Figure 13. H_2 hub tentative project phases and deliverables [11].

2.5.4 Current Fleet Demonstrations

Four DOE awards have been made under the DOE-FOA-0001817 to U.S. nuclear utility applicants to demonstrate the production of H_2 at NPPs. These projects have been highlighted at many public meetings, as well as the HFTO workshops on H^2@Scale and the Program Annual Merit Review. Amendment 014 to this solicitation was issued on August 8, 2022, requestion proposals to fund additional projects related to nuclear-hydrogen production and utilization demonstrations. The following provides a summary of the projects awarded up to this date.

Constellation

This project will explore the potential benefits of onsite H_2 production at Nine Mile Point Nuclear Station in Oswego, NY. The electrolyzer will be installed and operations are expected to begin in 2022. Constellation is partnering with Nel Hydrogen, ANL, INL, and NREL to demonstrate integrated production, storage, and normal usage at the station. A polymer-electrolyte membrane (PEM) electrolyzer will be installed and use the station's existing H_2 storage system and supporting infrastructure. The project will generate H_2 for colling the power plant turbine/generator set and for limited uses in the commercial and transportation sector.

Energy Harbor

Energy Harbor will install an low-temperature electrolysis (LTE) H_2 generation pilot plant unit at Davis-Besse Nuclear Power Station. The expected result of this project is to have a fully functional and operating H_2 generation skid that has been integrated into the normal operating routine of an NPP. The electrical switchgear for the electrolyzer was installed in August 2022.

This project includes technical-economic assessments for the potential hybrid systems at plants operated by Arizona Public Service (APS) and Xcel Energy, Inc. These studies, along with pre-front-end engineering design input from the collaborating utilities, will be used to produce reports to the senior offices of APS and Xcel Energy stating the business case for undertaking commercial-scale hydrogen production projects.

Xcel Energy

Xcel Energy will install and operate a 200+ kW high-temperature electrolysis module at the Prairie Island plant in the Minneapolis/St. Paul region and operate that system for a few hundred hours. Xcel Energy is working with Sargent & Lundy to design and execute a thermal connection to supply steam for H_2 production. Xcel Energy is responsible for the essential site preparations. The 200+ kWe HTE system will be supplied by a U.S. company.

The outcomes of the project will include: (1) the demonstration of thermal energy extraction at greater than 40 kWth from an NPP; (2) demonstration of efficient production of clean H_2 production using nuclear energy; (3) verification of reference U.S.-based HTE system design; (4) support for U.S. manufacturing and technology in H_2 production using nuclear energy; (5) simulations of HTE system performance at 200-MWe scale; and (6) engineering design for thermal energy extraction from the Palo Verde nuclear station, indicating the general applicability of project results.

Arizona Public Service

In a collaborative effort with Pacific Northwest Hydrogen LLC, INL, the NREL, and other participants from academia and industry, APS intends to demonstrate specific end-uses of H_2 produced from carbon-free nuclear power. The project will demonstrate the optimization and economic value of H_2 production as a vector for electric power storage, and as a feedstock for the synthesis of liquid hydrocarbons. Approximately 8 tons of H_2 will be produced daily using a 20-MWe PEM electrolyzer located at the APS Saguaro Power Plant north of Tucson with electricity that is dedicated from the Palo Verde plant and distributed on APS transmission lines. H_2 generated during periods of low grid demand will be stored and later co-fired in a natural gas (NG) turbine at the Saguaro Power Plant during periods of high demand. In addition to providing a responsive load to obviate the need for daily nuclear curtailment, blending H_2 with NG provides a cost-effective bridging strategy for existing turbines, with longer-term replacement by large turbine units fully capable of 100% H_2 operation as the U.S. transitions to a fully decarbonized future.

The project will also demonstrate the synthesis of hydrocarbons from produced H_2 and the reduction of an onsite source of CO_2 to CO. Conversion of the H_2 and CO_2 to liquid hydrocarbons will be completed at small-scale to inform the designs for large-scale production and to assess the economics for the commercial-scale production of high-value products like jet fuel and diesel. Fuels derived from carbon-free nuclear power can make large strides toward the difficult task of fully decarbonizing transportation.

2.5.5 EPRI Nuclear Beyond Electricity Initiative

In 2020, EPRI announced a broad initiative referred to as the Low-Carbon Research Initiative (LCRI) as well as the Nuclear Beyond Electricity Initiative (or NBE) [12]. LCRI is co-led with the Gas Research Institute and has the purpose of analyzing and developing clean energy markets. Nuclear Beyond Electricity will specifically focus on the role of nuclear energy relative to the value proposition of LCRI. FPOG leads are engaging with EPRI on both initiatives to leverage the outcomes and industrial collaborations that will be established. Table 3 below shows some of the EPRI objectives and their relevance to FPOG operations.

Table 3. EPRI Power Plant issues matrix relevance to Hybrid FPOG

EPRI General Concepts for Transitioning NPPs for Flexible Service	Possible Strategy to Mitigate Relevant Issue or Impacts (not all-inclusive of EPRI matrix)	Relevance to Dedicated or Hybrid FPOG Operations (grid plus industrial user)
Innovative Power Output Control Options / Revised Nuclear Power Plant Mission	• Limit flexibility to avoid the risk of fuel damage; operate during periods of low or negative wholesale electricity pricing • Grey rods enabling 100-30-100 flexibility are not used in U.S. reactors • Boric acid addition for core moderation has end-of-cycle restrictions and generates waste • Steam bypass around the power turbines results in high-heat rejection to condenser and possible thermal inertia that may perturb core heat rate (i.e., insufficient cooling) • EPRI initiative- “Nuclear Beyond Electricity”	• Dedicated and Hybrid FPOG provide optimized solutions for the sale of nuclear energy • Dedicated and Hybrid FPOG applications have the goal of keeping the heat rate near the design capacity to maximize the sale of energy to avoid fuel damage • Hybrid FPOG operation could include boric acid coolant cleanup for continuous recycling of water and reuse of boron • Dedicated and Hybrid FPOG designs will likely involve modifications to the steam bypass and will provide added flexibility in case of a fault by the industrial energy user • Nuclear Beyond Electricity is consistent with the proposed Dedicated and Hybrid FPOG alternative
Core Management Considerations	• Enhanced fuel or core design for 100-30-100 flexibility • Enhanced core monitoring and fuel conditioning and	• Some EPRI Concepts are relevant • Dedicated and Hybrid FPOG applications will avoid frequent core management considerations; new

EPRI General Concepts for Transitioning NPPs for Flexible Service	Possible Strategy to Mitigate Relevant Issue or Impacts (not all-inclusive of EPRI matrix)	Relevance to Dedicated or Hybrid FPOG Operations (grid plus industrial user)
	deconditioning guidance followed for 100-80-100 flexibility • PWR crud deposition risk mitigation through model benchmarking	procedures will likely be needed, and plant operators may require additional training to ensure core conditions will not be impacted by any single or multiple faults by the FPOG applications
Reactor System Considerations	• PWR core internals and pressurizer surge line impacts for 100-30-100 flexibility • BWR channel bowing for 100-30-100 flexibility • Long-term thermal fatigue monitoring for 100-80-100 flexibility • Long-term secondary side deposit management	• (See above)
Balance of Plant Equipment	• Increased turbine/generator wear limitation prescribed • Potential SCRAM increase • Strategies to handle increased pump(s) maintenance • BWR remote vibration monitoring	• EPRI Concepts are relevant • Dedicated and Hybrid FPOG operations must account for overall system costs such as turbine/generator wears and increased pump maintenance costs in economic assessments • SCRAM issues will be addressed with PRA adjustments for FPOG
Chemistry Considerations	• Tighten and ensure PWR pH control/H_2 control • Improve water management capacity and plan • Implement an effective boron regeneration system	• Chemistry of coolant not impacted • EPRI considerations are relevant; main steam chemistry contamination and scale could be higher
Radiological and Environmental Considerations	• The long-term impact of FPOs on Source Term and Dose • Enhanced radiation field data collection	• EPRI concepts are relevant
Organizational and Programmatic Considerations	• Scenarios for cost-benefit analysis of FPOs • Conduct pilot operations of pilot plant operations	• TEA are being prioritized and executed by the FPOG Pathway • Pilot plant testing and confirmation of FPOG interfaces are included in this Technical Program Plan • Pilot plant operations is deferred to DOE Funding Opportunities for private/public partnership R&D and demonstrations

2.5.6 Nuclear Regulatory Commission

The development of the scientific basis to support Subsequent License Renewal beyond 60 years and facilitate high-performance and economical operation of the existing LWR fleet over the extended period is the central focus of the LWRS Program. Therefore, coordination with both industry and the NRC is needed to ensure a uniform approach, shared objectives, and efficient integration of collaborative work for the LWRS Program. This coordination requires that articulated criteria for the work appropriate to each group be defined in memoranda of understanding that are executed among these groups.

NRC has employed a memorandum of understanding with DOE, which specifically allows for collaboration on research supporting the long-term operation of NPPs [13]. Although the goals of the NRC and DOE research programs may differ, fundamental data and technical information obtained through joint research activities are recognized as potentially of interest and useful to each agency under appropriate circumstances. Accordingly, to conserve resources and avoid duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost-sharing may be done in a mutually beneficial fashion.

2.5.7 Enabling Industrial and Engineering Companies

Ultimately, it will be the role of a commercial project venture and engineering and plant construction (EPC) companies that will provide the designs and complete the tie-in of NPPs to industrial processes. It is appropriate for the FPOG Pathway activities to engage architecture engineering firms to validate plant designs used for TEAs and FEED studies that are completed to identify the best options for FPOG applications. It is also imperative that Pathway engage technology providers in the FEED studies to ensure the technical feasibility of FPOG concepts. As a collective vision for FPOG options is understood by the chemical industries and technology providers, demonstration projects can be executed as partnerships are established based on the outcomes of the R&D conducted by the FPOG Pathway to evaluate the options.

Because FPOG applications necessarily entail early demonstration of the control systems and human factors that will enable an NPP to dispatch electrical and thermal energy to a non-electrical user, it is essential to demonstrate the technical feasibility, safety, and process control assurance of specific FPOG concepts and unique application prior to implementation and scale-up at an NPP. Technology providers can support these efforts by reviewing and attending testing that is completed using the capabilities of INL or by providing model simulations that can be incorporated into the nuclear plant simulators that are used to verify operating concepts.

An engagement strategy for manufacturing industries and technology suppliers will be conducted with the following tasks:

- Engage the support of commercial and university developers of NPP simulators.
- Engage relevant key technology providers in the design of FPOG physical and controls connections development and testing.
- Facilitate open communications, including stakeholder engagement meetings and forums where FPOG operating concepts can be discussed and where partnerships for project execution can be realized.
- Provide concepts for Small Business Innovative Research that lead to the development of enabling technologies that do not otherwise exist in commercial markets. An example is an energy storage media that may support stock-and-flow energy that is needed to satisfy hybrid FPOG applications.

2.5.8 University Engagement

University engagement through the Nuclear Energy University Program is considered an important part of the FPOG Pathway. As such, projects will be identified that will help advance concepts or innovations that will enable FPOG applications. This includes the development of computer models and simulators, plant control concepts, and novel technologies that can eventually be commercialized. When certain critical needs arise, the Pathway activity leads will contract directly with university faculty to support those studies that are critical path which the professors and graduate students and the university capabilities may directly aid in solving.

In FY 2022, an award was made to the University of Tennessee at Knoxville under the 2022 Consolidated Innovative Nuclear Research (CINR), Integrated Research Projects (IRP).[1] The title of this multi-university project is: "Developing the Technical Basis and Risk Assessment Tools for Flexible Plant Operation." The project description synopsis states: "This proposal addresses challenges related to operations and maintenance, human factors, and risk assessment to enable FPOG. Nuclear energy is potentially well suited to flexible missions, including efficient and cost-effective co-generation with industrial heat applications. There are inherent challenges and regulatory concerns associated with the expanded application of the existing fleet of LWRs to support on- and off-grid applications."

3. FY 2023 ACTIVITIES AND 5-YEAR PLAN

An approximate timeline of general activities is shown in . The goal is to raise the TRL of the integrated hardware and operational schema. The Pathway Technical Plan is shown for 5 years through FY 2027. However, each configuration may entail different integration hardware, instrumentation, and control approaches as a function of the selected subsystem technologies. Once demonstrated for current fleet plants, the relative scale of the technology gap for next-generation small modular reactors and other advanced reactors may be significantly reduced.

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[1] FY 2022 Integrated Research Projects Awards. https//neup.inl.gov/SitePages/FY22_IRP_Awards.axp

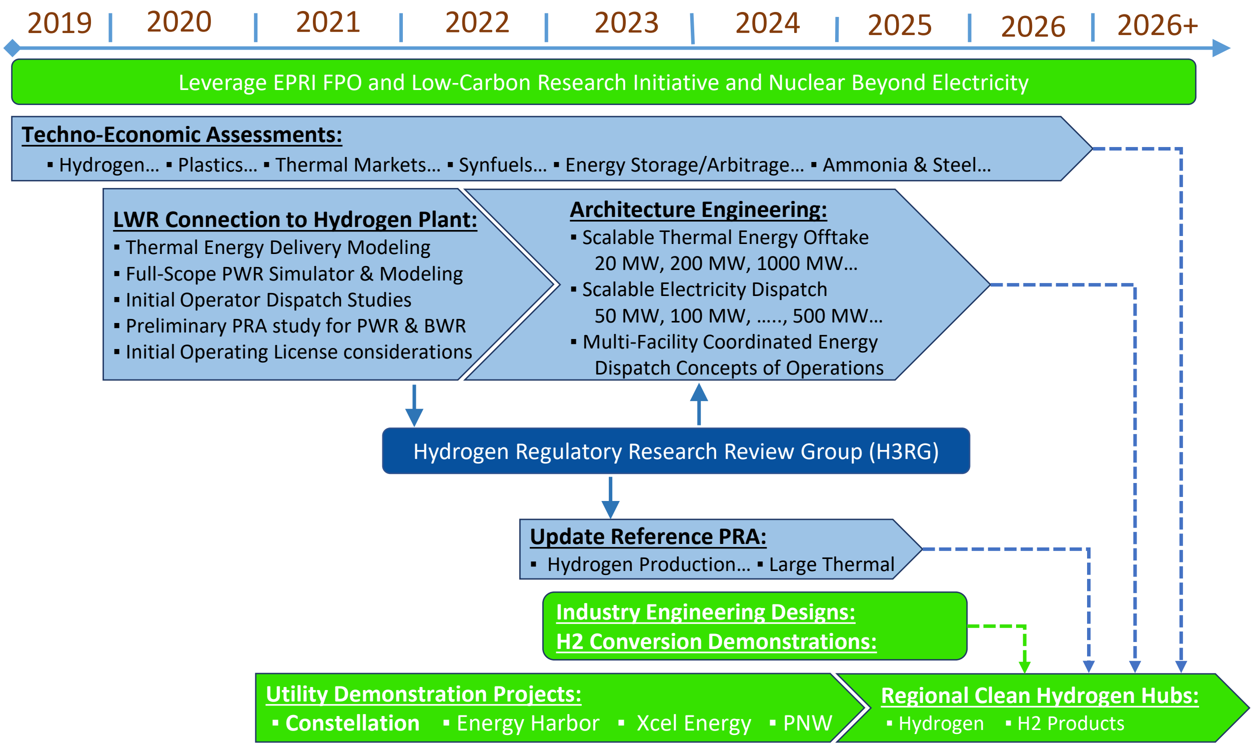

Figure 14. FPOG Pathway R&D activities and program coordination (updated September 2021).

3.1 Design and Economics R&D Activities

3.1.1 Summary of Progress and Accomplishments

Given the rapidly growing interest in clean hydrogen, initial TEAs have mainly focused on the potential to produce and sell hydrogen in local markets as well as derivatives that can be produced from hydrogen. The philosophy is hydrogen can begin with an electrical connection to the NPP switchyard, and then move to a thermal and electrical connection to the NPP for HTE in the future as the technology is proven and an understanding is gained on how to extract and deliver heat (as steam) to the electrolysis plant. The following list recaps the progress made to date to understand the case for hydrogen production with nuclear plants:

- Technical and economic assessments have proven nuclear plants will be able to produce hydrogen at scale for under $2/kg when the cost of electrolyzers is reduced through high-volume manufacturing. This will be true when just a few nuclear plants make the decisions to produce hydrogen. It will also be true when Regional Clean Hydrogen Hubs are proven with the federal stimulus of $8 billion to create these hubs and $1 billion to prove advanced electrolysis and to help stand up the manufacturing facilities.
- PEM electrolyzers (so-called LTE) only require an electrical input and will be able to produce hydrogen for under $2.5/kg-$H_2$. There is a small but growing market for this hydrogen to power fuel cell vehicles and data centers. The challenge is providing low-cost hydrogen storage and delivery systems, which are going to take time to implement.
- Solid oxide electrolysis cell (SOEC) steam electrolysis (so-called HTE) is more efficient and will be able to produce hydrogen for under $2/kg, possibly for as low as $1.5/kg in the near future. This requires about 20 MW-thermal for 100 MW-electrical offtake. For a generalized case of a 1 GWe

NPP, this implies about 7% of the total thermal energy from the NPP would need to be diverted to an HTE sized to match the electrical output of the NPP.

- One approach to HTE is to scale-up to 100 MWe/20 MWth in the next 5 years, and then move up to 500 MWe/100 MWth, and on to 1,000 MWe/200 MWth.
- Technical and economic assessments completed for Energy Harbor and Xcel indicate a large market for clean hydrogen may be possible for: (1) ammonia/urea fertilizer, (2) refining petroleum; (3) production of replacement fuels such as diesel, jet fuel, and motor gasoline that are fungible with existing transportation fuels markets.
- Hydrogen markets will be boosted by the $1 billion investment by the federal government in electrolysis technology manufacturing and verification and the $8 billion federal investment for Regional Clean Hydrogen Hubs. At least one of the hydrogen hubs are required to include nuclear energy that will spur LWR-hydrogen projects.
- Technical and economic assessments indicate hydrogen generation and storage for power production is better than utility-scale battery storage in the Southwest when the duration of storage approaches and exceeds about 8 hours.

The FPOG Pathway has also evaluated the plastics and polymers markets and synthetic fuels production. Thermal energy use by industry has also been evaluated. When considering industries, which consume about one-third of the energy used in industrially developed countries, energy is divided into steam and electricity duties and process heating duties. LWRs are capable of suppling over 80% of industrial energy use in the United States [14]. The objective is to match the large, concentrated source of energy available from LWRs with large industrial users (or a closely located complex of energy customers). Niche markets will not likely change the outlook for nuclear plants. Therefore, it is wise to answer some high-level questions:

3. What is the resource potential? The FPOG platform is collecting market data and working with companies and economists that understand developments and opportunities for growth in industrial markets. The objective is to identify the location, scale, and accessibility of the candidate industrial product markets, as well as process feedstocks that are available near each nuclear plant. This includes existing industrial markets that could benefit from nuclear energy, as well as future plant potential. For example, refineries and chemical industries require a large amount of energy. In regions where wood is purposely grown, wood products and pulp and paper industries are prevalent large users of energy. Agricultural regions provide feedstock for ethanol production which requires thermal energy to distill alcohol from water. These plants emit high-purity CO_2 that can be used as a feedstock to produce formic acid, transportation fuels, and lubricants. Minerals mining and conversion to intermediate chemical or metals are located near some nuclear plants in the United States.

   The project leads are evaluating opportunities for market synergy with NG. Two opportunities that stand out are the plastics and polymers industry and the gas supply industry. An electrochemical process using NG to produce ethylene and hydrogen is under development that may provide a disruptive approach to producing polymers using NPPs. Second, hydrogen can be added to NG pipelines to pass the clean energy produced by NPPs on to power generation turbines or industrial fired heaters.

   An understanding of transportation systems is taken into consideration for the growth of an existing industry or the addition of new industries. Short of a new national strategy, FPOG opportunities must have a clear path to open markets that are able to absorb or ship the products without significant additional expenses.

4. Is there a technology potential? How can nuclear energy be effectively applied to industrial markets? How can thermal energy be supplied to industrial users? To answer these questions, the FPOG Pathway is completing case-specific engineering studies. Certain FPOG applications will require the FPOG applications, such as hydrogen plants to cycle; hence, plant design and evaluations are being conducted to prove the feasibility of variable plant loads and operating cycles. The limitations of transient operations are being captured by physics-based thermal hydraulics and transient heat transfer models, chemical reactor kinetic models, and separations unit operations models. The impacts of thermal and electrical cycling needs are being evaluated for the nuclear plant as well as the energy delivery systems and the industry processes.

5. What is the impact of thermal power extraction to NPP systems? FPOG is applying standard tools and codes developed for NPPs to simulate nuclear plant operations, including full-scope simulation of the nuclear power plant systems and RELAP5-3D simulations [15] of the thermal-hydraulic systems, for new thermal energy delivery systems that are coupled to process models that pick up the thermal energy.

6. What is the economic potential? The value proposition of a dedicated FPOG option is straightforward and is being evaluated with case-specific process design models that provide a close approximation of the capital and operating costs of a plant as discussed in Appendix A. A discounted cash-flow model is then used to calculate the NPV, return on investment, or IRR for the project.

   The FPOG Pathway is completing pre-front-end engineering plant design studies and leveraging previous INL codes and capital equipment costing data to estimate capital cost and operating costs expenses.

   For hybrid FPOG applications, the economic potential requires a more sophisticated approach to calculating the NPV and return on investment/IRR. A projection of the local grid market is essential. Next, an optimization model is needed to optimally scale the hybrid plant to account for the dynamics of market transactions that will maximize the profits for the collaborating industries. The Pathway is developing plugin tools that leverage the RAVEN model [16, 17] to complete case-specific optimization for both regulated and deregulated markets.

7. What is the true market potential? While it is possible to show a new project has positive indicators that should incentivize an energy company or investment institution to fund a project, it is important to compare the project to other alternatives that may be even better. FPOG analysis looks to compare each case with the conventional processes as well as other emerging technologies and options. For example, the pathway is carefully comparing the elasticity of hydrogen production via steam-methane reforming (SMR). Similarly, it is important to compare the cost of heat production with NG combustion as shown in Appendix A.

   It is important to understand the electricity market well enough to project annual revenues and the FPOG operating paradigms. An assessment of renewable energy growth and production characteristics is needed to forecast the cost of electricity on short time scales for the life of proposed new projects. The FPOG Pathway is turning to the NREL and EPRI ReEDs and US-REGEN models respectively to help determine trends in the growth of renewable energy expansion. It is also important to consider the NG market which is driving the current retirement of coal plants in favor of NG combined cycle plants. Energy storage technologies also need to be evaluated to understand how FPOG may benefit along with those emerging opportunities and cost projections. The Pathway is drawing on the expertise of the ANL and EPRI for energy storage systems design and cost projections.

   Finally, because regulatory policy for low-emissions energy sources is becoming a reality in many states, the FPOG Pathway is conducting sensitivity studies to show the cost-benefits of nuclear energy in industrial product markets. ANL is supporting the Pathway with market information on the value of clean fuels credits and life-cycle analysis (LCA) of GHG and other pollutant emissions reduction that will be valued increasingly in the near future.

By the end of FY 2022, the Pathway has completed the following milestones addressing the value proposition of FPOG (Table 4). In Fiscal Year 2022, an evaluation of the business case for producing synthetic fuels via Fischer-Tropsch was undertaken. The Fisher-Tropsch process can make use of the hydrogen produced by an LWR when combined with CO_2 that can also be captured from an industrial source using NPP energy. A process model and assessment was completed by ANL under the DOE-NE Integrated Energy Systems program [18]. Two complementary milestone reports completed by FPOG evaluated the cost of transporting CO_2 from various sources in proximity to select NPPs. Analysis was performed to determine the cost of transporting CO_2 from the distributed sources to the centralized fuel synthesis plant as a function of the synfuel plant capacity and corresponding CO_2 demand. The energy from the NPPs was used to provide power to the electrolysis plant and the fuels synthesis plant. and shows the sensitivity of the price of fuel production to the cost of hydrogen and CO_2.

Figure 15 and Figure 16 show the sensitivity of the price of fuel production to the cost of hydrogen and CO_2.

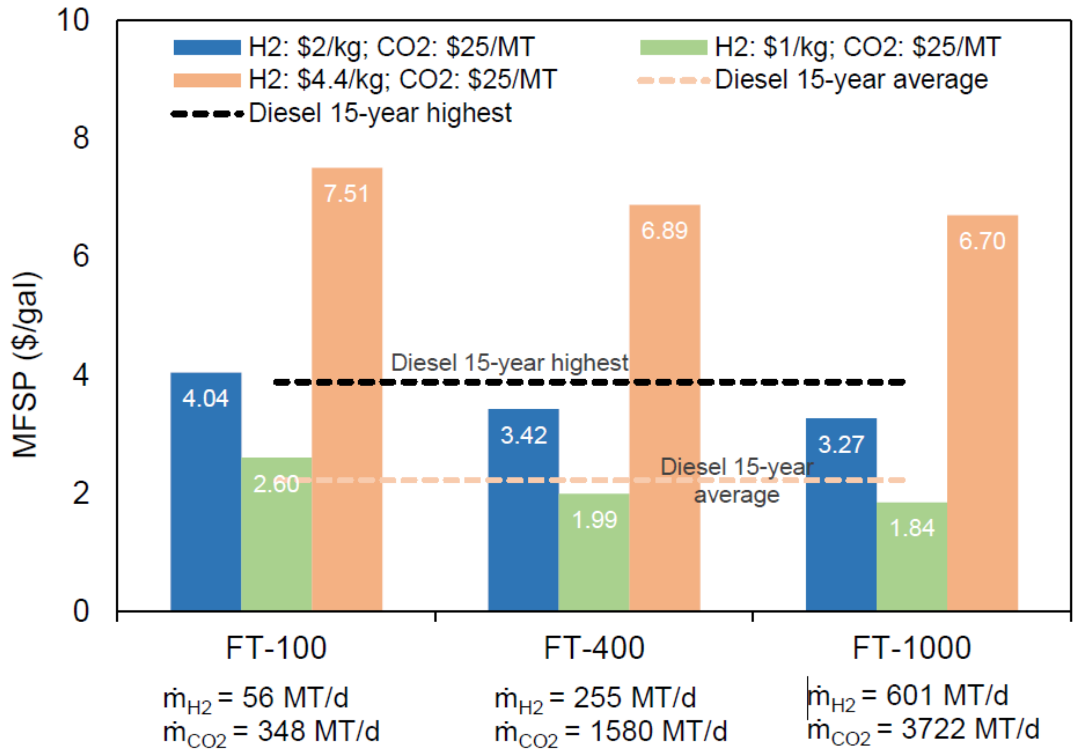

Figure 15. Production cost of Fischer-Tropsch (FT) fuel at different plant scales and H_2 prices. FT-100, FT-400 and FT-1000 refer to the different scales of 100 MW, 400 MW, and 1000 MW of combined power requirements for the high temperature electrolysis and FT plant needs.

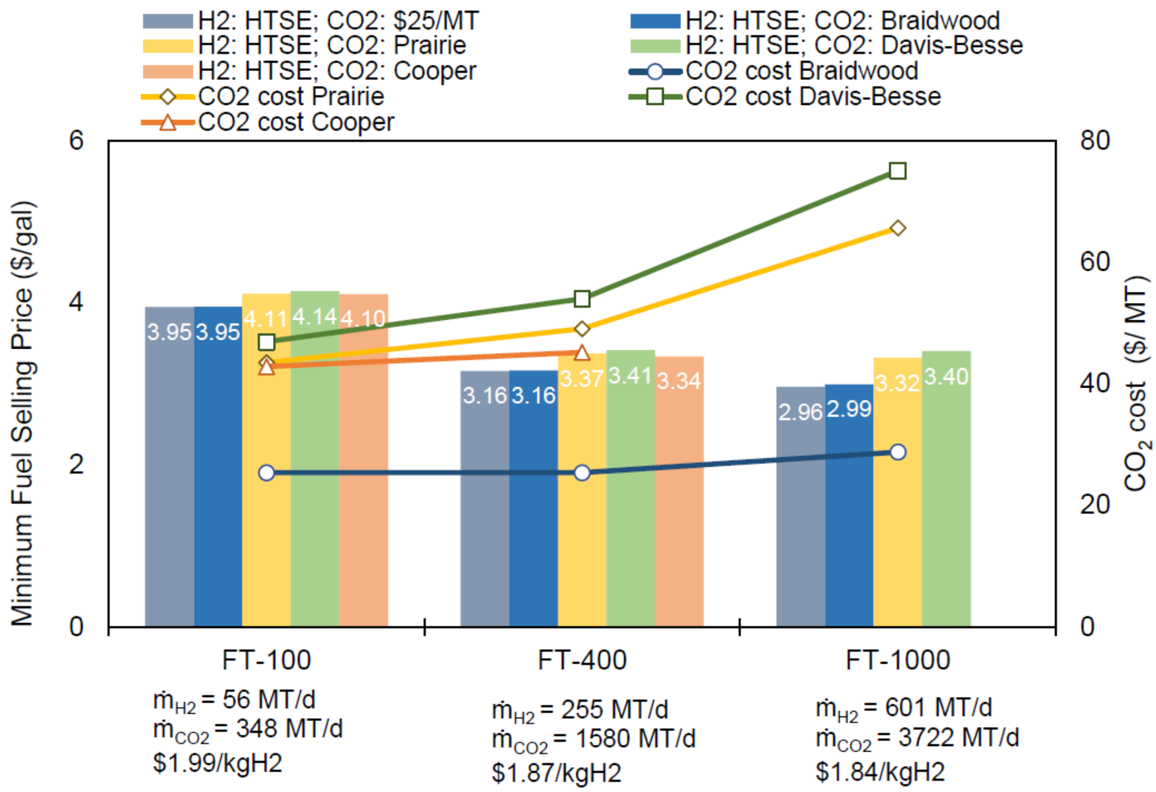

Figure 16. Influence of NPP location and CO_2 price on the production of FT fuel.

A case study analysis was performed to evaluate nuclear-powered synthetic fuel production in the Midwestern United States. A FT fuel synthesis plant design was used as the basis for the analysis. The FT plant design was configured to produce a product slate consisting of diesel fuel, jet fuel, and motor gasoline blend stocks from carbon dioxide and hydrogen feedstocks. The CO_2 feedstock for the FT plant was assumed to be sourced from biorefineries in the region around the Midwest LWR NPP. The analysis specifies that power from the LWR is used to produce hydrogen via HTE and to operate the FT synfuel production plant.

Capital costs were estimated for the FT plant while capital costs for the electrolysis plant were based on previous INL studies. In addition to labor and maintenance costs, operating costs include the energy costs for hydrogen production and FT plant operation as well as costs for carbon dioxide feedstock transport. The primary revenue streams are associated with sales of synthetic fuel products. Market analysis performed by the project identified that in the coming years synthetic fuel product prices are expected to command a price premium over conventional petroleum-based fuels and that customers may be prepared to pay several times more for clean synfuels than for conventional petroleum-based fuels.

The economic analysis calculated the NPV for cases involving steady-state synfuel production for comparison with the NPV for a business-as-usual case in which NPP continues to sell only electric power to the grid. The reference synfuel production case considered a scenario in which the electrolysis and synfuel plants utilized a combined electrical load of 400 MW-e from the LWR with the balance of the LWR power output being sold to the electric grid. The reference case specifies that electricity from the LWR is sold to the electrolysis and FT plants at a price equal to the recent average locational marginal price (i.e., the wholesale price) at the grid node where the NPP is located. The reference case included a synthetic fuel price premium of three times the price of conventional fuels projected in the U.S. Energy Information Administration 2021 Annual Energy Outlook minus federal taxes, state taxes, as well as marketing and distribution costs. The economic analysis also considered a case in which the Inflation Reduction Act of 2022 clean hydrogen production credits of \$3.00/kg and FT synfuel production credit of \$1.67/gal (\$1.25/gal base credit plus \$0.42/gal additional credit for 92% LCA reduction in CO_2 emissions) were incorporated into the revenue stream for the first 10 years of operation. The reference synfuel production case including the production tax credits specified in the 2022 IRA resulted in a NPV of approximately \$2 billion above the NPV for the business-as-usual grid power sales only case. The economic analysis suggests that price premiums for synthetic fuels combined with production tax credits from the Inflation Reduction Act of 2022 provide a market environment that would lead to considerable economic potential for near-term deployment of a nuclear based synfuel production plant (). The reference case corresponds to a 1000 MW Synfuel IES, synfuel prices equal to those projected for conventional fuels in the EIA 2022 AEO, residual electrical power sold to the grid at a price consistent with the historical LMP at the NPP node, and inclusion of 2022 Inflation Reduction Act clean hydrogen production tax credits.

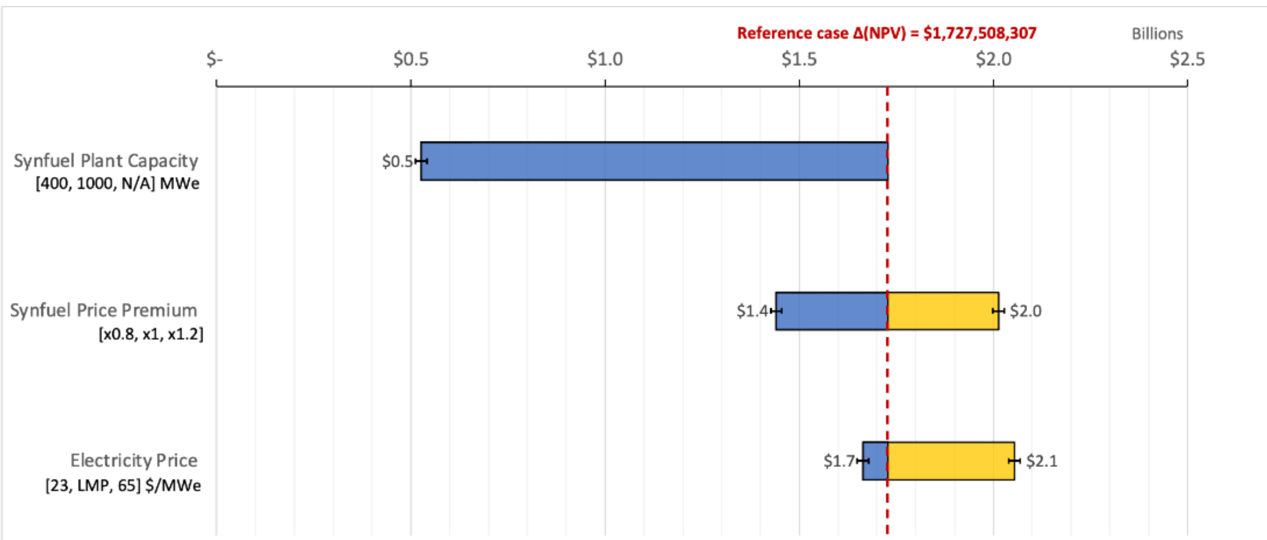

Figure 17. Nuclear based synfuel production sensitivity analysis. [20]

Table 4. Technical and economic assessments accomplishments through FY 2021

Activity	Outcomes and Significance	Report or Documentation
Techno-economic assessment (FEED study) of Non-electricity markets for nuclear reactors in the Upper Midwest U.S.	• Hydrogen production is a viable and competitive market path; current and future markets are growing in this region of the country; Markets may commence with low-temperature electrolysis and grow to large-scale plants providing hydrogen from the. • Hybrid hydrogen generation is feasible and can provide advantages to grid operations. • Polymers can be competitively produced with a novel electrochemical technology when this technology matures as projected in 5–7 years. • Large volumes of CO_2 can be delivered from ethanol plants to a synfuels plant at a cost of around $15/ton. This warrants a detailed evaluation of syngas production for various industrial processes.	INL/EXT-19-55090 August 2019
Detailed techno-economic (pre-FEED study) assessment of electrochemical ethylene production by ethane deprotonation	• Electrochemical ethylene and propylene production with LWR electricity and thermal heating will be disruptive to the market; by-product hydrogen is an advantage and additional source of revenue. • Process is more suited for a dedicated FPOG plant. • Polymer markets are increasing in the U.S.; surplus NG condensates, such as ethane and propane, provide impetus for a competitive U.S. domestic market. • 99% CO_2 emissions reduction will be an advantage to this process. • Report gives incentive to accelerate development of this process option. • Study outcomes need to be published and shared with petrochemical industries. • Further process improvement is possible with demonstration of membrane technology to separate ethylene from the product stream.	INL/EXT-19-56936 December 2020
Evaluation of scale and regionality of nonelectric markets for LWRs	• Begins a library of information relative to the demand market for nonelectric products in each region. • Study shows strong potential for dedicated or hybrid FPOG hydrogen and oxygen markets in the Minnesota area and other regions coinciding with the location of key nuclear plants in these regions; the strongest markets drivers for hydrogen are petroleum refining, heavy duty fuel cell vehicles, light duty fuel cell vehicles, and ammonia, respectively. Iron making and injection into the NG pipeline are not competitive with NG reforming unless CO_2 credits become significant.	INL/EXT-20-57885 March 2020

Activity	Outcomes and Significance	Report or Documentation
	• Hydrogen storage and transportation costs data are provided for project-specific economic assessments. • Provides the life-cycle CO_2 emissions assessment for LWR-hydrogen and derivative industrial products relative to conventional fossil fuels; a carbon tax of $25/ton could strongly incentivize NPPs to switch to hydrogen production. • Formic acid production can support a revenue-generating role in a multipurpose dedicated FPOG, but the world-wide market is small and could be met with a single NPP. • Validates polymer markets are growing and 73% of ethylene and polyethylene demand is within 700 miles of Monaca, Pennsylvania; several nuclear plants in the Eastern U.S. could support this market when electrochemical deprotonation of ethane is commercially viable.	
Identification of clean energy credits for production of hydrogen, steel, and ammonia using nuclear energy	• Production of steel and ammonia with electricity and hydrogen produced with nuclear energy could create zero-emissions credits (ZEC) or “low-carbon” green energy credits that can be used by obligated industry entities needing to reduce their carbon footprint. • Compares LCA of nuclear power generation to renewable energy and provides justification to maintain operation of NPPs to achieve federal and state decarbonization goals across multiple energy sectors. • Zero-carbon hydrogen can enable faster deployment of zero-emission hydrogen fuel cell vehicles in all zero-emissions vehicle (ZEV) states (including CA and NY), thus reducing the time to achieve ZEV goals in these states, and significantly reduce air pollution created by transportation the sector.	INL/EXT-20-58508 May 2020
Survey and assessment of thermal energy markets for LWRs; Calculation for the LCOH delivery to industrial users	• Preliminary modeling and LCOH estimates reveal LWRs can compete with conventional heating using NG burner even before clean energy credits are applied; steam, molten salts, and synthetic oil can cost effectively transport thermal energy up to 10 km from a LWR power plants. • An evaluation of industrial processes suitable for LWR thermal integration was completed for four categories of industry: (1) Electrochemical processes requiring heat input; (2) Exothermic thermochemical processes ($T > 350°C$); (3) Endothermic thermochemical processes with associated carbon capture ($T > 700°C$); and (4) Mature industrial demand sources with technical potential ($T < 200°C$).	INL/EXT-20-58884 June 2020

Activity	Outcomes and Significance	Report or Documentation
	• Concepts for a complex of thermal energy users comparable to the thermal energy output of an NPP are explored; the goal of an Energy Park is to manufacture multiple industrial products at competitive costs while using LWR energy to minimize greenhouse gas emissions.	
Analysis of LWR pathways for producing select synfuels with co-electrolysis of H^20 and CO_2	• The detailed study indicates there are significant environmental benefits to producing synfuels through a co-electrolysis route. However, the cost of fuels production is around $4.0/gallon of gasoline equivalent. • Inclusion of carbon credit at $100/tonne can make the process more competitive with petroleum fuels. GHG analysis indicates that the fuels have 92% less GHG emissions than petroleum fuels (diesel) and could conceivably qualify for the highest renewable identification number credit if approved by the Environmental Protection Agency (EPA). This, along with additional state incentives could bring an even higher potential credit for the LWR/CO_2 derived fuels.	INL/EXT-20-59775 September 2020
Comparison of energy arbitrage options for use with LWR Nuclear Power Plants	• Compares the cost of converting electrical power to three forms of energy storage that can be reconverted into electricity for arbitrage. • Hydrogen storage for electricity production is generally the lowest-cost option for storage periods exceeding 6 hours in duration or when energy storage is greater than approximately 1,500 MWh. • Battery storage is more cost-effective for short duration or power storage, or when energy storage is less than approximately 1,500 MWh. • Thermal energy storage does not appear to be cost-effective for energy arbitrage. • Liquid nitrogen production and refrigerant production may provide additional markets for nuclear plants. • Nuclear plants can provide the lowest-cost power for CO_2 capture and sequestration.	INL/EXT-21-62939 Revision 2 September 2021
Techno-Economic Analysis of Product Diversification Options for Sustainability of the Monticello and Prairie	• DOE-iFOA award study for Xcel Energy. Outcomes provide relevant projections for the cost of hydrogen production with nuclear supported electrolysis versus conventional SMR. • Study investigates hydrogen markets in proximity to the Prairie Island and Monticello nuclear plants. • The public report is listed and available on OSTI.	INL/LTD-21-62562 August 2021 INL/EXT-21-62563 Revision 1 November 2021

Activity	Outcomes and Significance	Report or Documentation
Island Nuclear Power Plants		
Development and application of a RAVEN Plugin tool for optimization of hybrid FPOG operations	• The foundational basis for HERON was established in which stochastic differential analysis of the NPV was completed for dispatching the Palo Verde Generating Station to the grid in response to the buildout of solar energy in the Southwest. • Based on the assumptions and inputs used in this analysis, we conclude that on average and in greater than 99.9% of scenarios, it is profitable to operate the Palo Verde Generating Station in a load-following mode.	INL/EXT-19-55614 September 2019
Application of HERON to optimize a Hybrid FPOG application for hydrogen production in a deregulated market	• Development of RAVEN plugin HERON completed for deregulated electricity markets; software quality assurance documentation completed. • Model used to explore the parametric optimization of hybrid FPOG operating conditions for optimizing nuclear plant revenues. • The significance and influence of energy storage is observed in the outcomes of this study.	INL/EXT-19-56933 December 2019
HERON public release	• Documentation of HERON application as a plugin to RAVEN to perform stochastic techno-economic analysis of gird-energy systems in a general approach completed. • Public access for use in analyzing LWR FPOG cases is provided.	INL/EXT-20-00464 July 2020
Evaluation of Hybrid FPOG Applications in Regulated and Deregulated Markets Using HERON	• RAVEN/HERON used to find optimal system size and component size given market conditions. Partnered with EPRI to model capacity expansion in Illinois. • Under varying assumptions of pricing (nuclear and Variable Renewable Energy), environmental policy (carbon tax, Renewable Portfolio Standards, nominal base case), and market regime (regulated and deregulated) evaluated IES based on H_2 market access, H_2 storage, and hydrogen production technology. • Differentiating market focus required building into HERON adjustment parameters to reflect each market type: (optimization parameters, generator bid prices, regulator choice versus market outcome, clearing price versus operating costs). Required study of economic drivers in each regime. • Results show that for: - Carbon tax, there is a strong benefit for an IES in a deregulated market. In a regulated market, not as strong of IES benefit because of limited nuclear buildout.	INL/EXT-20-60968 December 2020

Activity	Outcomes and Significance	Report or Documentation
	- Scenarios where nuclear was present but not running continuously, IES was highly beneficial. Scenarios where nuclear was either always deployed or never available then IES not beneficial. IES beneficial for nuclear between max and min power. - Scenarios with Renewable Portfolio Standards, nuclear was either not used or completely used with little midrange usage.	
A Technical and Economic Assessment of LWR Flexible Operation for Generation/Demand Balancing to Optimize Plant Revenue	• The HERON model was evaluated for performance and prepared for public release. It remains as an expert code; therefore, it can be turning over to a well-staffed software company while improvements are made to make it more user friendly. • HERON is now servicing LWRS TEAs and is proving useful to inform strategy decisions. • Concludes energy storage requires a significant differential in the market price to paydown the capital it will take. • For the assumptions invoked, thermal energy storage appears to be promising. Hydrogen storage is a close second and requires further analysis including an assessment of reversible solid oxide electrolysis and fuel cell systems. The hydrogen could also be burned in a gas turbine.	INL/EXT-21-65473 December 2021
Release of Public Version of HERON (HERON 2.0) with Improved Algorithms for the Treatment of Energy Storage	• Summarizes updates made to HERON 2.0. • Function-based Control Mechanics, by comparing a price-based dispatch strategy with the original perfect foresight baselines • Incorporates artificial control algorithm into the dispatch of IES components. • Adding the “debug” node to the Case node in a HERON XML input allows a custom, simplified run that only performs a select set of dispatches and produces plots of dispatch decisions. • Allows users to use the “activity” of a component as the source of values for cash-flow entries. This is particularly useful for the Cash-Flow Driver, where often the amount of resources consumed or produced by a component leads directly to a Cash-Flow such as variable operations and maintenance costs or sales profits. • Allows Reduced-Order Models trained by RAVEN to be used as fixed-source data types, such as pricing models or demand generators. • Round-Trip Efficiency: Allows storage units to include a “loss” factor for round-trip resource acquisition and release. HERON simulates this loss as occurring in equal parts as	INL/RPT-21-65476 December 2021

Activity	Outcomes and Significance	Report or Documentation
	the resource is absorbed and as it is released, multiplying by the square root of the round-trip efficiency at each stage to apply loss. • More sophisticated dispatch strategies are required to improve the model performance.	
Synfuels Assessment	• Based on ANL effort and report funding by IES. • LWRS-FOPG Evaluation of CO_2 Markets near NPPs. • Daniel Wendt, Marisol Garrouste, William Jenson, Qian Zhang, Tanveer Hossain Bhuiyan, Mohammad Roni, Frederick Joseck, and Richard Boardman. "Analysis of Fischer-Tropsch Synthetic Transportation Fuel Production using Energy from a Light Water Reactor Nuclear Power Plant." Idaho National Laboratory. INL/RPT-22-69047. September 2022.	INL/RPT-22-69047 September 2022

3.1.2 Plans and Schedule

The objective for FY 2023 is to evaluate the sensitivity of flexible production of electricity and hydrogen to market factors and regulatory incentives by completing the following tasks:

- Develop a spreadsheet tool that applies simple user input to approximate LWR revenue sensitivity to electricity market prices and hydrogen market prices, relative to market structure (regulated or de-regulated), and regulatory incentives, including production tax credits, clean energy credits, and other legislative actions.
- Project the power generation capacity expansion and locational marginal price (LMP) in a representative deregulated (e.g., PJM) and regulated (e.g., Minnesota) electricity market given U.S. Energy Information Administration Energy Outlook for high, reference, and low NG prices and high, reference, and low and high buildup of wind and solar energy, and regulator incentives.
- Project the market price of clean hydrogen with an updated calculation of NG steam-methane reforming costs and large-scale low-temperature electrolysis powered by wind and solar energy.
- In FY 2024–2027. Expand the tools for revenue estimation to include power arbitrage options and hydrogen markets, including fertilizer, fuels., steel, hydrogen filling stations, and power options.

Benefits to industry include:

- NPP owners and operators will benefit from the outcomes of the analysis completed using the tool, as well as having the tool to quickly evaluate market conditions and regulatory incentives that are often unique to each power plant in their respective electricity market and surrounding hydrogen market.
- This work will benefit LWR owner/operators by informing strategic decisions relative to FPOG options. It will help inform the chemicals and fuels industries of viable options that will increase commercial competitiveness. These efforts support developers of clean energy parks, including hydrogen hubs.
- An understanding of the hydrogen versus electricity market sensitivities is paramount to utility strategy planning and decisions to move ahead with large hydrogen project and participating in Regional Clean Hydrogen Hubs.
- This tool will also be valuable to entities looking to establish Regional Clean Hydrogen Hubs.

Objectives:

The main objective of this activity is to provide a simple tool that can be readily used by nuclear plant owners to understand the value of producing electricity versus hydrogen or a combination of both under certain market conditions that are difficult to evaluate. The work completed in FY 2023 will prove this tool under a couple of real market scenarios where renewable energy capacity is expanding in consideration of the price of NG for power production and regulatory incentives that are difficult to understand. The tool will not be computationally challenged and will be shared with LWR owners, utility companies, and transmission offices to help make decisions relative investments or commitments to sell power to hydrogen producers, or to store power for delayed dispatch.

3.2 Thermal/Electrical Energy Dispatch and Controls

The approach being taken to evaluate and develop energy delivery systems is to adapt NPP simulators to model candidate processes. The simulators are being coupled to thermal-hydraulic computer models that are being designed for delivery of thermal energy to close-coupled industrial users. These simulators are being installed at the INL HSSL to identify and develop operating concepts for FPOG operations. The HSSL, in turn, is being tied to a representative thermal energy delivery system to validate the computer models and to demonstrate the technical feasibility of energy dispatch with representative physical processes.

3.2.1 Summary of Progress and Accomplishments

Table 5 catalogs the milestone reports that have been completed through FY 2022 related to energy dispatch development. A Level 2 Milestone report was completed that validated the HTE in a Reduced-Order – Thermal Power Dispatch – Pressurized Water Reactor (RO-TPD-PWR) simulator, an initial test was performed at INL, including heating a Bloom HTE system to approximately 800°C and producing hydrogen at 0.75 kg/hr [19].

In FY 2022, a subcontract was made to an Architectural/Engineering company to begin developing the conceptual design for thermal energy extraction and delivery ranging from 20 MWth to 100 MWth. The rationale was to provide sufficient heat for a 100-MWe-DC and 500-MWe-DC HTE plant. This work will be completed by December 2022. It will be incorporated into a program milestone due April 2023. This activity has indicated technical and economic risks that were not evident using the RELAP and HYSYS process modeling tools because an actual plant layout is complicated and the new steam lines must be installed in a manner that does not adversely disturb the existing critical infrastructure and power deck equipment and piping access.

A separate activity undertaken by the INL Activity Lead for FPOG interfaces continued with the development of plant simulators to study potential challenges of thermal energy extraction [19]. Model validation was completed for a generic full-scope RO-TPD-PWR (Reduced-Order - Thermal Power Delivery - Pressurized Water Reactor) with a 15% thermal power dispatch simulator to support the analysis of PWR's control and operation. The detailed modeling equations and model integration was followed by the steady-state and dynamic validation using the existing TPD-GPWR simulator-based on the generic PWR simulator developed by the GSE Systems, Inc. (Sykesville, Maryland, USA). This initial case is based on Option 1 shown in . The simulator incorporated HTE as the coupled industrial thermal process receiving part of the process steam produced by the steam generator. In this work, the system was interfaced to a Real-Time Grid Simulation (RTDS) environment and a Bloom Energy 100-kW HTE modular demonstration unit.

The results indicate that the simulator is able to predict the steady-state and transient response of a PWR plant with acceptable accuracy as shown in . Therefore, the RO-TPD-PWR simulator can help explain nuanced relationships between parameters, including those between steam flows in the TPD system, turbine system, feed water heaters, and the main steam lines. This work indicates that the thermal power dispatch system must be carefully designed to maintain the temperature of the feedwater entering the steam generator as high as possible so that the steam generator operation is not perturbed more than necessary. Current work is exploring the option of extracting steam from the turbine system rather than the main steam line, which will help maintain the heat balance in the steam generator and minimize impacts on plant operations due to relatively high levels of thermal power dispatch.

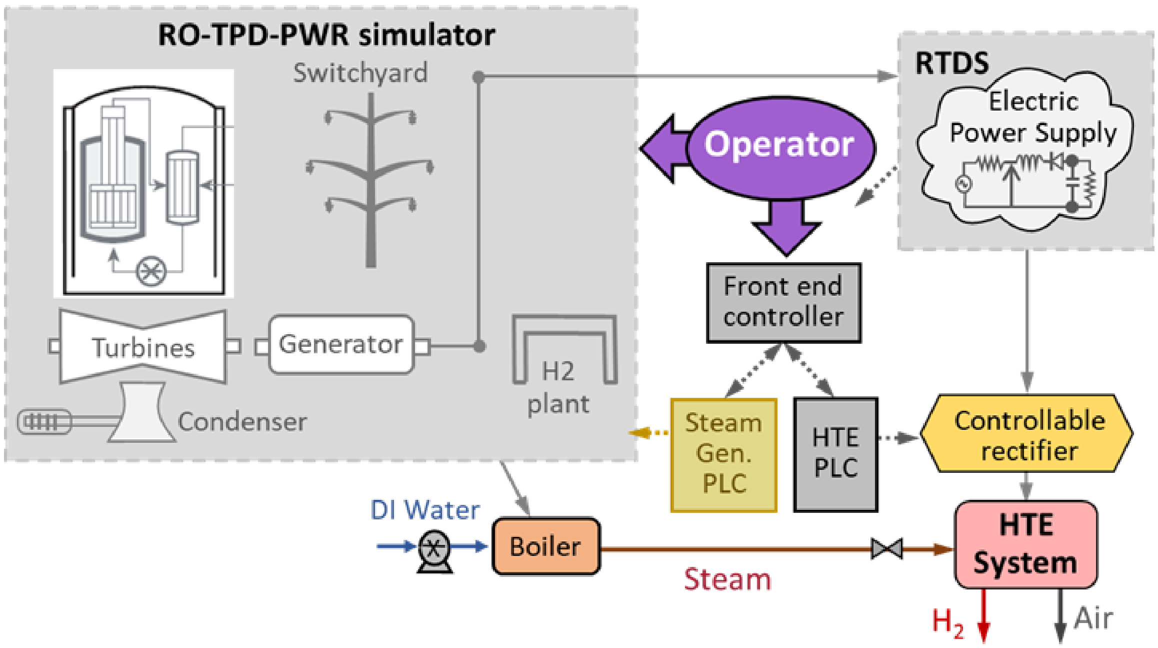

Figure 18. Interfaces between the RO-TPD-PWR and RTDS simulators (grey boxes), human operator, and physical equipment in hardware-in-the-loop and human operator-in-the-loop tests.

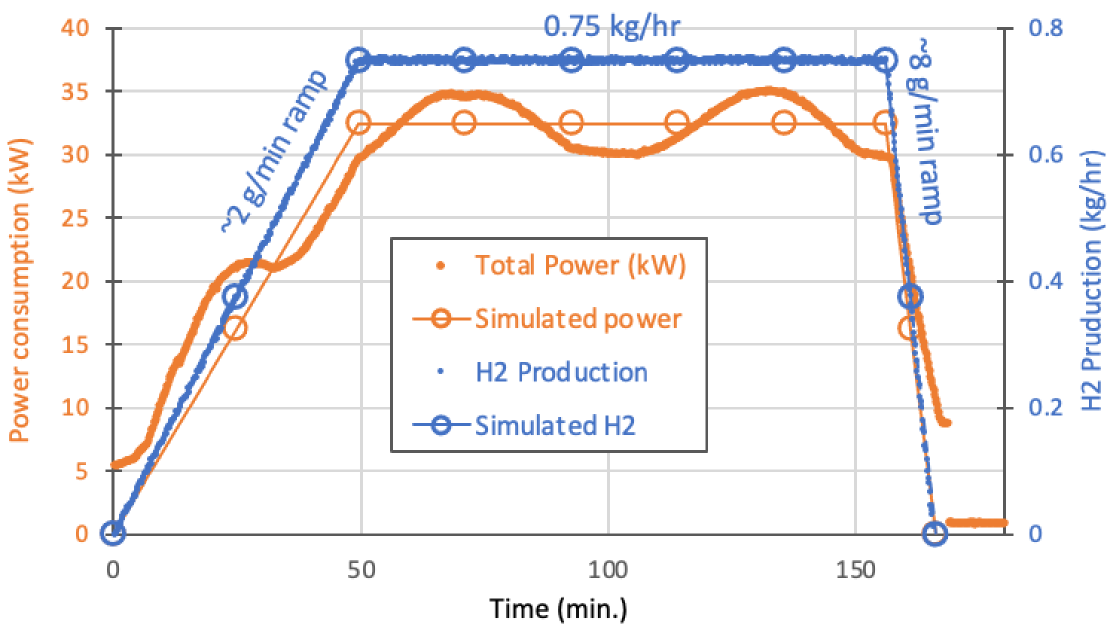

Figure 19. Electric power consumption and hydrogen production for a demonstration using a 100-kW Bloom HTE Test Module.

Major accomplishments through FY 2022 are summarized in Table 5.

A research plan for power dispatch concepts was developed in the final quarter of the Fiscal Year 2022 [21]. This plan focuses on developing technological solutions including the physical and control system design and concept of operations to support steam extraction via the main steam system header, thermal energy transfer through the thermal power dispatch system, and condensed steam return to the plant. The plan contains three research activities including a high-fidelity plant-specific simulator, high-fidelity generic simulator, and reduced-order model simulators. The three research paths provide complimentary research capabilities all of which are necessary to perform a full-scope simulator-based operator-in-the-loop study with integrated simulations representing the nuclear power plant, electric grid, a hydrogen production plant use case.

A primary objective is demonstration of operator-in-the-loop full-scope simulator-based study with representative scenarios designed to evaluate normal and abnormal, i.e., fault, thermal power dispatch scenarios. The demonstration will provide industry with technical implementation details to accelerate utilities in adopting thermal power dispatch capabilities to augment existing electrical generation revenue by partnering with an industrial thermal energy consumer such as a high-temperature steam electrolysis hydrogen production plant. Furthermore, the demonstration and evaluation will identify critical findings and evidence to determine the upper limit for the magnitude of the thermal power dispatch before the impacts mandate a license amendment request. The study will evaluate incremental increases in magnitudes of thermal power dispatch associated with a hydrogen plant operating at up to 500 MWe and 120 MWt to identify nuclear power plant system existing operations impacts.

The approach adopted by the researchers will follow a regulatory informed, NUREG-0711 approach, which establishes a roadmap of good practices for utilities to develop their plant-specific implementations with prescribed development and evaluation activities that fulfill nuclear regulatory requirements in the event the plant opts to adopt a thermal power dispatch capability requiring a license amendment request.

Table 5. Energy dispatch development accomplishments through FY 2022.

Activity	Outcomes and Significance	Report or Documentation
LWR Energy Dispatch Technical Feasibility Screening Study and Recommendations	• Modified full-scope PWR simulators to confirm thermal energy can be extracted from Main Steam within the normal operating conditions of the reactor core. • Steam bypass enables a higher percentage of thermal energy to be removed, and at a faster rate compared to direct extraction with a heat exchanger; this study proved the impacts can be minimal for energy removal levels as high as 30% of the total reactor power and for rates as high as 5%/min; this is sufficiently high for the purposes of net grid following the accounting for renewable generation. • Study recommended additional testing on operational changes, including accident scenarios, is required to quantitatively determine limits of heat removal for different design configurations. • Verification of simulator predictions will be needed to ensure their robustness; pilot-scale verification tests should include: (1) manual control of systems, so that feedback mechanisms between different systems can be carefully tested, and (2) advanced automated control mechanisms to verify the performance of the pilot-scale system under automated control.	INL/LTD-19-54530, June 2019
Incorporation of Thermal-Hydraulic Models for Thermal Energy Dispatch into an LWR Power Plant Simulator	• Thermal-hydraulic modeling was performed using both RELAP5-3D and Aspen HYSYS, with two scenarios being simulated by both software packages. Agreement between the modeling approaches was very good, despite slightly different assumptions upon which the different models were based. • The steam extraction line was designed to remove steam from the main steam header and then transfer heat to a second thermal delivery loop that transports the thermal power to the end-user, which may be a kilometer or further away. • Design requirements and decisions for the integrated energy system are reviewed; Control schemes based on static and dynamic pressure conditions in Main Steam were developed and tested. • Thermal-hydraulic modeling was performed for multiple heat transport scales, including 200 kW, 15 MW, and 150 MW with thermal transport distances of 0.1 km, 0.5 km, and 1.0 km. • The primary operating heat dispatch modes of the integrated nuclear/HTSE system were tested: - Cold Shutdown – the thermal power extraction (TPE) line and TPD loop both have zero flow and are at ambient temperature	INL/LTD-19-58766, June 2020

Activity	Outcomes and Significance	Report or Documentation
	- Hot Standby – the TPE line and TPD loop have minimal flow to maintain hot conditions in both lines and at the HTSE plant - Heat dispatch – the TPE line and TPD loop have sufficient flow to provide the desired thermal power to the industrial process.	
Monitoring and Control Systems Technical Guidance for LWR Thermal Energy Delivery	• Provides initial technical guidance with technical requirements and operating characteristics for FPOG operations concepts. - The nuclear plant operators must have full control of the steam flow in the TPE line with prerogative to completely stop steam flow in that loop without possibility of interference from the hydrogen plant. - Risk of reactor thermal power exceeding 100% (2900 MWh-thermal) must not be increased due to changing the rate of steam diverted to the TPE line from 0% (0 steam flow) to 5% (2.9·105 kg/hr, 6.5·105 lbm/hr steam) of total thermal power. - Use of the TPE line must not adversely affect the existing UFSAR DBA analyses (specifically, any effects on the step load decrease transient). • Isolation flow control valves will be installed in the TPE line operable from the MCR to allow NPP operators to stop flow at any time. • Steam pressure in the main steam header or steam flow rate in the TPE line are preferred as control variables. • The control system will be designed to allow switching at least 90% of power delivery from the hydrogen plant to the electric grid in less than 10 minutes, such that the hydrogen plant can act as a dispatchable load. The integrated system shall be capable of cycling power to and from the hydrogen plant at least two times in each 24 hours. • Condensate from the TPE line will be returned to the condenser, which is designed to handle steam dumps of this quantity. Future work may also consider returning condensate, which has a temperature of approximately 182°C (360°F), to the feed water heater system to increase efficiency.	INL/EXT-20-57577, February 2020
Remote Operator TPD Concept of Operations Evaluation	• An initial TPD concept of operations was evaluated to demonstrate and acquire lessons learned for coupling an NPP to a nearby hydrogen production plant. • Procedures were developed for basic FPOG operating scenarios, which include evolutions to move between different states, including from Shutdown to Hot Standby, from Hot Standby to Online, from Online to Hot Standby, and from Hot Standby to Shutdown.	INL/EXT-20-00626, September 2020

Activity	Outcomes and Significance	Report or Documentation
	• A prototype HSI was developed to interface with the model and allow operators to execute the procedures to test the system running through the basic operating conditions. • NPP operators remotely performed think-aloud protocol to narrate their experiences during mock FPOG maneuvers. • Several lessons learned came out of the initial testing that underscore the high relevancy of developing and testing human factors and operational concepts for FPOG.	
Incorporation of Thermal-Hydraulic Models for TPD into a PWR Power Plant Simulator	• Robust, full-scope simulator (GPWR) is now capable of investigating the ramification of thermal energy dispatch from a PWR using either a once-through steam heat extraction systems or a closed heated oil loop. The baseline operation of the TPD-GPWR Simulator comes with three primary operating TPD modes of the integrated nuclear power/hydrogen production system, which are: A. Cold Shutdown – the extraction steam line (XSL) and delivery steam line (DSL) both have zero flow and are at ambient temperature B. Hot Standby – the XSL and DSL have minimal flow to maintain hot conditions in both lines and at the hydrogen plant C. TPD – the XSL and DSL have sufficient flow to provide the desired thermal power to the industrial process. • Operator role is to transfer energy from the turbine to the energy transfer system and back on the schedule of alternate energy operations. • Operational modes for the Energy Transfer System (ETS) are (1) Energy Transfer, (2) Hot Standby, and (3) Cold Shutdown. • Operators can isolate the energy transfer system at any time for any operational reason. • Custom control panel automates this transfer at an acceptable ramp rate, very similar to turbine power maneuvers. • Simulated industrial loads less than approximately 60 MWe can be couped to the TPD-GPWR as a house load while still being able to meet the requirement that a single unit auxiliar transformer be able to support all auxiliary loads. The electrical connection to industrial loads larger than 60 MWe will need to follow a standard industrial facility connections to the bulk	INL/EXT-21-63226; June 2021

Activity	Outcomes and Significance	Report or Documentation
	power grid in which the power connection is made on the high-voltage side of the Generator Step-Up transformer to protect the generator of the NPP from sudden trips at the hydrogen plant or failures of the transmission line. Either situation would be similar to any nearby loss of load, and the impact to the generator would follow normal "generator load rejection" protection schemes and would be evaluated accordingly.	
Dynamic Human-in-the-Loop Simulated NPP TPD System Demonstration and Evaluation Study	• Full-scope simulator used in operator study; two operators; 15 normal and off-normal scenarios with mock procedures. • Alternate energy systems will have their own operators outside the protection area. Control room operators will coordinate and control energy transfer. • Operators will be able to respond to grid contingencies and respond to operational conditions in the alternate energy systems, including load rejection. • TPD system can be safely ramped up and down but needs automated control system and isolation to minimize operator burden. • Control scheme ensures no feedback to reactor control (e.g., Tavg-Tref mismatch stays in dead band to prevent rod motion). • Likely operational control is to initiate a turbine ramp (up or down) and the ETS control system will modulate the ETS control valve to maintain Tavg-Tref mismatch at essentially zero. • Tavg-Tref mismatch signal must have compensation for decreased turbine impulse pressure during ETS operations.	INL/EXT-21-64329; September 2021
Validation of a Reduced-Order PWR Power Dispatch Simulator	• Validation of a reduced-order simulator for PWR that incorporates coupled electrical and TPD to an industrial process • Simulator can be used to guide the controls of laboratory tests so that equipment in those tests, including an electric steam boiler, an AC/DC power rectifier, and a pilot-scale 100-kW Bloom Energy prototype high-temperature electrolysis (HTE) system may operate in a manner that is relevant to full-scale PWR operations • A key purpose of the simulator is to scale between lab-size equipment (~100 kW) and full-scale NPPs (~1 GW) by adjusting only a few parameters in the models, such as fluid masses and heat exchanger areas.	INL/EXT-21-64481; September 2021
Incorporation of Thermal-Hydraulic	• Documents the development and use of a full-scope BWR simulator for thermal and electrical energy dispatch to industrial processes.	INL/EXT-21-64479; September 2021

Activity	Outcomes and Significance	Report or Documentation
Models for TPD into a BWR Power Plant Simulator Industries	• Design requirements ensure multiple purposes are accomplished, including safety of the NPP and efficient use of nuclear energy for the industrial purpose. • Addresses the advantages and disadvantages of using superheated steam or synthetic oil as the heat delivery fluid. • Explains the operating modes for Cold Shutdown, Hot Standby, and TPD. • Shows the simulations results for up to 15% TPD, including impacts on flows and temperatures through the turbine and feedwater heater systems.	
Validation of a Reduced-Order PWR Power Dispatch Simulator	• This report describes the validation of a reduced-order thermal power dispatch pressurized water reactor (RO-TPD-PWR) power plant simulator that incorporates coupled electrical and thermal power dispatch to an industrial process. • Simulator is built on models that have been developed in previous work, including a Rancor Microworld model developed by INL and the University of Idaho as well as a reactor core and secondary system models that have been published previously. • Simulator also includes a scalable model of a high-temperature electrolysis (HTE) system developed at INL under separate work. • Key findings from that work are that the RO-TPD-PWR simulator can simulate the thermal hydraulics of an NPP with suitable accuracy and comparing results of the RO-TPD-PWR simulator with results from a high-fidelity full-scope simulator, it is possible to identify and quantify nonlinear phenomena in the thermal hydraulics of the NPP, including the turbines, feedwater heaters, and steam generator.	INL/INT-21-64481; February 2022
Human-Machine Interface and Controls Systems Development Plan for Close-Coupled Nuclear/Electrolysis Plants	• Describes the Fiscal Year 2023 through 2025 simulator development for concepts of operation and human factors testing of FPOG applications. • Three research simulator tracks provide complimentary capabilities to develop simulator integration and communication capabilities, multifacility (Energy Innovation Laboratory HSSL and Energy Systems Laboratory Real-time Data Simulator and High-Temperature Steam Electrolysis Test Module) experimental protocols development, and scenario-based simulator human-in-the-loop concept of operations development and evaluation.	IN/EXT-22-02672; September 2022

3.2.2 Plans and Schedule

R&D plans for FY 2023 will continue to be taken up under three work activities: (1) Thermal Energy Dispatch Research and Development, (2) Controls Systems Interfaces Research and Development, and (3) Electrical Energy Dispatch Research and Development.

Three research activities are planned for parallel execution, as summarized in Table 6 The first activity will work with an architectural engineering firm, such as Westinghouse, to develop and test full-scope NPP simulators that include dynamic thermal and electric power dispatch to a tertiary industrial load. The architectural engineering firm will provide the modified full-scope simulators, including automated control systems for dynamic thermal and electric power dispatch. INL will support developing the required HMIs for the simulators and operator tests. The operators will interact with the simulator through a realistic HMI in a control room environment, and these tests will include real-time simulation of the bulk transmission grid around the nuclear plant. The operator tests will include realistic digital and human communications between the NPP, the tertiary industrial load, and the electric grid ISO scheduling coordinator. In the first year of the project, the industrial plant will be a SOEC hydrogen plant that requires a relatively small thermal power extract (less than 7% of the rated reactor thermal power). This first track comprises the bulk of the effort for this work package and provides the engineering verification for the operability of the automated controls, the application of human factors in the design development, and the anticipated interactions between the NPP, the industrial plant, and the grid ISO scheduling coordinator. In the second year of the project, operator and grid simulation tests with a different industrial plant will be conducted with a thermal power dispatch in the range of 30% to 70% of the rated reactor thermal power. The specific amount of thermal power dispatch will be determined based upon modeling in other work packages that identifies an appropriate thermal power dispatch target.

The other two research activities are complementary to the first activity. It is expected that the automated control systems developed and used by an architectural engineering (A/E) firm for their full-scope NPP simulators will be proprietary. The full control strategy will not be shared with INL, and it may not be allowable to install and operate a complete simulator code at INL that can interface with other computer systems, including SOEC technology vendors, for hardware-in-the-loop (HIL) tests.

A full-scope NPP simulator development company, such as GSE Systems®, will be used to develop and test dynamic thermal and electric power dispatch to a tertiary industrial load. Publishing detailed descriptions of the control systems along with their performance in simulator scenario tests will benefit the industry by showing the direct relationship between the control system design and its performance in different scenarios, such as transitions between operating modes, rapid ramping of the industrial plant, and off-normal events. The work will build on work already completed by INL and GSE Systems in which full-scope simulators for PWR and BWR plants were already modified for thermal power dispatch and tested for performance. The publicly available control system design will be used to support cost estimates for dynamic thermal and electric power dispatch to tertiary industrial plants. A few universities already have access to the GSE Systems modified full-scope simulators, and this track will provide opportunities for collaboration and future independent research by universities.

The full-scope NPP simulators developed with GSE will focus on relatively low levels of thermal power dispatch (less than 10% of rated reactor thermal power) and will employ simplified electric power dispatch models compared to the simulators developed with the A/E firm.

Table 6. Three-Year Plan Pressurized Water Reactor and Boiling Water Reactor Planned Research Activities and Timeline

Fiscal Year 2023 Pressurized Water Reactor __ Mw_t Thermal Power Dispatch __ Mw_e Hydrogen Plant			
Activity	Milestone/Accomplishment	Date	Notes
General (applies to all activities)	Complete a plan for developing and verifying human-machine interface and simulators to test operator/machine performance of close-coupled nuclear/electrolysis Plants	30-Sep-2022	(This document)
	Complete connection of hydrogen electrolysis pilot plant operations and electricity grid simulator to nuclear power plant simulators installed at the Human Systems Simulation Laboratory	15-Dec-2022	Needed to connect physical electrolysis equipment and grid simulations to NPP simulators.
Activity 1 (R/O model; partnership with University of Idaho)	Develop reduced-order thermal power dispatch PWR simulator with automated controls. Perform HIL tests using a 25+kW high-temperature electrolysis (HTE) system that verify interoperability of controls and communications between the HTE system and the simulator.	30-Jun-2023	Will build on the existing reduced-order simulator developed with the University of Idaho. This simulator can be shared with industrial partners to support close-coupled demonstration projects.
Activity 2 (partnership with GSE)	Develop generic thermal power dispatch PWR simulator with automated controls. Verify standard operations can be performed automatically while maintaining the PWR in normal operating conditions.	30-Jun-2023	Will build on the existing GSE full-scope, high-fidelity GPWR simulator that has manual controls. Will help guide and validate work in Task 1.
Activity 3 (partnership with A/E firm)	Install and demonstrate a vendor-developed simulator on the HSSL for dispatch of LWR electrical power to a close-coupled electrolysis plant.	22-Dec-2022	This simulator will be provided by an A/E firm with deep expertise in NPP controls systems for NPP/grid interactions.
Intended for Activity 3 with simulator from A/E firm. Activity 1 is also an option.	Complete an evaluation and verification of PWR operator capability to dynamically dispatch 93% electric power and 7% thermal power to a HTSE hydrogen plant and the grid for meeting non-spinning reserve requirements.	30-Sep-2023	Requires integration with non-INL hardware. Integration with simulator from A/E firm may be challenged due to intellectual property protection concerns. The R/O model may be used, if necessary.

Fiscal Year 2024 Work will continue on PWR simulators from FY2023 and corresponding work will start for BWR simulators. All milestones/ accomplishments in FY2023 will be repeated for BWR simulators. In addition, new milestones for PWR simulators will be completed as documented in the following rows.			
Goal	PWR __ Mw_t Thermal Power Dispatch __ Mw_e Hydrogen Plant BWR __ Mw_t Thermal Power Dispatch __ Mw_e Hydrogen Plant		
Activities 1 and 3 (R/O simulator and simulator provided by A/E firm)	Develop reduced-order thermal power dispatch PWR simulator with automated controls for thermal power dispatch between 30% and 70% of rated reactor power. Perform HIL tests using a 100+ kW high-temperature electrolysis (HTE) system that verifies interoperability of controls and communications between the HTE system and the simulator.	30-Jun-2024	Similar to June 2023 milestone above but with higher TPD.
Activity 2 (partnership with A/E firm)	Install and demonstrate a vendor-developed simulator on the HSSL for thermal power dispatch between 30% and 70% of rated reactor power and corresponding 30% to 70% electric power dispatch to an industrial load.	22-Dec-2023	Similar to December 2022 milestone above but with higher TPD.
Activity 3 (partnership with A/E firm)	Complete an evaluation and verification of PWR operator capability to dynamically dispatch greater than 50% thermal power to a dispatchable industrial load and corresponding electric power to the grid for meeting non-spinning reserve requirements.	30-Sep-2024	Similar to September 2023 milestone above but with higher TPD.
Fiscal Year 2025 (storage)			
Goal	PWR __ Mw_t Thermal Power Dispatch __ Mw_e Hydrogen Plant BWR __ Mw_t Thermal Power Dispatch __ Mw_e Hydrogen Plant		

The third track will introduce reduced-order NPP simulators that can be readily interfaced to real-time grid simulations as well as pilot-scale hydrogen production hardware for HIL tests. By employing physical hardware in the tests, the interoperability of the industrial equipment in the operating environment can be fully ensured prior to installation in an actual nuclear facility. These tests will allow HTSE and other non-nuclear technology vendors to gain experience coupling their equipment to realistic nuclear plant simulators and performing integrated dynamic electric and thermal power dispatch. The reduced-order NPP simulators are particularly advantageous for these tests because they can be shared with and even used by the technology vendors, so that they can get direct insight into how the close coupling between the different plants is accomplished and how the dynamic thermal and electric power dispatch is performed in daily operations. The reduced-order simulators can also be made available to other partners, including universities, to facilitate a wide range of beneficial partnerships. The reduced-order NPP simulators can be fully validated against the full-scope simulators provided by the architectural engineering firm and by GSE to ensure they have sufficient accuracy for their intended purpose. The third track can build on work already completed by INL and the University of Idaho in which a reduced-order simulator was developed and tested for dispatching thermal energy from a PWR. That previous work indicated that the reduced-order simulators can be readily developed that calculate performance within

15% of that predicted by the high-fidelity simulators. That level of accuracy is sufficient for HIL and grid interoperability simulator tests and can be further improved by cross-validation, if desired

3.2.2.1 Thermal Energy Dispatch Research and Development

This activity encompasses the design, simulation, and assessment of thermal energy extraction, delivery, and storage for FPOG applications. It includes (a) modification of existing nuclear plant simulators to model the new thermal-hydraulic systems and (b) Architecture and Engineering (A&E) supported feasibility studies and preliminary Front-End Engineering Designs (Pre-FEED), and the use of qualified commercial software to evaluate the impacts of thermal energy extraction on nuclear reactor core reactivity, the power turbines and generator sets, and the plant condensers or cooling systems.

The following tasks are planned:

- In FY 2022, a preliminary engineering design, technical analysis, and cost of thermal energy extraction systems will be completed for up to 100-MWth offtake to provide the essential heat for up to a 500-MWe nominally rated steam electrolysis plant will be completed.
- In FY 2023, a preliminary engineering design, technical analysis, and costing of thermal energy extraction and temporary storage systems will be completed for supporting up to about 30% of the total thermal energy produced by a nominal 1,000-MWe PWR nuclear reactor for thermal energy power arbitrage and industrial uses. The Preliminary FEED study for 30% thermal energy extraction will include the conceptual design, equipment sizing and specification, thermal-hydraulic flow analysis, and cost range estimate. This study will also elucidate potential challenges with operations in normal and off-normal conditions.
- In FY 2023, plant impacts due ramping dynamic thermal-hydraulic systems will be analyzed using GSE, PEPSE, or Modular Accident Analysis Program tools for thermal energy extraction ranging up to 30% of total LWR production.
- In FY 2024, depending on the outcome of a technical and economic feasibility study for 50% and 70% thermal energy extraction costs/benefits, an engineering design study for this amount of energy extraction will be completed.
- In FY 2024, based on the outcomes of a feasibility study for 50% and 70% thermal energy extraction costs/benefits, repeat PEPSE (a steady-state energy balance, design, diagnostics, and performance software program) and Modular Accident Analysis Program assessment of the system safety.

Benefits to Industry:

- The activity directly engages industry and the H3RG committees with the design of the hardware interfaces and control software necessary to scale-up and commercialize hydrogen production and thermal energy storage at a nuclear plant site. The designs also help establish a supply chain of materials produced by industries, which must be produced in high-volume to build cost-competitive production of non-electrical goods and services.
- 30% thermal power extraction (or about 1,000 MWth) for energy storage and arbitrage will provide a reasonable case study for utilities and industry relative to costs and benefits. This is a significant jump in thermal energy extraction and delivery. This amount of heat can service many industries within 5–50 km of nuclear plant.
- It is important to quantify the impact of thermal energy extraction on turbine performance to conduct an accurate PRA and to address all included costs in hydrogen production and energy arbitrage applications.

3.2.2.2 Electrical Energy Dispatch

This is a new activity that is starting in FY 2023 and will focus on the development of electrical power dispatch from NPPs to 500-MW hydrogen plants considering issues such as minimizing NPP downtime for switchyard modifications or new equipment installation, as well as behind-the-meter power offtake and grid coupling. Taking these considerations into account, the analyses will provide realistic preliminary design and cost estimate. The objective is to develop a Phase I Preliminary Conceptual Design and cost estimate for electric power delivery from a nuclear reactor to a hydrogen plant based on a rigorous physics-based digital Electricity Transient Analysis of Power model using Power Systems Computer-Aided Design or a comparable software package to model a LWR switch yard. This design will be based on the preconceptual design developed by December 2022 and will seek to discover and incorporate improved design features to reduce cost, such as locating the hydrogen plant within the nuclear protection area.

An A&E firm will develop the preliminary design and cost estimate, including technical design criteria, for NPP switching between the electricity grid and a nominally 500-MWe HTE plant. Key options that will be considered include behind-the-meter power offtake and grid coupling as well as the potential need for a separate switchyard for the hydrogen plant electrical power offtake that can be installed with minimal NPP downtime.

In FY 2024, a study on scalable electricity offtake approach for hydrogen buildout in increments of 50 MWe, to 1,000 MWe.

Benefit to Industry

Electrical energy dispatch to a given FPOG option involves direct coupling to an industrial process behind the bus bar that connects the NPP to the grid. Both LTE and HTE, and other electrochemical processes that are directly coupled to the switchyard of the nuclear plant require new switchgear and transformers to directly couple the plant to an industrial user and to perform rapid switching between the nuclear plant and the electricity gear without increasing a fault or "trip" at the nuclear reactor. Direct coupling to the secondary user will enable the nuclear plant to sell power to the customer at the wholesale price it chooses.

3.2.2.3 Controls Systems Interfaces

With the support of an EPC, a detailed plan will be prepared for the development, demonstration, and verification of FPOG control systems to develop and prove the essential data links, human factors, and control functions for the dynamic dispatch of electricity and thermal power to a hydrogen production plant and thermal energy storage. A data-link connection is being set up between the HSSL and a RTDS platform and electrolyzer modules at INL and NREL.

These tests will validate the concept of operations for coupled electric and thermal power dispatch from PWR NPPs coupled to HTE plants and to the electric grid to enable FPOG. The validation includes automated control system responses, operator oversight, and interactions with the control system through the HMI, and interactions between the reactor operators, the switchyard dispatcher, and the hydrogen plant operator.

The following additional tasks will be completed in FY 2023.

- Modify the controls of a generic PWR and BWR simulator to create a realistic HMI (i.e., with a simple switch function) that maintains the "line-of-sight" to the nuclear plant reactivity and meets the UFSAR for a model LWR license.
  - Provide a generic PWR simulator with control logic to switch thermal and electrical power between a full-scale hydrogen plant and the bulk grid in such a way as to meet non-spinning reserve requirements.

- Complete connection of hydrogen electrolysis pilot plant operations and electricity grid simulator to NPP simulators installed at the HSSL, due December 15, 2022.
- Install and demonstrate a vendor-developed simulator on the HSSL for dispatch of LWR electrical power to a close-coupled electrolysis plant.

- Use the simulator to technically prove a nuclear plant operator can dispatch energy to ramp an electrolysis plant from 5% to 95% of nominal capacity for a 500-MWe low-temperature proton-exchange membrane (PEM) electrolyzer and a 500-MWe/100-MWth high-temperature solid oxide electrolyzer plant.
  - Conduct operator-in-the-loop tests to verify the capability of a PWR to switch power between the grid and a full-scale hydrogen plant.
  - Evaluate the impacts to the existing concept of operations to demonstrate energy dispatch does not significantly impact the plant requirements.

  In FY 2024 the above two tasks will be completed for a BWR.

Benefit to Industry

A generic PWR and BWR simulator that can be used to “realistically” test operator control of large thermal and electrical energy dispatch is needed to further develop and prove human factors and operator performance of FPOG operations. It is important to demonstrate nuclear plants can function as 10-min reserve capacity to receive capacity payments for rapid response to the capacity market. This will significantly increase the potential revenue of a nuclear plant. This test will demonstrate this new paradigm for nuclear plants and will help chief strategy planners. A simple operating concept is needed to avoid a significant LAR or request.

3.3 Safety Assessments and License Modifications

A key research area required to validate the feasibility of integrated hydrogen production at NPPs is related to how supporting design changes would conform to the licensing regulatory framework required by the NRC. Design changes are routinely performed at operating U.S. nuclear power reactors through a process where the licensee confirms that the proposed design change remains within the intent of the approved operating license. This process is controlled under 10 CFR 50.59. When a change is determined not to be within the limits described by the approved operating license or licensing bases, a formal license amendment process is required with specific NRC approval.

The H3RG was formed to begin to identify the technical and safety risks that may need to be addressed to follow 10 CFR 50.59 requirements. The H3RG includes a broad collaboration with primary participants from DOE-supported national laboratory research leads, contracted architect engineering participants, and nuclear utility licensing and design personnel.

3.3.1 Progress and Accomplishments

A key research area required to validate the feasibility of FPOG is related to how supporting design changes conform to the licensing regulatory framework required by NRC. This activity engages LWR plant engineers and licensing leads to help guide FPOG R&D activities that conduct general safety hazards and risks assessments that are required to prove FPOG operations can be carried out under the approved LWR plant licenses or, if a license modification is needed, then provide a technical basis, guidance, and preliminary risks assessments that be leveraged to pursue a license amendment. Table 7 provides a summary of accomplishments and milestone reports completed through FY 2022 in the area of safety assessments and license modifications assessments.

In FY 2021, a preliminary PRA was completed for the integration of a HTE plant with a representative PWR and BWR, respectively, based on a preconceptual design and hydrogen plant operation assumptions. In FY 2022, the decision was made to form an advisory team to get a grasp on the needs of the nuclear plant owners and utility companies looking to FPOG for solutions. The notional coupling of an NPP to a hydrogen plant presents many questions relative to permitting. While the outcomes of a preliminary PRA showed a hydrogen plant could be sited close to an NPP, several questions arise regarding the rigor in the PRA and its relevance to individual plants. Therefore, the FPOG pathway looked to forming a stakeholder group, and the Hydrogen Regulatory Research and Review Group was formed with the assistance of CERTREC and consultant with significant prior plant design, startup, and operations experience.

A summary of H3RG tasks, interim accomplishments, and plans in the first year was documented in a milestone report [2]. The H3RG will continue to identify and inform research-related licensing approaches (based on traditional NRC licensee requirements) that support the introduction of hydrogen production by HTE as an alternate energy stream at nuclear facilities. There are two primary goals:

- Gather experience-based insights from LWR plant owners and operators applicable to regulatory approval of planned flexible hydrogen operations at nuclear facilities.
- Provide expert regulatory, design, and operational input to inform the work of laboratory scientists and contracted architect engineers tasked with preconceptual nuclear integrated HTE designs and 10 CFR 50.59 deliverables.

The common intent in both areas is to integrate real-world industry regulatory operating experience into national laboratory research in support of the timely rollout of flexible hydrogen projects at U.S. nuclear facilities. Foremost in these considerations are how such proposed design changes and operating methods may impact the plant's safety analyses. These safety analyses are contained in the updated UFSAR and form the cornerstone of each plant's licensing basis.

The H3RG is organized under several industry subcommittee research areas with leads selected from the pool of expert participants supporting the H3RG (see). The leads oversee reviews of individual regulatory subcommittee areas that will later be aggregated to support a generic 10.CRF.50.59 template deliverable. These include the following subcommittee areas:

Internal/external events and PRA considerations

- Integrated operations and reactor impacts
- Electrical and switchyard considerations
- Control system interactions and modifications
- Regulatory strategies.

The supporting architect engineering primary project path has the assigned development activity of proposing an integrated nuclear-hydrogen preconceptual design and draft 10 CFR 50.59 evaluation. A generic 4-loop PWR plant design is being used as the research model to characterize how a generic nuclear integrated hydrogen design concept may be implemented as a nuclear facility change under 10 CFR 50.59. Inputs being considered in the assumed design include:

- Steam line connections and mass steam flow for operational and faulted conditions.
- Consideration of steam leak assumptions on existing plant analyses.
- Secondary plant dynamics and operator control issues.
- Analog and digital control schemes and limits of manual control including human-system dynamics.
- Operational considerations related to thermal energy extraction including any effects on the reactor core.
- Dispatch limitations and transitions between electrical and hydrogen production.

- Electrical system design interactions and power offtake dynamics.
- Hydrogen equipment physical plant stand-off requirements and onsite storage limits based on detonation analysis design requirements.
- Plant PRA considerations – CDF and LERF.
- Licensing basis events compatibility.
- A sensitivity study element will be included in the architect engineer (AE) modeling to identify any limits for percent-of-plant thermal power (steam extraction) that may define what regulatory approval processes would be required.
- A starting premise for the H3RG is that a design change to implement nuclear integrated hydrogen by HTE must be screened for effects on the existing facility and procedures as described in the UFSAR, as well as the integrated licensing bases, and that a formal 10 CFR 50.59 evaluation will likely be required. In support of informing regulatory approval approaches under the 10 CFR 50.59 process, expert review also will be leveraged for:
    - Comparative reviews of historical industry examples where approval of changes to the facility were appropriately completed under 10 CFR 50.59—especially for FOAK and fundamental operating approach changes.
    - Detailed reviews of historical 10 CFR 50.59 NRC industry feedback and lessons learned on the limits of use of the 10 CFR 50.59 process for approving changes to the facility.
    - Review of ongoing industry 10 CFR 50.59 evaluations that are being issued in support of LTE modifications or small-scale (kW level) HTE demonstrations.
    - Consideration of historical regulatory challenges related to combustible gas concerns at nuclear facilities.
- The approval feasibility of the envisioned preconceptual mechanical-thermal, electrical, and controls changes under a 10 CFR 50.59 evaluation process will ultimately be determined from an integrated design perspective. However, the H3RG leverages a subcommittee structure that evaluates these piece-part design and operational review areas as stand-alone topics. This allows for targeted use of expert review resources for early identification of discrete subcommittee assigned areas that indicate likely success paths or a need for additional research consideration. The subcommittees do not work in isolation. A web-based work platform (Taktix®) allows information sharing and questions between the subcommittees as well as INL and contracted A/Es that are responsible for developing preconceptual design aspects of the pilot project.

Table 7. Activities that were completed and FY 2022.

Activity	Outcomes and Significance	Report or Documentation
Preliminary Probabilistic Risk Assessment of a LWR Supply Heat to a Hydrogen Production plant	• Developed a steam line break initiating event fault tree. • Completed a generic PRA of a heat extraction and delivery system from the secondary side of a PWR for use in a hydrogen production facility. • Two potential licensing approaches which do not require a full NRC licensing review were identified. - 10 CFR 50.59 licensing approach would not be justified due to the change in initiating event frequency for some DBAs increasing by more than 10%. - The initial PRA results for CDF support the use of RG 1.174 as a valid pathway to change without a full LAR. - Recommendations were made for further efforts, which will remove assumptions and conservatism going forward. • Further efforts to remove assumptions and conservatism going forward are recommended. • Dialogue with NRC on the application of RG 1.174 going forward is recommended.	INL/LTD-19-55884, September 2019
Hybrid LWR Systems Licensing Pathway	• The pathway that utilizes an evaluation of the change in DBA frequencies first uses 10 CFR 50.59, to determine if a LAR would be required via 10 CFR 50.90. Changes that meet the requirements of 10 CFR 50.59 do not require additional NRC review and approval. • Regulatory Guide 1.174 (RG 1.174) "provides general guidance concerning analysis of the risk associated with proposed changes in plant design and operation." Specifically, thresholds and guidelines are provided for comparison with Level 1 PRA results for CDF and LERF.	INL/LTD-19-55885, September 2019
Hydrogen Safety Analysis	• Evaluate for the safety specifications of the proposed HTE Hydrogen Production Facility.	Sandia National Laboratories
Preliminary PRA for High-Temperature Steam Electrolysis Hybrid FPOG	• The results of the PRA indicate that application using the licensing approach in 10 CFR 50.59 is justified because of the minimal increase in initiating event frequencies for all DBAs, none exceeding 5.6%. • PRA results for CDF and LERF support the use of Regulatory Guide 1.174 as further risk information that supports a change without a full LAR. • Further insights provided through hazard analysis and sensitivity studies confirm with high confidence that the safety case for licensing a heat extraction system addition and a high-temperature electrolysis facility sited at 1.0 km from the NPP is strong and that the placement of an high-	INL/EXT-20-60104; October 2020

Activity	Outcomes and Significance	Report or Documentation
	temperature electrolysis facility at 0.5 km is a viable case. Site-specific information can alter these conclusions.	
Report on the Creation and Progress of the Hydrogen Research Regulatory Review Group	• The H3RG was formed to begin to identify the technical and safety risks that may need to be addressed to follow 10 CFR 50.59 requirements. • H3RG includes a broad collaboration with primary participants from DOE-supported national laboratory research leads, contracted architect engineering participants, and nuclear utility licensing and design personnel. • Report discusses H3RG tasks, interim accomplishments that are consistent with NRC requirements. • The early findings will be refined as new information is provided by engineering studies and operational considerations.	INL.RPT-22-66844; April 2022

3.3.2 Plans and Schedule

In FY 2023, meetings with a H3RG will continue to be held. The preliminary generic PRA will be updated to match progressive A&E firm and EPC design and operating feasibility studies and preliminary Front Energy Engineering Design (pre-FEED) of the thermal-hydraulic, electrical connections, and operating controls systems for specific FPOG options.

The following tasks have been planned:

- Continue to hold H3RG meetings to provide input and review of plant modifications, operating concepts, and PRA updates relative to FPOG hydrogen production:
  - Develop H3RG Guidance and Recommendations to Contributing Nuclear Utilities and Industrial Leaders of Regional Clean Hydrogen Hub Project Demonstrations with Nuclear Energy.
  - Determine a reference plant or a reference hypothetical plant for hydrogen safety analysis and a realistic PRA that can be leveraged by utilities to conduct plant-specific probability and safety analyses.
  - Provide the guidance developed with support from the H3RG to the contributing H3RG members and utilities and industries conducting studies relevant to Regional Clean Hydrogen Hub demonstration projects.
- Complete a comprehensive and bounding hydrogen production and storage safety analysis using Hydrogen Risk Assessment Models in support of an updated PRA based on a preliminary A&E design of the coupling between the nuclear plant and up to 1,000-MWe hydrogen production capacity with up to 1,000 kg of hydrogen storage; address hydrogen safety and plant design and operation scenarios that minimize the possibility and impacts of hydrogen deflagrations, potential detonations, and potential explosion “missile” impacts on the NPP.
- Complete an updated PRA and sensitivity analysis using SAPHIRE-based on the A&E designs for various hydrogen plant sizes for thermal energy offtake, electrical switchgear, and the location of the hydrogen production plant and appurtenant hydrogen storage and delivery systems within and without the protected area of the NPP.

1. Translate the SAPHIRE-based PRA to Computer-Aided Fault Tree Analysis System for a specific LWR power plant selected by the H3RG subcommittee to provide a referenceable PRA that is consistent with LWR licensing basis and practices.

   The following out-year activities will be considered:

- In FY 2024, continue H3RG meetings as the interests and needs of the contributing members is warranted.
- In FY 2024–2027, complete a referenceable PRA for 30% Thermal Energy Extraction Based on an A&E Feasibility Study.

Benefits to Industry

This work has direct relevance to the scale-up of demonstration projects to commercial-scale. The outcomes of these efforts apprise the FPOG applications industries of the need to design systems that will help reduce or mitigate safety risks. Eventually, it will be the joint responsibility of the FPOG user application to work with the LWR plant owners to address nuclear plant licensing and state/EPA permitting of the industrial operations.

- Plant owner/operator support of a Hydrogen Regulatory Research Review Group benefits the entire LWR industry. It engages commercial developers of control simulators and software needed to execute FPOG options.
- These tasks provide a relevant PRA for LWR owners and hydrogen plant owners/operators who establish plant design basis and operating requirements.
- The outcomes of this activity will be provided to utilities and industry that are proposing to build a regional hydrogen hub using nuclear energy. The milestones provide an initial, bounding proxy for case-specific nuclear-hydrogen demonstrations until case-specific hydrogen studies are completed for commercial demonstration projects.
- These tasks also provide the nuclear utility and industries with an example PRA that can be leveraged for plant-specific PRA and licensing activities to be conducted by the nuclear plant.

4. QUALITY ASSURANCE

Quality assurance requirements for this research program are defined in INL/EXT-10-19844, “Light Water Reactor Sustainability Program Quality Assurance Program Document.” This Quality Assurance Program is based on the requirements in American Society of Mechanical Engineers NQA-1-2008, 1a-2009, “Quality Assurance Requirements for Nuclear Facility Applications.” It covers all the R&D activities of the program, including any quality assurance requirements applicable to the technologies and related concepts developed and implemented under the pilot projects.

A specific quality assurance plan is developed for the work package associated with each pilot project, employing an assessment matrix that examines each task in the project to classify it according to the type of research it represents basic, applied, or development. These research types correspond to a graded approach to the quality assurance requirements, in which the quality assurance requirements appropriate to each type are applied.

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Appendix A

Flexible Plant Operation and Generation

Appendix A
Flexible Plant Operation and Generation

The light water reactor (LWR) fleet is vital to the United States (U.S.) national security. Not only does it produce approximately 20% of our clean electricity (about 8 Quads), but it maintains the reliability of the grid. It is increasingly being viewed as a source of power generation that can also provide resiliency to the grid, meaning it can support voltage and frequency control that helps and help regulate the grid.

Nuclear energy lies within the nexus of three components of national security (). Nuclear power plants provide clean, concentrated, dependable, and affordable energy that can help stabilize climate change by avoiding greenhouse gas emissions (GHG), as well as avoiding the air pollutants emitted by combusting fossil fuels and minimizing the amount of land occupied or altered by energy production.

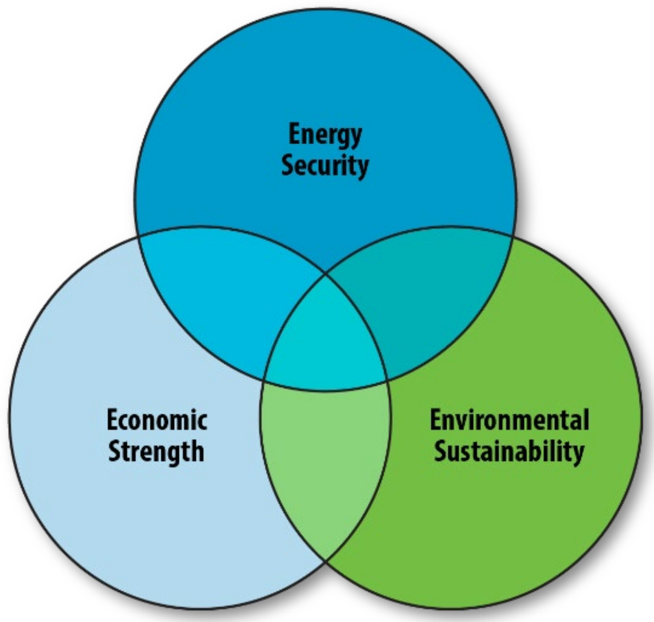

Figure 20. Nuclear energy contributions to national security.

The current fleet of light water reactors (LWRs) nuclear power plants (NPPs) have five potential operating options:

- Traditional Baseload. The nuclear plant operates as a baseload power station, at near full capacity except during regular outages to refuel and perform maintenance or plant upgrades. This mode of operation is declining in the United States as baseload capacity demand shrinks in both deregulated and regulated markets, and as the selling price of electricity– locational marginal price (LMP), or around-the-clock (ATC) price - falls below the total electricity production cost of nuclear stations.
- Flexible Plant Operation. A nuclear power station dispatches power by ramping down and up to meet the electricity market generation demands meeting “net power for load minus renewables.” Besides selling less electricity throughout the year, this mode of operation could impact revenues due to higher maintenance costs and impacts on the fuel cycle.
- Dedicated Energy Park. A traditional nuclear power generation station is dedicated to selling power and thermal energy (steam or a secondary heat delivery loop) to one or more energy users according to the energy demands of the user or users under a direct energy purchase agreement. This paradigm

will require a coordinated buildup of energy users near the power plant where a dedicated, off-the-grid, power line and heat delivery system supplies energy to the industrial users. An earlier market study by Idaho National Laboratory (INL) and the NREL showed a wide variety of industrial users could take advantage of the low-cost steam produced by an LWR.

- Hybrid Operations. The nuclear plant participates in the electricity grid market while apportioning electricity or thermal energy to one or more energy users according to market signals. The purpose of this mode of operations is to optimize revenue for the nuclear plant. The business case for hybrid options depends on the efficient use of both the energy and the capital of the overall system. Hybrid operations will usually require energy storage to ensure a constant supply of energy is sent to the industrial manufacturing plant. Hybrid operations open the potential of the nuclear plant to be used as either spinning or non-spinning reserves when the industrial customer rapidly ramps down energy use and gives up the electricity to the grid. Then, once the grid load generation is stabilized by reduced generation demand or other capacity reserves, the industrial user will ramp back up to normal operations. If the industrial energy user involves large resistive loads, then it may also be possible to provide voltage or frequency regulation by taking up or giving up power to the grid in a matter of a few seconds or less. The industrial loads tied to the nuclear plant can also be curtailed or increased to adjust the power factor of the grid.
- Power Revenue Optimization. The nuclear plant produces and stores energy during periods of oversupply to dispatch additional electricity to the grid during periods of scarcity. This mode of FPOG can also be considered a special case hybrid operation. It is unique in the sense that Power Revenue may be optimized with energy storage (as thermal, electrical, or chemical forms) with the pure motive of regenerating electrical power to send to the grid. In this case, new concepts for energy diversion will be required that are similar to hybrid operations.

All but the first option constitutes a form of FPOG and subscribe to the goal of optimizing the revenue of each of the participating partners. FPOG operations are naturally becoming necessary in regions of the country where wind or solar energy are increasing and in regions where the low-cost and high availability of NG has driven down the price of electricity. Many nuclear plants have responded to increasing volatility in net demand by operating flexibly. Although this practice preserves the contribution of nuclear energy to grid stability, it does not reduce the plant operating costs. It increases the cost of nuclear-sourced electric power ($/MWh) as the fixed costs of operations are allocated to a lower production base. Nor does it represent full asset utilization from a capital investment standpoint.

illustrates the concept of FPOG hybrid plant operations. The nuclear power plant dispatches power to the grid or sends steam and electricity to an industrial user. In this manner, the nuclear reactor can produce nonelectric products during periods of excess power generation capacity when these plants are not able to clear the day-ahead electricity market. This practice preserves the contribution of nuclear energy to grid stability and reduces economic losses associated with negatively priced electricity sales. It provides an offtake for energy produced by a nuclear power generating station when the price offered for committing electricity to the grid is lower than the cost of producing this electricity. A secondary user benefits by purchasing electrical power, steam, or thermal energy directly from the nuclear power plant at a cost that is presumably lower than can be purchased from the grid at either the electricity transmission-customer level or the electricity distribution-customer level.

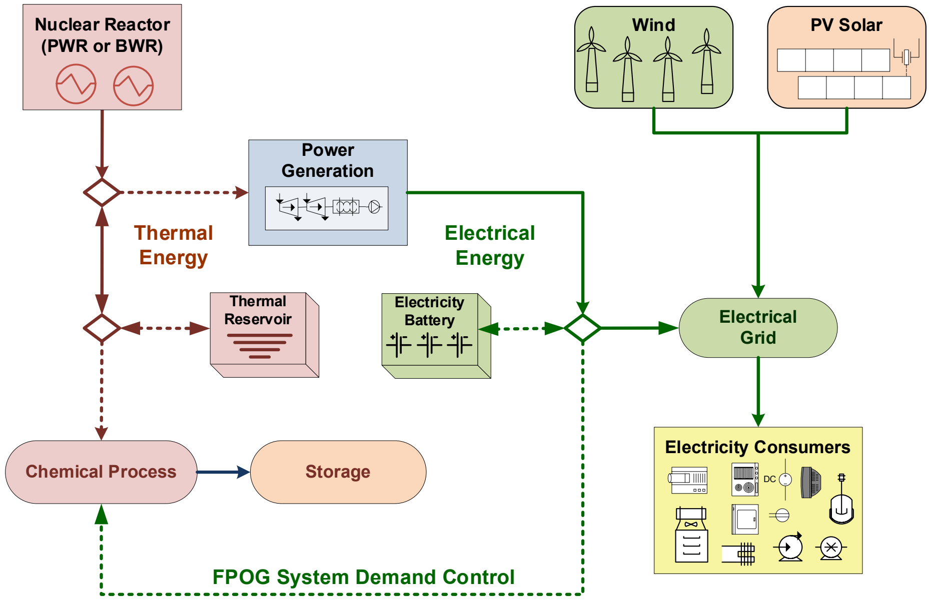

Figure 21. FPOG concept for nuclear power plant.

Understanding Electricity Markets

Electricity markets are undergoing rapid transition given the advent of low-cost wind and solar energy that is driven as much by policy incentives in the form of investment tax credits and production tax credits for clean energy as it is for lowest-cost power generation sources. Regardless of public policy and preferences, renewable energy is projected to increase in the South/Southwest and Midwest where there is a high capacity of solar and wind energy, respectively. The variable nature of wind and solar energy requires that other generation sources respond to load demand capacity in an increasingly dynamically responsive manner. illustrates the consequences of the buildout of roof-top and utility-scale solar photovoltaic energy. Unable to compete with the marginal cost of electricity production from those sources, NPPs and other baseload must either be curtailed or pay renewable generators to curtail.

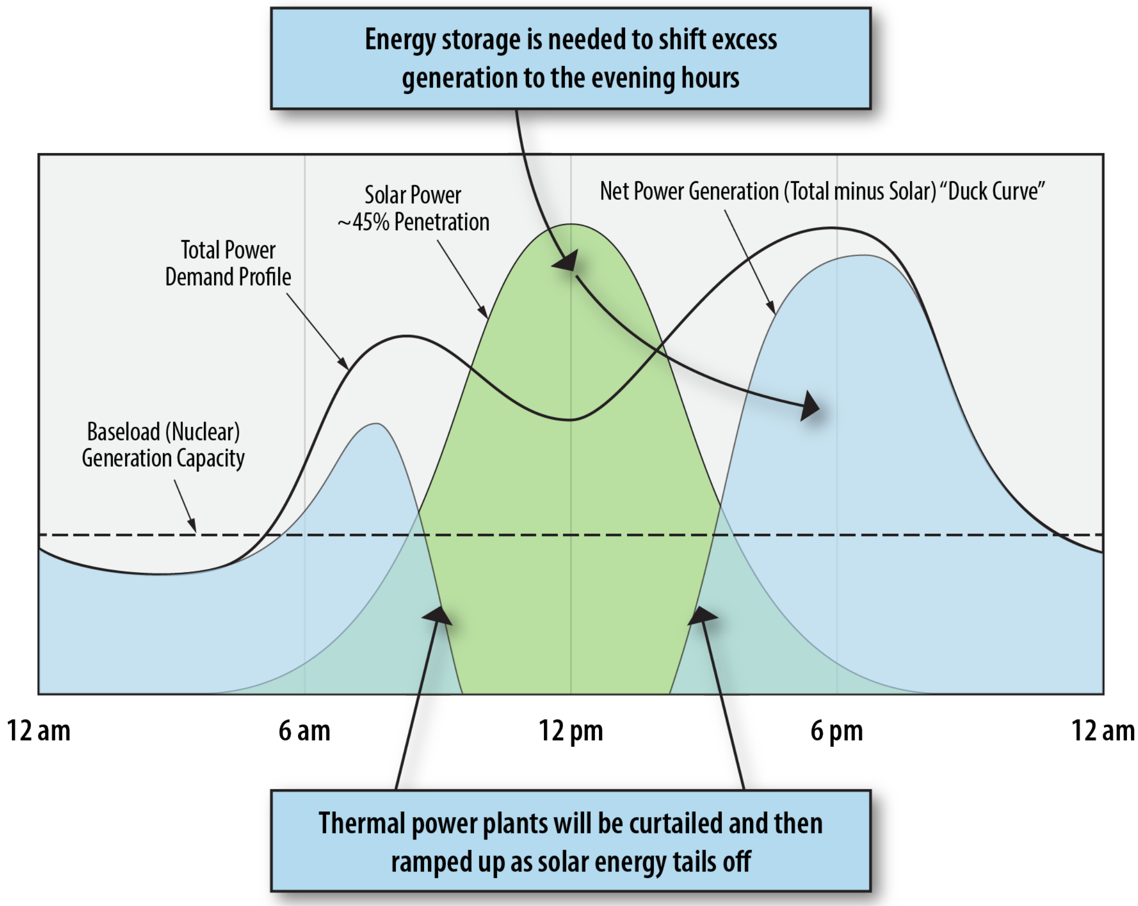

Figure 22. Illustrative consequences of excess solar energy power generation.

Excess generation capacity is having a profound impact on minute-by-minute electricity pricing dropping during the day hours. Instances of negative pricing have been experienced and this trend will likely continue. This phenomenon is well understood and is being addressed by public utility commissions and power cooperatives. It is the impetus for energy storage solutions that can reserve excess power for late-afternoon and evening power demand as solar energy tails off. It has motivated utility-wide demand response studies and implementation of smart appliances

Wind energy has a similar impact on the grid load-matching generation demand, except greater uncertainty in wind output increases uncertainty in net load makeup that must be met with conventional generators. Variation in wind generation output also requires steeper ramp rates and range.[a]

Geothermal capacity in the United States produced 16 GWh in 2019. This is equal to just 0.4% of total U.S. utility-scale electricity generation.[b] In 2019, the total U.S. conventional hydroelectricity

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a Renewable Electricity Futures Studies, National Renewable Energy Laboratory, https://www.nrel.gov/analysis/re-futures.html

b U.S. Energy Information Agency; https://www.eia.gov/energyexplained/geothermal/use-of-geothermal-energy.php#:~:text=Energy%20Information%20Administration%20-%20EIA%20-%20Official%20Energy,the%20top%20five%20states%20for%20geothermal%20electricity%20generation.

generation capacity was 79,746 megawatts (MW)—or about 80 million kilowatts.[c] Neither geothermal nor hydropower are projected to increase substantially, and seasonal generation capacity varies according to precipitation and policies that are intended to protect anadromous fish. With the current drought in the West, the capacity of hydropower is becoming less reliable.

In all regions of the country, but especially in the Northeast, Midwest, and Southeast, low-cost NG is leading to the retirement of coal-fired power plants. The load is shifting to NG turbines. This is having a profound impact on the prices of electricity wholesale markets.

plots the cost of electricity futures for West-PJM versus the cost of NG. The data show the correlation between NG prices and electricity prices which vary according to seasonal demand for NG. Higher demand for heating during the winter months changes the ATC price of NG, which in turn is reflected in the cost of electricity production which is now dominated by NG generation facilities in this region. Extreme weather events can impact both heating and electricity demand that outstrips the installed capacity of the system. During these periods, baseload thermal plants can sell electricity and generate substantial revenue. However, throughout the balance of the year, the LMP of electricity (or ATC) averages less than $30 MWh as seen in the price duration curve plotted in .

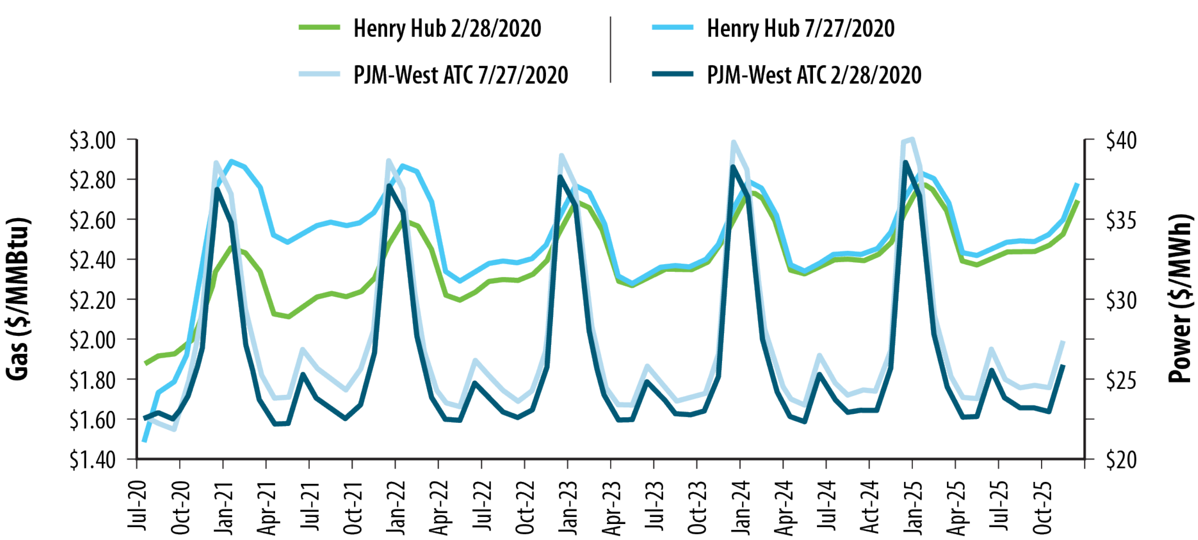

Figure 23. Henry Hub and PJM-West ATC wholesale futures prices.[d,e]

c U.S. Energy Information Agency; https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php#:~:text=Energy%20Information%20Administration%20-%20EIA%20-%20Official%20Energy,states%20for%20hydropower%20generation%20capacity%20and%20hydroelectricity%20generation.

d https://group.met.com/energy-insight/natural-gas-prices-forecast/3

e https://www.pjm.com/markets-and-operations/energy/real-time/it-sced-forecasted-lmps.aspx

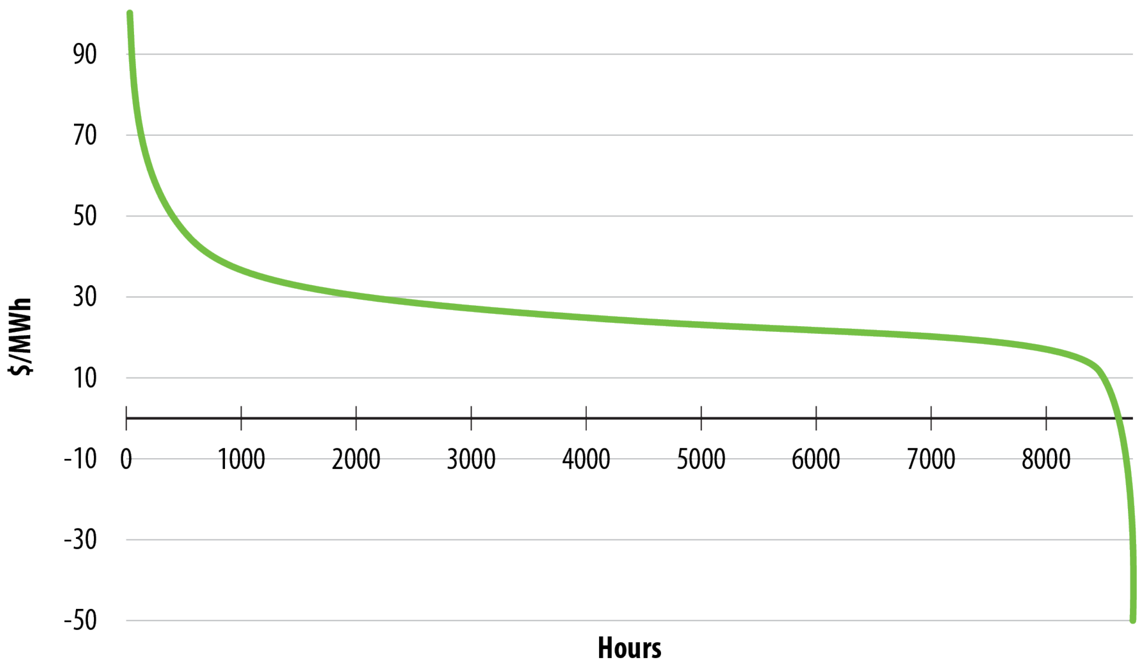

Figure 24. Price Duration Curve for a West-PJM Location[f]

While the price of NG has historically be highly volatile, energy forecasts project the price will continue to be relatively low in the United States and will only rise monotonically as domestic and international demand for NG climbs. Because NG supply in the United States is tied to shale fracturing to produce oil, any policies affecting fracturing practices, or any decline in demand for petroleum fuels could increase the volatility of NG pricing.

Spare power generation capacity exists to ensure power supply reliability. The buildout of variable renewable generation requires that sufficient backup capacity to meet power demand throughout the entire year, including peak seasonal demand during the winter and summer months, is provided. The addition of NG turbines throughout the country has reduced the need for coal-fired steam plants to provide reserve capacity. Energy storage in the form of hydro-electric plants, grid-scale batteries, pumped hydro, and compressed air are being used, or are being considered to support reserve capacity, but the costs or geographic locations that can accommodate these systems is currently a barrier. FPOs may give NPPs an opportunity to maintain, or to regain payments for providing reserve capacity.

Grid frequency is maintained by balancing supply (generation) with demand (load) on a continuous basis. Maintaining grid frequency is the responsibility of grid operators and balancing authorities. Some grid operators currently provide financial compensation for resources that are capable of regulating grid frequency. As more variable renewable generation enters the market, the need for grid regulation services is projected to increase. FPOG operations that are designed to make rapid adjustments in power demand may provide financial advantages to a nuclear power plant.

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f Boardman, R.D., Wendt, D. et al. 2019, "Region-specific Merchant Hydrogen Market and Techno-Economic Assessment of Electrolytic Hydrogen Generation," Cooperative Research and Development Agreement Report for limited distribution to CRADA partners, INL/LTD-19-55247

As the level of grid-connected photovoltaics penetration continues to rise, the importance of power factor and power factor correction is becoming increasingly relevant to the grid and customers.[g] The supply of reactive power is important in an AC power grid. The amount of reactor power produced by generators must closely match that which is being consumed. A leading power factor in the systems (due to capacitive loads) causes the voltage to rise while a lagging power factor (due to inductive loads) will cause the voltage to fall. Power factor is best corrected locally. If the reactive power is either under or over supplied, the voltage on the network may rise or fall to a point where generators must decrease generation or switch off to protect themselves. Because most inverters connected to the grid inject power at unity power factor (meaning they only produce active power), this in effect reduces the power factor, as the grid is then supplying less active power, but the same amount of reactive power. This implies that corresponding power factor adjustments may be needed by thermal power generators rather that the selection of inverter products that can adjust the power factor for solar PV units. FPOG applications that can change the power factor to accommodate both the buildup of solar PV and industry user may offer additional revenue to the nuclear power plant.

Some FPOG systems may be capable of dispatching load to the grid by quickly shifting power from the industrial user to the grid. Under this mode of operation, depending on the characteristic response time of the specific FPOG system, the hybrid system would be dispatchable as spinning reserve, non-spinning reserve, or replacement reserve, as represented in . The load is shifted back to the principal industrial user once other less expensive capacity is brought onto the grid. Some hybrid nuclear plants could also regulate reactive power as well as frequency if the response time constants of the integrated system are sufficiently agile. Such ancillary grid services may someday be valorized by the regional reliability office or grid balancing authorities.

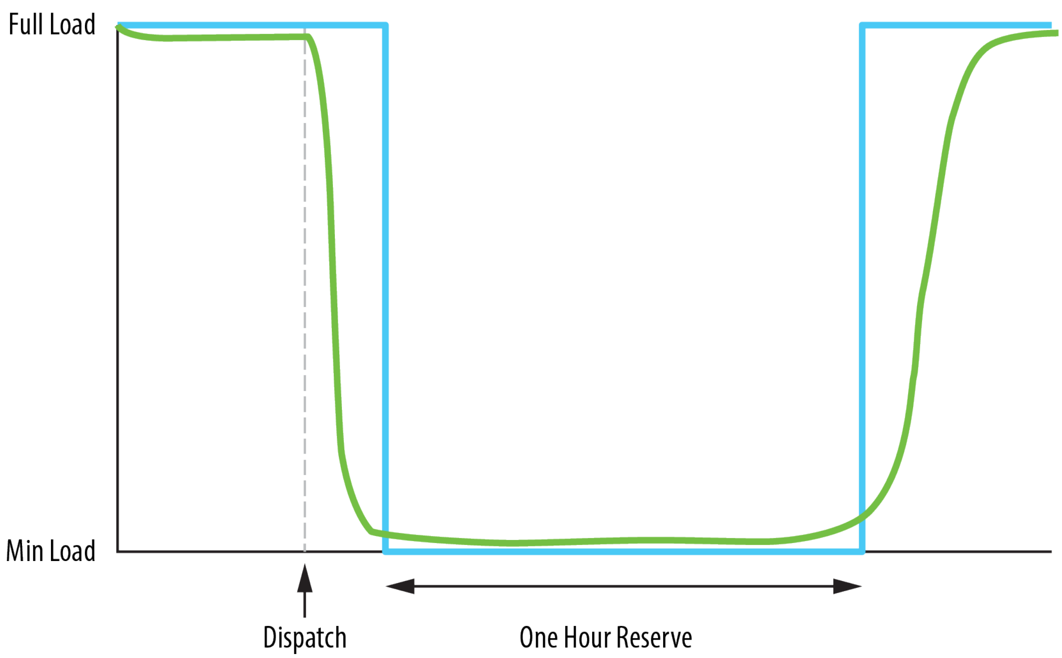

Figure 25. Example of FPOG functionality as grid spinning reserve capacity.

g https://www.gses.com.au/wp-content/uploads/2016/03/GSES_powerfactor-110316.pdf

Some FPOG cases may require approval of governing utility commissions, depending on whether flexible operations can affect grid supply and pricing, and in consideration of provisions for grid-capacity payments that may apply to a hybrid system. The benefit of nuclear energy as a clean energy source is becoming a relevant value proposition that can enter into consideration as detailed life-cycle assessment of FPOG are completed and included in technical and economic assessment.

In summary, FPOG is driven by several current grid market realities and future uncertainties that provide incentive to develop alternative market opportunities for the U.S. NPPs.

- Expansion of renewable energy and NG power generation sources is increasing; this reduces the demand on conventional thermal generation sources.
- The variability of renewable energy increases is causing conventional generation sources to ramp up and down more frequently to make up net power generation; besides selling less electricity throughout the year, this mode of operation could impact revenues due to higher maintenance costs and impacts on core fuel cycles.
- The low-cost of NG is reducing the clearing price of electricity bids; in some locations, the average wholesale price of electricity is insufficient to cover the costs of operating a nuclear power plant.
- Because nuclear energy has low-carbon emissions that are comparable to wind and solar energy, nuclear power can help states and utilities achieve clean energy targets.
- The role of NPPs in providing grid services, including reserve capacity, frequency regulation, and power factor adjustment may increase plant revenue. FPOG may enhance these market opportunities by providing power transactions with the grid.

Understanding New Markets for Nuclear Plants

The diverse manufacturing, agriculture, and transportation systems around the country, and in particular the Midwest, Southeast, and Gulf Shores, provide several advantages in converting a nuclear power plant to a hybrid plant that produces feedstock commodities, such as methanol, polyethylene, iron-ore pellets, and transportation fuels. Hydrogen is again emerging as an energy currency that can be used for the production of iron pellets, nitrogenous fertilizers, polymers, synthetic fuels, forest products, and food products. Hydrogen is also being considered for large-scale and long-term energy storage when power generation capacity exceeds the demand of the grid. It can also be injected into NG pipelines and burned as fuel for heating and power generation with a fuel cell or gas turbine. If hydrogen is produced from clean, low-emissions energy sources, this will have a significant impact on air quality and can help significantly reduce greenhouse gas emissions in the United States and throughout the world. A U.S. DOE concept referred to as H2@Scale (pronounced “hydrogen at scale”) explores the potential for wide-scale hydrogen production and utilization in the United States to enable resiliency of the power generation and transmission sectors while also aligning diverse multibillion-dollar domestic industries, domestic competitiveness, and job creation. was developed by the DOE Hydrogen and Fuel Cell Technology Office with input from a team of the DOE National Laboratories.

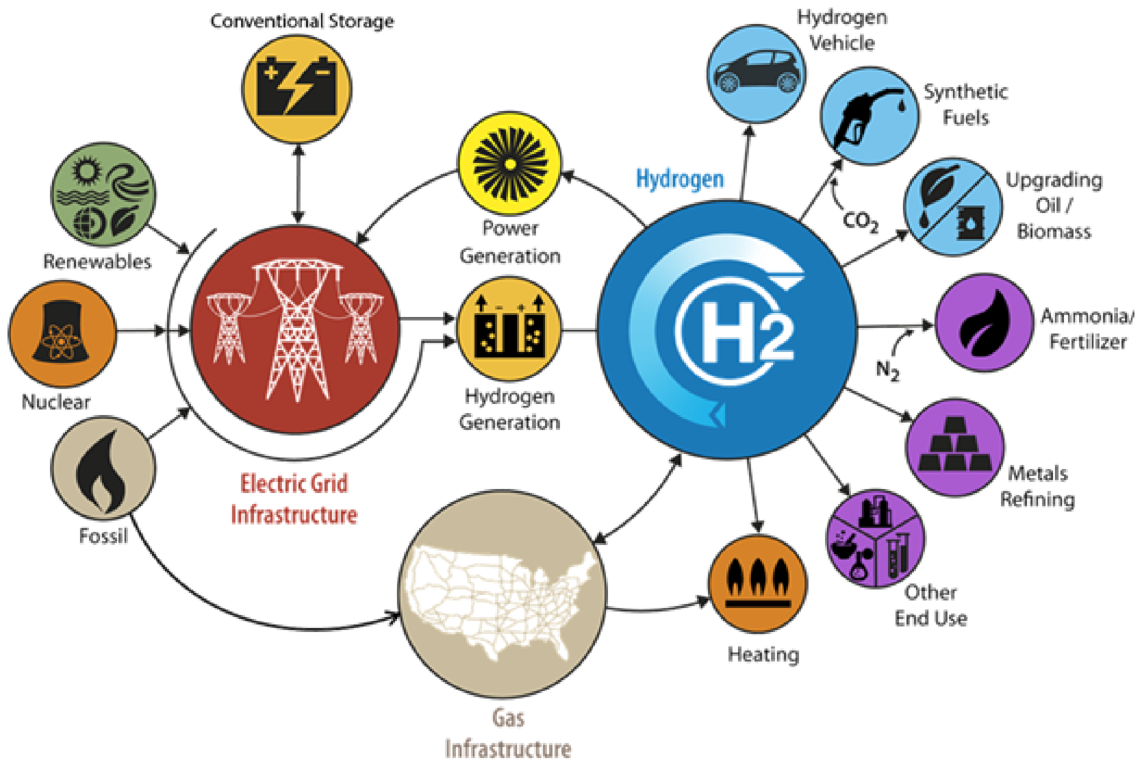

Figure 26. Visualization of DOE concept for H2@Scale.[h]

The conventional process for producing hydrogen is SMR, which uses steam and high-temperature heat to convert NG into H_2 and CO_2. NPPs can provide steam to SMR plants, but this would require changes to the current advanced auto-thermal SMR processes. Alternatively, electrolysis can be used to split water into hydrogen and oxygen using electricity or pure thermal energy. With assistance from DOE, advanced water-splitting materials and technologies are rapidly being advanced by electrolysis-technology-development companies. This includes the use of alkaline electrolysis, PEM electrolysis, and HTE. HTSE improves the overall efficiency of water-splitting. When nuclear or renewable electricity and heat are used, environmental emissions are near zero.[i] The emission rate for SMR is about 8 kg-CO_2/kg-H_2. Thus, if 20 NPPs were converted to hydrogen production, with each plant producing 250,000 tonne-H_2/y, this would cut U.S. CO_2 emissions by 50 million tonnes annually. This is approximately 1% of the total U.S. CO_2 emissions of 5,130 million metric tonnes in 2019 [https://www.statista.com/statistics/183943/us-carbon-dioxide-emissions-from-1999/].[j] An important key is that this emission reduction can be passed on to those industries consuming this hydrogen.

A large, consistent supply of clean hydrogen near a nuclear plant would draw new industries to the area, especially those shown in Figure 27. Some hydrogen users, such as iron-ore reduction plants and ammonia plants, could practically take all the approximately 250,000 tonnes of hydrogen per year that could be generated by a single nuclear power generating station. An oil refinery producing 250,000 barrels per day oil refinery requires about 75,000 tonnes merchant hydrogen per year; thus, one nuclear plant could supply hydrogen to about three typical refineries. The nation's first synthetic fuels (synfuels) plants could also be sited near this hydrogen plant to convert CO_2 collected from the several ethanol

h DOE Hydrogen and Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/h2scale

i Kim, J.S., Boardman, R.D., Bragg-Sitton, S.M., 2018, "Dynamic Performance Analysis of a High-Temperature Steam Electrolysis Plant Integrated within Nuclear-Renewable Hybrid Energy Systems, Applied Energy, 228.

j https://www.statista.com/statistics/183943/us-carbon-dioxide-emissions-from-1999/.

plants in the region into methanol-based chemical feedstocks and fungible biofuels. With these perspectives in mind, initial TEA completed by the FPOG Pathway have evaluated the business case for the following hybrid plant operations. The outcome of these studies provided incentive for two nuclear plant owners/operators to apply for DOE funding to demonstrate the production of hydrogen using an offtake of electricity from the plants.k A workshop sponsored by the University of Toledo in January 2020 highlighted the markets that could be built around scale-up of the pilot test facility. These options were captured in a report with the graphic picture shown in .

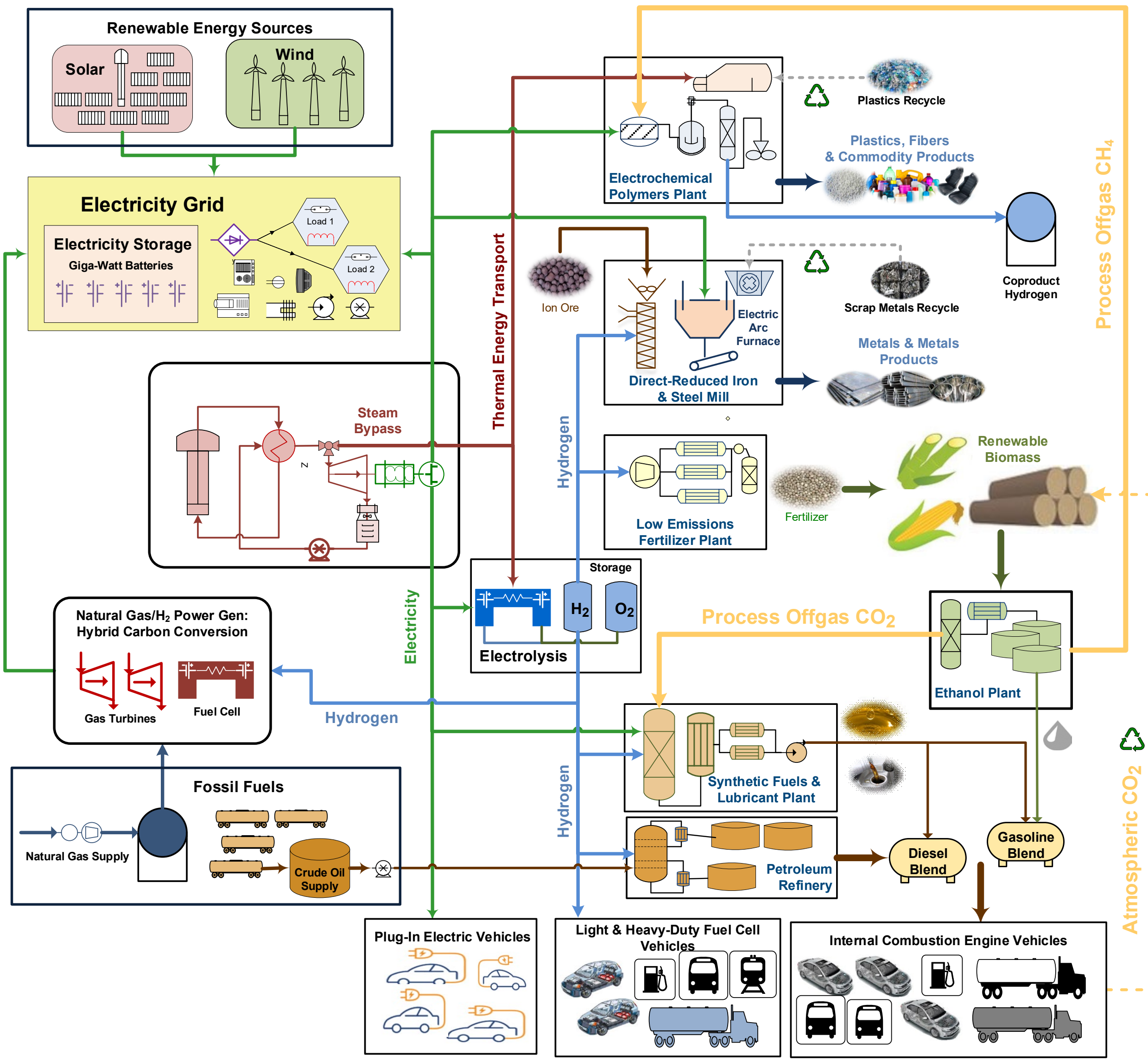

Figure 27. Example of FPOG energy complex shifting clean energy to chemical and fuels production.

Calculations have shown the existing fleet of nuclear reactors can reliably produce cost-competitive, moderately high-pressure steam (5.2 MPa, ~300°C) for the projected life of a large capital investment project (see). The cost of steam generation and delivery by an existing LWR is already lower than the

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k Otgonbaatar, U., Clean Nuclear Energy for Industry, 2020, https://gain.inl.gov/SiteAssets/GAIN_WebinarSeries/2020.04.16_Part1-CleanNuclearEnergyForIndustry/2020.04.16_CleanNuclearEnergyForIndustry.pdf.

cost of producing steam with a new industry-scale NG package boiler. In addition, while the cost of NG production could stay historically low for many years, this depends on several factors, and the price of NG could rise at any time before resource scarcity is realized. The cost of nuclear fuel, on the other hand, is projected to remain flat for decades to come, with little or no volatility in price up to 40 to 60 years of future LWR operations. This assumes LWR upgrades for license renewal remain within plant maintenance and refurbishing activities. Hence, one objective of this Pathway is to help design the thermal energy delivery systems and control interfaces that will enable FPOG to support industrial heat utilization.

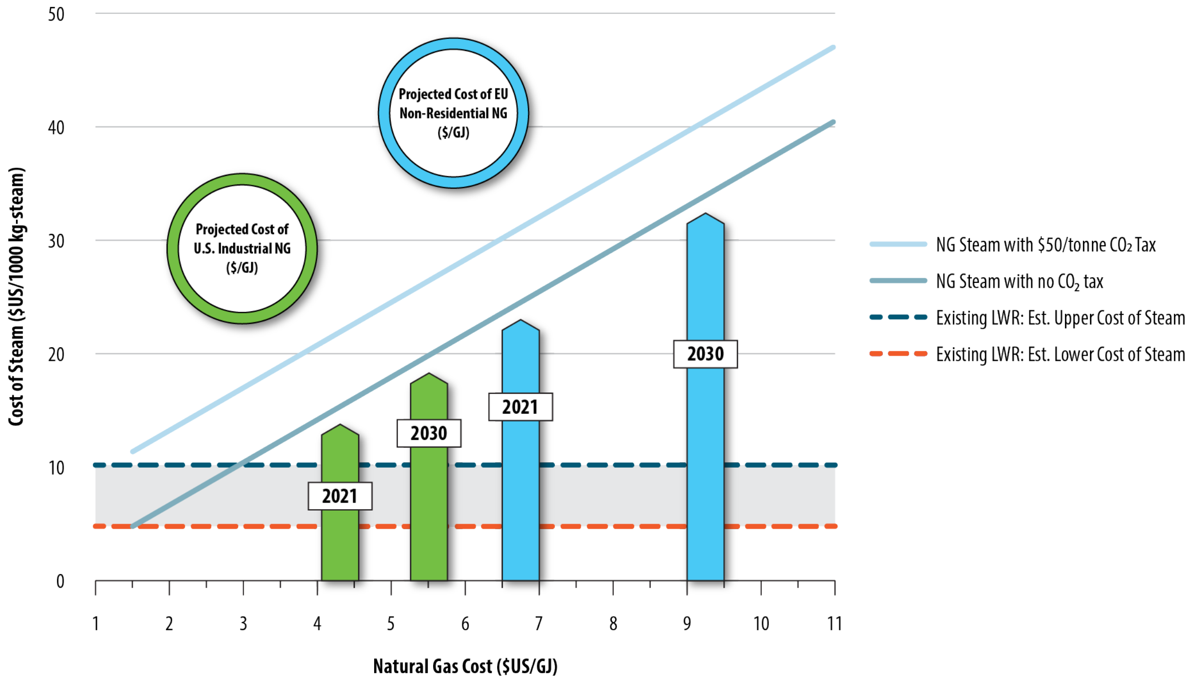

Figure 28. Comparison of steam production costs for LWR versus NG.

In general, processes that integrate well with LWRs are those that require substantial water evaporation (e.g., specialty chemicals, chlor-alkali, paper and pulp, and food processing) or have large electrical and thermal demands (e.g., ethane non-thermal deprotonation). In the petrochemicals industry, LWR process heat can be used to satisfy heat duties in specialty chemical processes, typically for downstream separations, purifications, or plastics processing (to melt the polymer material). Heat duties in the chlor-alkali, paper and pulp, and food processing industries can demand 100-MWth to 250-MWth steam duties. When combined in an industrial park, these facilities would consume a significant fraction of an LWRs energy output even before considering the (substantial) electrical demands. A well-designed industrial park containing multiple interacting processes could produce a variety of value-added chemical processes efficiently and with minimal GHG emissions, reducing the climate impact of key industrial processes.

Clean Energy Markets

The trend toward clean, zero-emissions carbon energy may also impact future energy pricing of NG. Fourteen states have raised clean energy goals since 2014. Seven of these are targeting 100% carbon-free standards (viz., NY, CA, NM, NV, WA, ME, and VA). The most recent is Virginia, where Investor Operated Utilities must serve 100% of load with carbon-free sources by 2050. Five additional states are in discussions to further expand clean energy policies currently (viz., AZ, IL, PA, DE, and UT). In response to these state policies and increasing customer preference for clean energy, nearly 30 utilities have adopted voluntary carbon reduction targets (Table 8).

Table 8. Utilities with emissions reduction commitments

Utility	Clean Energy Goal	Target Date	Utility	Clean Energy Goal	Target Date
Alliant Energy	80% CO_2 Reduction	2050	IDACORP	100% Carbon-Free	2045
Ameren Missouri	80% CO_2 Reduction	2050	MGE Energy	Net-Zero Carbon	2050
Arizona Public Service (APS)	100% Carbon-Free	2050	MidAmerican Energy	100% Renewable Target	None
AVANGRID	Carbon Neutral	2035	National Grid	80% Carbon Reduction	2050
Avista	100% Carbon-Free	2045	NiSource	90% CO_2 Reduction	2028
CMS Energy	90% CO_2 Reduction	2040	OG&E	50% CO_2 Reduction	2050
Dominion Energy	Net-Zero CO_2	2050	PG&E	80% GHG Reduction	2050
DTE	100% Carbon Neutral	2050	Portland General Electric	100% Carbon-Free	2050
Duke Energy	Net-Zero CO_2	2050	PSEC	Net-Zero Carbon	2050
Entergy	50% Emissions Reduction	2030	Southern Company	Net-Zero Carbon	2050
Evergy	80% CO_2 Reduction	2050	Tucson Electric Power	30% GHG Reduction and 30% Renewables	2030
Energy Harbor	90% CO_2 Reduction	2045	WEC Energy Corp	80% CO_2 Reduction	2050
Great River Energy	50% Renewable	2030	Xcel Energy	100% Carbon-Free	2050
Hawaii Electric Light	100% Renewable	2045			

Because New York and California may be setting the national trend for clean energy standards it is important to understand how policies in these states are changing not just the electricity market, but transportation and industrial manufacturing. The state of California developed ZEV mandates to curb air pollution emissions from vehicle tailpipes. This spurred the deployment of both battery electric vehicles (EVs) and hydrogen fuel cell electric vehicles. California also developed its low-carbon fuel standard (LCFS) to regulate carbon intensity (CI) of fuels produced, purchased, and used within the state. The CI is calculated based on the life-cycle GHG emissions of the used fuel, or well-to-wheels analysis, accounting for all steps involved in producing, transporting, and consuming the fuel. The LCFS uses ANL's GREET model[l] for the well-to-wheels analysis to calculate the CI of alternative transportation fuels, including hydrogen pathways for use in fuel cell vehicles. In April 2020, more than 4 million metric tons of CO_2e were traded in the California LCFS market, with the price of CO_2 credits near $200/ton at times.[m] LCFS credits do not expire but can only be held by obligated parties under LCFS.[n] Other jurisdictions, such as the Pacific Coast Collaborative, a regional agreement between California, Oregon, Washington, and British Columbia, align policies with California to reduce GHG emissions within their states. If California regulations were to consider nuclear power as near zero-carbon, i.e., like "renewables", this would open the LCFS credits to the nuclear power generators for electricity and hydrogen production.

New York is currently establishing both a "renewable hydrogen credit"[o] and a "curtailed hydrogen credit" that is worth 1.5 times the "renewable hydrogen credit." The obligated parties will be gas utilities. The size of the credit and the obligation amount are to be decided by the New York State Energy Research and Development Authority. This is currently the only credit scheme in the U.S. that will be specifically established for hydrogen and not restricted to transportation fuels like the California LCFS and EPA RFS. Note that the nuclear power capacity in New York State is over 5 GW and contributed over 37% of total electricity generated in the state in 2019.[p] Furthermore, nuclear power generation in New York State represents 58% of its zero-carbon electricity generation. The 5 GW of nuclear electricity has the capacity to produce over 2000 metric tons of hydrogen each day (0.8 million metric tons of hydrogen annually), capable of powering over 4 million zero-emission fuel cell vehicles in the state.

More generally these credits can be termed ZEC, including renewables and nuclear energy. For example, electricity, hydrogen, and products produced from hydrogen such as steel and ammonia could create ZECs or "low-carbon" green energy credits that can be used by obligated industry entities needing to reduce their carbon footprint. Green steel produced from hydrogen using nuclear energy could qualify for very large (~$150/tonne) carbon credits in the European export markets. Other reports completed by the DOE LWRS Program have highlighted the vast and diverse markets for nonelectric products that can be produced using nuclear energy.[q,r,s,t]

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l https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/lut-doc.pdf.

m https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

n https://stillwaterassociates.com/lcfs-101-a-beginners-guide/?cn-reloaded=1.

o https://www.rff.org/publications/issue-briefs/investment-tax-credits-hydrogen-storage/.

p https://www.eia.gov/state/data.php?sid=NY#SupplyDistribution.

q Knighton, L. Todd et al., "Scale and Regionality of Nonelectric Markets for U.S. Nuclear Light Water Reactors" (March 2020). Idaho National Laboratory, INL/EXT-20-57885, https://www.osti.gov/biblio/1615670.

r Knighton, Lane T, et al., "Clean Energy Credits for Hydrogen Produced from Nuclear Energy" (May 2020). Idaho National Laboratory, INL/EXT-20-58508, https://www.osti.gov/biblio/1773640.

s Hu, Hongqiang et al., "Technoeconomic Analysis on an Electrochemical Nonoxidative Deprotonation Process for Ethylene Production from Ethane" (December 2019). Idaho National Laboratory, INL/EXT-19-56936, https://lwrs.inl.gov/Flexible%20Plant%20Operation%20and%20Generation/Technoeconomic_Analysis_on_an_Electrochemical_Nonoxidative_Deprotonation_Process.pdf.

t Frick, K. et al., "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest." (September 2019). Idaho National Laboratory, INL/EXT-19-55395, OSTI1569271. DOI: 10.2172/1569271.

With this precedent for nuclear energy being included in existing and proposed clean energy frameworks and legislation, it is important to understand the following:

- How the retention of nuclear power generation can help achieve federal and states' decarbonization goals across multiple energy sectors.
- How nuclear power can produce near zero-carbon hydrogen to further decarbonize energy use in transportation.

How the contribution of nuclear power to zero-carbon power markets can be extended further to serve other energy sectors such as transportation, as well as building and industrial heat demand, thus contributing to the goals of decarbonization across multiple energy sectors.