

Light Water Reactor Sustainability Program

Multi-Facility Coordinated Thermal Power Dispatch Research Plan



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Multi-Facility Coordinated Thermal Power Dispatch Research Plan

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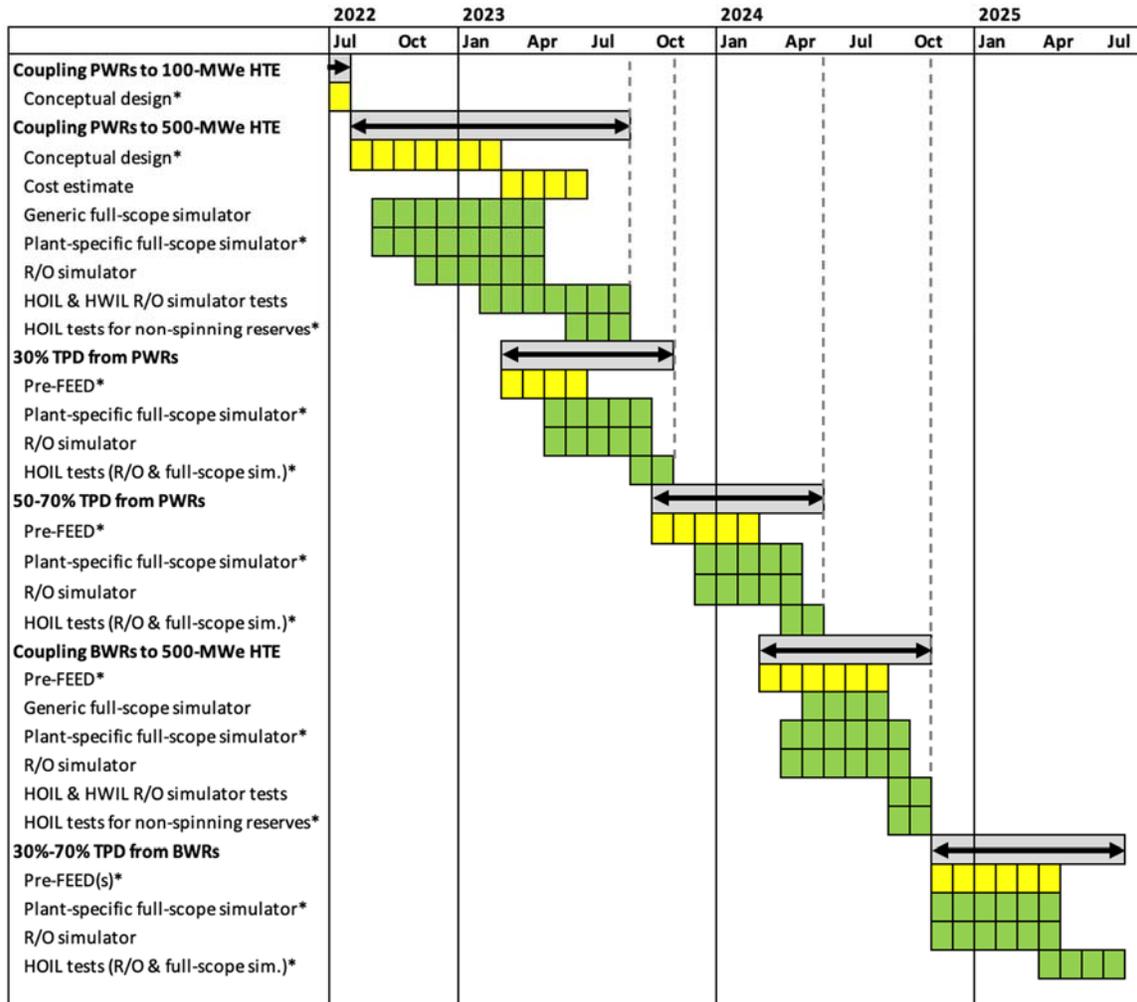
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Office of Nuclear Energy
[Light Water Reactor Sustainability Program](#)**

ABSTRACT

This report presents a multi-facility coordinated research plan for fiscal years 2023 through 2025 for analyzing integrated electric and thermal power dispatch from commercial light water reactors (LWRs) to tertiary industrial loads. The work will be performed within the U.S. Department of Energy (DOE) Light Water Reactor Sustainability Program (LWRS)—Flexible Plant Operation and Generation Research (FPOG) Pathway. A Westinghouse 4-loop reactor has been selected for analysis as being representative of PWRs in general. During the second and third years of the project, a single representative BWR will also be selected for analysis. Other specific configurations of LWRs will not be analyzed in this project. Analyses will include detailed thermal-hydraulics modeling, electric power modeling, and utilization of reduced-order and full-scope nuclear power plant (NPP) simulators, as described in Section 2. The analyses will include +/- 30% cost estimates for modifications that will be needed for the proposed operations.

Analyses will include pre-front-end engineering design (pre-FEED) studies as well as development of corresponding simulators. Those simulators will be used to verify proposed concepts of operation for integrating dynamic thermal and electrical power dispatch from LWRs to the grid and to potentially multiple tertiary industrial loads. This project will use real-time process simulators with human operators as elements in the control loops of the NPP simulator, the tertiary industrial load simulator, and an electric grid simulation to explore and test proposed concepts of operation.

As shown in ES Figure 1, effort in the first year of the project will focus primarily on coupling PWRs to high temperature electrolysis (HTE) hydrogen production facilities at a nominal scale of 500 MWe(DC). Work in 2023 will also focus on a different, unspecified tertiary load that consumes as much as 1,100 MWt (approximately 30% of the total rated thermal power of a 4-loop Westinghouse PWR). Toward the end of 2023, attention will shift to higher levels of thermal power dispatch (TPD) between 50% and 70% of the total rated reactor power from PWRs. The exact level of TPD will depend upon plant impacts predicted by thermal and electric power analyses as well as potential regulatory restrictions. In 2024, work will commence on thermal and electric power dispatch from a representative BWR, following the research pattern established for PWRs.



ES Figure 1. Gantt chart for planned activities. Tasks marked with “*” symbols include milestones that will be reported to the USDOE.

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ACRONYMS

A/E	Architectural and Engineering Firm
BWR	Boiling water reactor
CRADA	Cooperative Research and Development Agreement
DI	Deionized or demineralized water
DOE	Department of Energy
DRTS	Digital real time simulation
EIL	Energy Innovation Laboratory (Human Systems Simulation Laboratory)
ESL	Energy Systems Laboratory (Physical Testbeds and Real Time Data Simulator)
ETAP	Electrical power transient analysis software
FDW HTR	Feed water heater
FEED	Front-end engineering design
FPOG	Flexible Plant Operations and Generation
GE	General Electric
GONUKE	Guideline on Nuclear Usability Knowledge Elicitation
GPWR	Generic Pressurized Water Reactor
GSU	Generator step-up
H ₂	Hydrogen
H3RG	Hydrogen Regulatory Research and Review Group
HMI	Human-machine interface
HOIL	Human-operator-in-the-loop
HP	High-pressure
HSI	Human-system interface
HSSL	Human Systems Simulation Laboratory
HTE	High temperature electrolysis
HTSE	High temperature steam electrolysis
HWIL	Hardware-in-the-loop
I&C	Instrumentation and Control
INL	Idaho National Laboratory
LAR	License amendment review
LDRD	Laboratory Directed Research and Development
LP	Low pressure
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability Program

MCR	Main control room
MSR	Moisture Separator Reheater
MVA	Megavolt-amperes
MWe	Megawatt electric
MWt	Megawatt thermal
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Document
OMCF	Open Meta Calculation Framework
PEPSE	Thermal-hydraulics modeling software
PRA	Probabilistic risk assessment
PSCAD	Electric power modeling software
PWR	Pressurized Water Reactor
R&D	Research and development
R/O	Reduced-order
R/O-TPD-PWR	Reduced-order model for thermal power dispatch from pressurized water reactor
RAM	Random-access memory
RTDS	Real Time Data Simulator
S&L	Sargent & Lundy
SOEC	Solid oxide electrolysis cell
TEMS	Transactive Energy Management System
TPD	Thermal Power Dispatch
UAT	Unit auxiliary transformer
VLAN	Virtual local area network
VM	Virtual machines

MULTI-FACILITY COORDINATED THERMAL POWER DISPATCH RESEARCH PLAN

1. INTRODUCTION

1.1 Background and Overview

The Light Water Reactor Sustainability (LWRS) program within the United States Department of Energy supports extending the operation of the U.S. commercial nuclear power plant (NPP) fleet. Within the LWRS program, the Flexible Plant Operation and Generation (FPOG) Pathway works to diversify the revenue streams of light water reactors (LWRs) by opening opportunities for the co-generation of non-electric products in addition to supplying electrical power to the grid. Recent events have added greater motivation to these efforts. For example, the recent Inflation Reduction Act passed by the U.S. federal government offers substantial tax incentives for producing clean hydrogen, the technology readiness level of dispatchable and high-efficiency hydrogen production has dramatically increased in a short time, and societal response to world climate change is driving a transition away from fossil fuels.

This document presents a three-year plan for analyzing integrated electric and thermal power dispatch from commercial light water reactors (LWRs) to tertiary industrial loads. A Westinghouse 4-loop reactor has been selected as being representative of PWRs in general. Of the 63 operating PWRs in the U.S., 28 of them (45%) are Westinghouse 4-loop reactors. During the second and third years of the project, a single representative BWR will also be selected for analysis, although that selection has not yet been made. Other specific configurations of LWRs will not be analyzed in this project. Analyses will include detailed thermal-hydraulics modeling, electric power modeling, and utilization of reduced-order and full-scope NPP simulators, as described in Section 2. The analyses do not include probabilistic risk assessments (PRAs) or license amendment reviews because those topics will be covered in separate work. The analyses will include +/- 30% cost estimates for modifications that will be needed for the proposed operations.

As shown in Table 1, the effort in the first year of the project will focus primarily on coupling PWRs to a high-temperature electrolysis (HTE) hydrogen production facility at a nominal scale of 500 MWe(DC), not including balance of plant electricity demand and thermal energy demand. This facility at maximum production is expected to consume approximately 500 MWe as DC power to drive the electrochemical reaction, 50 MWe as AC power for plant auxiliary loads, and 120 MWt for producing steam that is consumed as a reagent. Such a facility is expected to produce approximately 285 tonnes of hydrogen per day. Work in 2023 will also focus on a different, unspecified tertiary load that consumes as much as 1,100 MWt (approximately 30% of the total rated thermal power of a 4-loop Westinghouse PWR). That work will include a pre-front-end engineering design (pre-FEED) study as well as the development of corresponding simulators. Those simulators will be used to verify proposed concepts of operation for integrating operations at PWRs with thermal and electrical power dispatch between the grid and potentially multiple tertiary industrial loads. There is no existing concept of operations governing the coordination between the NPP, the tertiary industrial load, and the grid balancing authority, and this project seeks to meet that need. This project will use real-time process simulators with human operators as elements in the control loops of the NPP simulator, the tertiary industrial load simulator, and an electric grid simulation to explore and test proposed concepts of operation.

Table 1. Use cases that will be studied in this project for thermal and electric power dispatch from LWRs.

Approx. Year	Reactor Type	Tertiary Coupling	Thermal Storage	Licensing Implication [‡]
2023	PWR	500 MWe DC HTE H ₂ plant	No	Uncertain
2023	PWR	30% of rated reactor thermal power	No	Yes
2024	PWR	50-70% of rated reactor thermal power	Yes	Yes
2024	BWR	30% of rated reactor thermal power	Yes	Yes
2025	BWR	50-70% of rated reactor thermal power	Yes	Yes

[‡]Licensing implications refer to performing a license amendment review which may require a license amendment request. Licensing implications are somewhat speculative.

As shown in the timeline of project tasks, Figure 1, after the development of the 500 MWe HTE model with 30% TPD of the total rated reactor power from pressurized water reactors (PWRs), toward the end of 2023, attention will shift to higher levels of TPD between 50% and 70% of the total rated reactor power from PWRs. The exact level of TPD will depend upon plant impacts predicted by thermal and electric power analyses as well as potential regulatory restrictions. In 2024, work will commence on thermal and electric power dispatch from a selected BWR, following the research pattern established for PWRs.

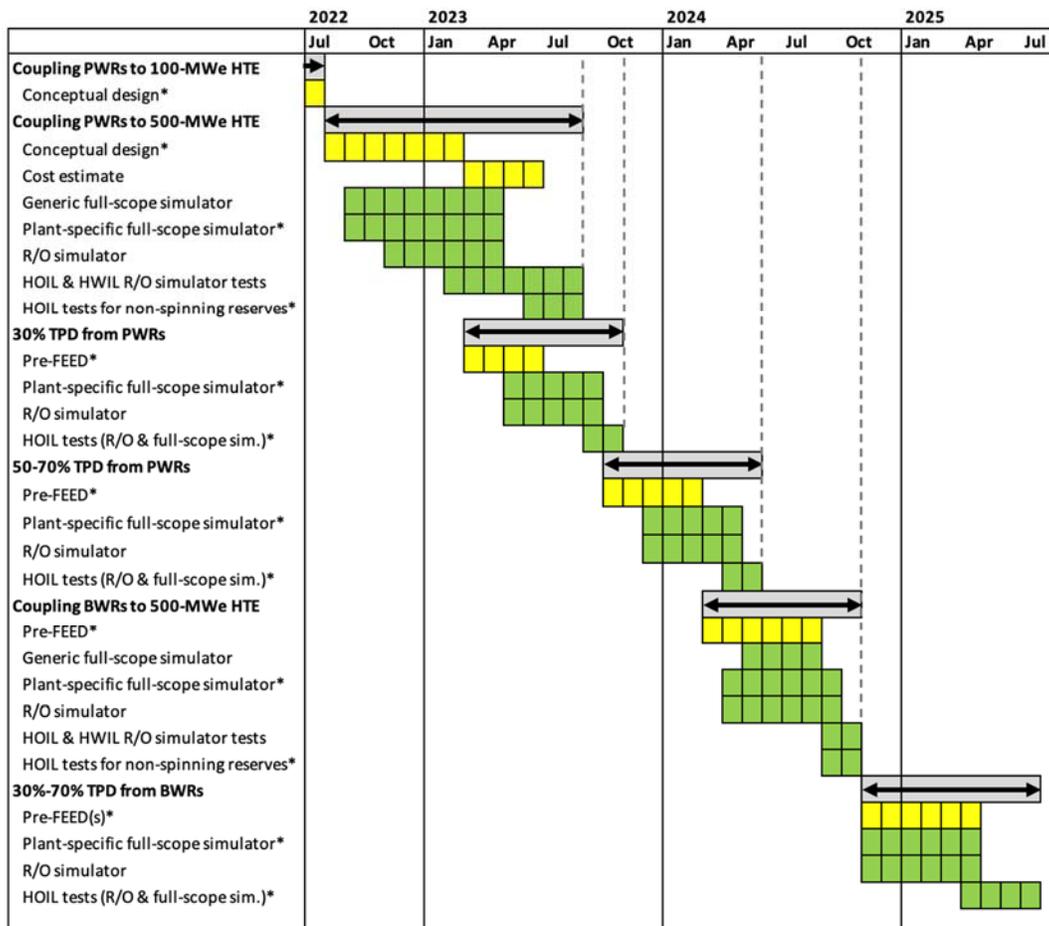


Figure 1. Gantt chart for planned activities. Tasks marked with “*” symbols include milestones that will be reported to the USDOE.

1.2 Research Objectives

Research objectives include:

- Developing design and cost estimates for thermal and electric power dispatch from a representative PWR and representative BWR to tertiary industrial loads at different levels ranging from 3% to 70% of the total rated reactor power. Specific designs will consider coupling to a 500 MWe(DC) HTE hydrogen production facility as well as tertiary loads that require larger thermal power input.
- Developing concepts of operation for dispatching thermal and electric power from representative LWRs to the electric grid and tertiary industrial loads
- Developing automated control systems for these operations. Different control systems will be developed independently that can be used to rigorously meet the requirements of the Nuclear Regulatory Commission (NRC) for specific plants and for sharing with stakeholders to assist in hardware integration.
- Testing proposed concepts of operations and integrated system performance using human operator-in-the-loop (HOIL) and hardware-in-the-loop (HWIL) tests. These tests will employ reduced order and full-scope simulators, as needed, to demonstrate the feasibility of dynamic operations in normal and off-normal events.

2. Combined MODELING AND TESTING APPROACH

2.1 Approach Overview

The general structure of the approach is:

1. Preparing appropriate models, including thermal and electric power dispatch, energy storage, grid power, and market simulations, as needed
2. Developing and testing automated controls systems to enable transitioning between thermal and electric power dispatch operating modes in such a way as to meet safety, regulatory, and economic performance requirements
3. Implementing the models with modified NPP simulators for HOIL and HWIL testing with representative scenarios of potential future industrial operations.

A timeline of the project tasks is shown in Figure 1. Broadly, during most of 2023, the work will focus on coupling PWRs to 500 MWe HTE plants, including the development of conceptual designs with thermal-hydraulic and electric power modeling as well as the development and testing of multiple simulators. As described in detail below, each of the simulators serves a different purpose. Plant-specific, full-scope simulators have the highest fidelity but are proprietary such that only the simulation results can be shared. Generic, full-scope simulators also offer good fidelity and realistic human/machine interfaces (HMIs), but the engineering analyses supporting the thermal power dispatch (TPD) is not as rigorous as that of plant-specific, full-scope simulators. Reduced order (R/O) simulators tend to have slightly lower fidelity but their full details, including control system designs, can be openly shared with stakeholders to facilitate teaming and hardware integration. The lower number of parameters also makes them more amenable for general use, such as coupling to hardware.

For complex systems in which human operators perform control actions at multiple levels within the controls systems, such as nuclear power plants performing TPD, there are key benefits from conducting tests in which the human operators interact with the control system as “in-the-loop” control elements to ensure the system stability and safety (Samad, 2020). In this project, those tests are referred to as HOIL tests. Also including physical hardware in selected tests, referred to as hardware-in-the-loop or HWIL tests, provides additional confidence that the concept of operations is robust against issues encountered with realistic physical equipment, such as thermal inertia, thermal losses, unexpected component failures,

and non-ideal valve operations. Combined HOIL and HWIL tests provide opportunities to verify the interoperability of controls and communications between human operators, control systems, and physical equipment more realistically than can be tested using virtual models alone. The physical equipment will be actual high-temperature solid oxide electrolysis cell (SOEC) hardware or other thermal power loads at approximately 100 kW scale.

The subsections below describe the modeling approaches for TPD, electric power dispatch, energy storage, and industrial loads, as well as controls system development and testing, combined HOIL and HWIL testing using an Open Meta Calculation Framework (OMCF) with human factors.

2.2 Thermal Power Dispatch Modeling

Thermal energy dispatch to an external plant will require 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 and not require a license amendment. 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. The most promising options for thermal power extraction use existing steam bypass lines or newly installed lines from either the main steam line in the power generation deck or the cold reheat (downstream of the high-pressure turbine exhaust and upstream of the moisture separator reheater, i.e. MSR). These two options are shown as generalized line taps in Figure 2. Tapping into the secondary system downstream of the main steam stop valves will greatly reduce the time and permits that will be required to modify the plant's thermal energy distribution systems. For both options, the subcooled condensate from the extraction heat exchanger is returned to the main condenser.

Extracting heat from the cold reheat (Option #2 in Figure 2) has the least impact on the high-pressure (HP) turbine and the overall plant electric power output but has less capacity for thermal power extraction. For example, preliminary analyses indicate that as much as approximately 100 MWt can be extracted from the cold reheat with minimal plant impacts but will require two extraction steam lines that are each approximately 14 inches in diameter. Alternatively, extracting 100 MWt from the main steam line decreases the performance of the HP turbine and reduces the NPP electric power output by approximately 15 MWe but will require smaller diameter steam extraction lines, approximately 8-inch diameter, because the HP steam can be transported through smaller lines.

Thermal modeling of the various options at different TPD levels will be performed using standard industry software. For example, PEPSE is an industry-standard, steady-state energy balance software program available from Curtis-Wright (Brea, CA) that calculates the performance of electric generating plants, fossil-fired plants, nuclear plants, gas turbine plants, combined cycles plants, and plants with atypical fluid systems. PEPSE has already been used by Sargent & Lundy (S&L) within this project to perform the thermal analyses for extracting 25 MWt and 125 MWt from a Westinghouse 4-Loop PWR, and the results of those analyses will be released in a report circa December 2022.

A key issue that must be considered in thermal power modeling is that the extraction pressures from multistage turbines are a highly nonlinear function of fluid flow. It is common to neglect this nonlinearity in modeling utility power cycles in situations in which the turbines operate close to their design loads, which is equivalent to assuming the turbines have constant flow coefficients. For the simulations in this work, in which the turbine may operate at off-design loads, correctly modeling the nonlinear turbine flow behavior will be increasingly important as the quantity of TPD increases and the turbines are subjected to off-design conditions. PEPSE can accurately calculate the performance of the turbines and other hardware in these anticipated off-design conditions.

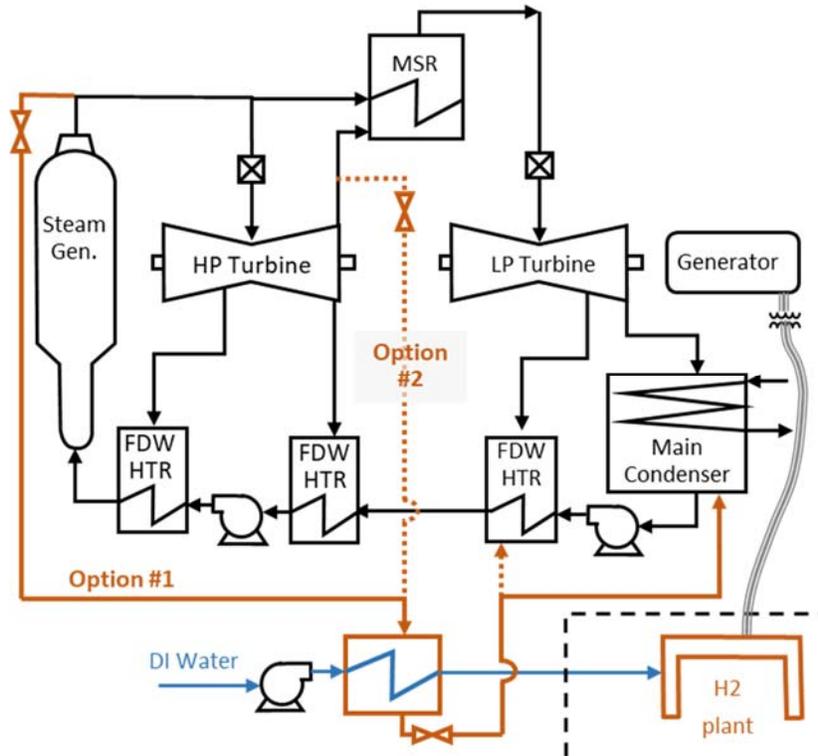


Figure 2. Two promising options for extracting steam from pressurized water reactors. (MSR - moisture separator reheater; FDW HTR - feed water heater; DI – deionized or demineralized water).

2.3 Electric Power Dispatch Modeling

For coupling PWRs to hydrogen production facilities that consume as much as 500 MWe of nominal DC power the total load consists of a maximum of approximately 500 MW that is rectified to DC power and approximately an additional 50 MW of AC power that is used for auxiliary loads at the hydrogen plant. In this case, the connection of the hydrogen plant to the PWR will follow a standard industrial facility connection to a power plant in which the power connection is made on the high voltage side of the Generator Step-Up (GSU) transformer. Transmission cables at switchyard voltage will carry power to the hydrogen plant. A sudden loss-of-load at the hydrogen plant would be similar to any nearby loss-of-load and the impact on the generator would follow normal generator load rejection protection schemes and will be evaluated accordingly. As an example, General Electric (GE) generators have load rejection relaying that will trip the main generator on a 40% mismatch between reactor power and generator output. Note that for relatively smaller amounts of electric power demand by the coupled industrial process, electric power could be supplied by an additional unit auxiliary transformer (UAT). It is anticipated that the maximum amount of electric power that can be supplied by an additional UAT is approximately 67 MVA (Hancock, Westover, Luo, 2021), which is well below the amount of power needed by the hydrogen plants considered in this work, so supplying power for the hydrogen plant at moderate voltage through a UAT is not evaluated further.

As noted above, the power connection for the hydrogen plant or other tertiary industrial load will be made on the high voltage side of the GSU transformer. The expected components in that connection include:

- GSU transformer
- Motor-operated disconnect switch
- Circuit breaker
- High voltage transmission line
- Disconnect switch
- Step-down transformer (345 kV to 13.8 kV with three windings)
- Medium voltage switchgear (one for each winding).

PSCAD, ETAP, or similar software will be used to perform electrical transient analyses to evaluate the impacts of sudden trips of the hydrogen plant load on the existing NPP generator. These analyses are currently being done by Sargent and Lundy (S&L) for the nominal 100 MWe and 500 MWe HTE plant preconceptual designs described that will be available circa December 2022. These first analyses approximate the hydrogen plants are lumped electric loads. Future work will refine those analyses to obtain more accurate transient calculations by considering the individual electric power loads at the hydrogen plants, including the power rectifiers, hydrogen compressors, pumps, blowers, and other equipment.

Electrical short-circuit and load flow/voltage drop analyses will be performed to evaluate the power flow and short-circuit impacts of coupling NPPs to hydrogen production plants. S&L has already completed these analyses for a nominal 100 MWe hydrogen plant. The power rectifiers represent greater than 80% of the electric load of the hydrogen plant. Diode-based rectifiers only allow an electric current to flow in one direction and, therefore, do not supply short-circuit current back to the power system. The analysis conducted by S&L concluded that the amount of short-circuit current supplied by the motor loads is negligible in comparison with the short-circuit current supplied by the high voltage transmission system and NPP generator. It is expected the same conclusion will be reached for larger hydrogen plants. The voltage drop analysis performed by S&L for the 100 MW hydrogen plant indicated that the hydrogen plant step-down transformer will not require an on-load tap changer if the transmission voltage is maintained within approximately a $\pm 2.5\%$ bandwidth, which applies to NPPs that operate per a voltage schedule and that require strict voltage regulation for offsite power per NUC-001. An on-load tap changer on the hydrogen plant step-down transformer would provide additional flexibility for locations where the transmission system operating voltage may vary over a wider range and for locations where the hydrogen facility may operate while the NPP is in a refueling outage. Similar analyses will be performed for larger hydrogen production facilities considering the individual electric power loads at the hydrogen plants.

2.4 Controls Systems Development

Coupling the power generation deck of a nuclear power plant to a hydrogen production facility will require developing and implementing a new concept of operations. Modifications and additions will need to be made to the nuclear plant operating procedures, new (digital) instrumentation will be required, and new controls will be needed for dispatching thermal and electrical power in normal and off-normal situations. The NRC requires that licensed operators maintain sovereign control of all nuclear plant operations that could impact core heating [USNRC 10 CFR 50.54(i)]. The HTE TPD control system must be designed to ensure this requirement is met. Furthermore, the coupling of the hydrogen plant or other load must not significantly increase risks or introduce other adverse effects to the nuclear reactor. These requirements are ensured by regulatory evaluations that are performed under the 10 CFR 50.59 or license amendment review (LAR) processes for any modifications to operating nuclear facilities. The full

requirements that will be imposed on the new control systems depend upon the anticipated operating conditions. Rapid power ramping of the hydrogen plant or other tertiary load will require rigorous automated controls to switch electric power between the grid and the tertiary load as well as steam between the turbine system and the tertiary load without significantly adding to the workload burden sustained by the nuclear power plant operators. If the tertiary load is not expected to ramp power rapidly, the sophistication of the control system modifications could be relaxed, but it is anticipated that the control system must be capable of automatically isolating all tertiary loads during an off-normal event to allow operators to focus their full attention on the nuclear island and the power generation deck of the NPP. The HTE TPD control system will also need to be redundant and highly reliable.

Three types of control systems will be developed in this work. The three control systems differ in their fidelity and the associated level of public accessibility. Models with high-fidelity and complexity are proprietary and are much more difficult to use, while the R/O models with lower fidelity can be made publicly available and have much lower barriers to learn and modify.

The first type of control system will be a generalized system that applies to R/O simulators and is described in greater detail in subsequent sections. This control system will be developed and implemented in python or a similar universal programming language and will be shared with partners to support collaborations to advance coupling NPPs to tertiary industrial loads.

The second control system will be provided by a full-scope NPP simulator vendor and will include dynamic thermal power dispatch to a tertiary industrial load, such as a hydrogen plant. This control system will be embedded in a modified full-scope NPP simulator and will have a relatively simplified automated control system with complete descriptions published for public dissemination and unrestricted use. The control systems developed by full-scope nuclear power plant simulators vendors will focus on relatively low levels of TPD (less than 10% of rated reactor thermal power). The actual design and function of the control system will be made available to partner institutions, such as universities, that have a license to the base full-scope NPP simulator. A few universities already have licenses to these types of full-scope simulators, and this activity will provide opportunities for collaboration and future independent research by universities.

The third control system will be provided by an architectural/engineering (A/E) firm and will be tested by human operators using a modified full-scope NPP simulator also provided by the A/E firm through a Corporate Research and Development Agreement (CRADA). The operators will interact with the simulator and control system through a realistic HMI in a control room environment described in the next section. The control system provided by the A/E firm will be designed to meet all applicable requirements as determined by the A/E working with partner groups, such as S&L and the Hydrogen Regulatory Research and Review Group (H3RG). The design requirements and control system results will be openly published, but the actual control system will be proprietary and will not be shared.

2.4.1 Ramping Requirements Development

Prior research using simulations has estimated hydrogen plant power ramping requirements for optimized economic operations of coupled nuclear plant/hydrogen production systems (Westover et al., 2021). These simulations employed a transactive energy management system (TEMS) that was developed in a previous project. The TEMS accounts for electric and thermal power dispatch to the HTE plant, representative wind energy, other generators and loads, hourly electricity prices, and potentially variable hydrogen prices in the grid power/market. The TEMS includes both slow and fast loop calculations to determine optimized hydrogen production schedules to maximize revenue while meeting operational constraints. The fast loop calculations provide capabilities to participate in 10-minute and 30-minute spinning reserve markets, while the slow loop calculations focus on optimized economic operations over long time periods of hours and days.

The TEMS was used in an example market simulation for a nominal 100 MW HTE hydrogen plant operating in the New York ISO during 2019 (8,760 hours). Available hydrogen storage was assumed to

be 100,000 kg (100 tonnes), and the capacity factor of the hydrogen plant was assumed to be 80%. Figure 3 shows the optimized hydrogen production times as red dots superimposed over the 2019 New York ISO electricity prices. In this scenario, the hydrogen plant ramps down power during times of high electricity pricing but must maintain the daily hydrogen supply quota of 45.1 tonnes-H₂/day, accounting for hydrogen storage, which offers approximately a two-day buffer between hydrogen production and the sales quota. It is evident that for optimized operations, the hydrogen plant must ramp up and down rapidly (on the scale of hours or less) to make use of low-cost electricity to reduce hydrogen production costs and maximize revenue from electricity sales from the NPP, even with a relatively large amount of available hydrogen storage of 100 tonnes. Enabling the hydrogen plant to ramp power consumption on the scale of 10-minutes or 30-minutes could enable the nuclear power plant to provide 10-minute or 30-minute spinning reserves to the grid and qualify for additional revenue by providing those ancillary grid services. Another interesting feature of Figure 3 is that the threshold price point at which the hydrogen plant ramps up and down varies throughout the year, so that the control system, the NPP operators, and power dispatchers must nimbly respond to market prices to optimize the operation of the integrated energy system. The threshold price point changes occur because the average electricity price changes on a daily and weekly basis. For example, electricity prices were relatively high from January 1 through the end of March (0-2200 hours) and from mid-June to mid-August (4100-5500 hours), so the threshold price point at which hydrogen production had to ramp up and down during those times had to adjust accordingly. The hydrogen storage capacity of 100 tonnes and an operating capacity factor of 80% result in a requirement that the hydrogen plant operates approximately 38 hours in each 2-day window to meet production quotas, regardless of the average daily electricity price.

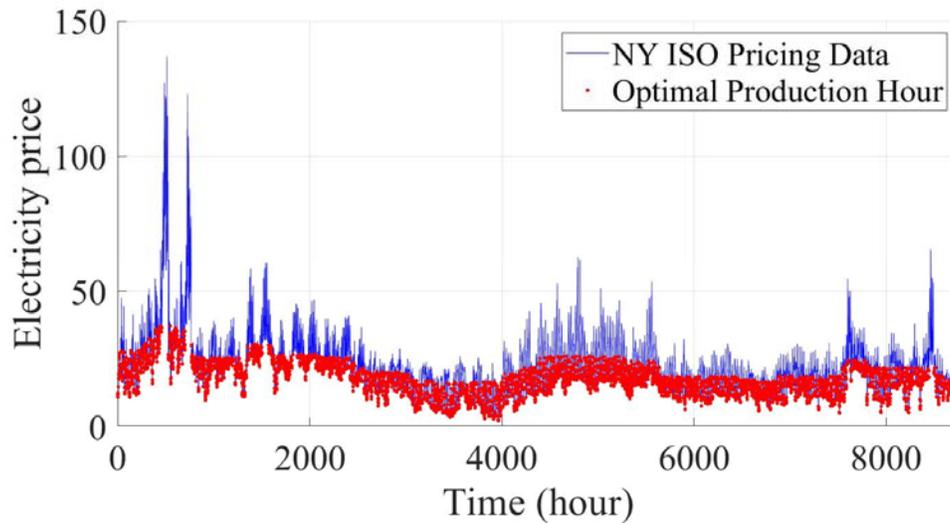


Figure 3. Optimal hydrogen production hours (red dots) for a nominal 100 MW hydrogen plant operating in the NY ISO during 2019 with an 80% capacity factor and hydrogen storage of 100 tonnes.

2.5 Human Operator- and Hardware-in-the-Loop (HOIL & HWIL) Testing

Coupling the power generation deck of a nuclear power plant to a hydrogen production facility introduces new possibilities for operational transients, which must be addressed. In particular, the startup and shutdown of the hydrogen production facility need to be evaluated to ensure there are no adverse effects on the operation of the existing NPP. The concept of operations involving the NPP, the hydrogen plant, and the electric power grid must be tested using modified or newly developed NPP operating procedures and grid power dispatch schedules working in harmony with hydrogen plant operators and grid power coordinators.

HOIL tests will be conducted in Human Systems Simulation Laboratory (HSSL) at INL. The HSSL at INL is a full-scale virtual NPP main control room (MCR) simulation environment with glass top instrumentation panels. The HSSL supports the safe application of advanced simulation and modeling techniques for the development, evaluation, and validation of new and improved human-system (machine) interface (HMI) designs to enhance existing concepts 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 as can be seen in Figure 4. 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 motorized height and angle adjustability. The high-resolution monitors provide greater flexibility for integrated prototypes overlaid on the virtual analog panel representations 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 angled control panels with aprons.



Figure 4. Human Systems Simulator Laboratory (HSSL) with virtual touch screens used to reproduce analog control panels to support TPD scenarios.

The simulator contains virtual equipment representations identical to the high-fidelity and certified training simulators used in NPPs. The participating operators can view the emulated analog instrumentation and controls (I&C) 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 TPD system) can be rapidly introduced and reconfigured following the same approach adopted by NPPs performing digital updates to their control rooms.

The HSSL is being used to support the FPOG pathway to evaluate issues associated with human performance in hybrid FPOG operations to ensure high levels of 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 and solutions that benefit operator performance to improve 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 plant control panels can be integrated into a realistic representation of the actual system and validated against defined performance criteria that meet regulatory standards (NUREG-0700; O'Hara, 2012). These may be undertaken alongside plant modernization activities and provide complimentary human factors methods to the nuclear industry.

As noted, it is expected that some tests will include actual hardware, which provides additional confidence that the concept of operations is robust against issues encountered with realistic physical equipment, such as unexpected component failures and non-ideal valve operations. The HWIL tests will be performed with a simulation of a representative power grid, including renewable energy generation to understand integrated operations in a hybrid nuclear/renewable energy environment. Figure 5 shows the coordination of simulated and physical equipment in the HWIL tests. The nuclear plant, and other energy resources including variable renewable energy sources, and hydrogen resources will be modeled as part of the electric grid using digital real-time simulation (DRTS). The hydrogen plant and the system that extracts heat from the nuclear power plant will be included as HWIL. Human operators provide the ultimate control between the NPP and the tertiary power load and the power grid. These tests will include exploration of design basis-accident scenarios and can also measure system efficiencies, equipment wear, and hydrogen embrittlement of key components to show the technical and economic viability of the proposed technology integration.

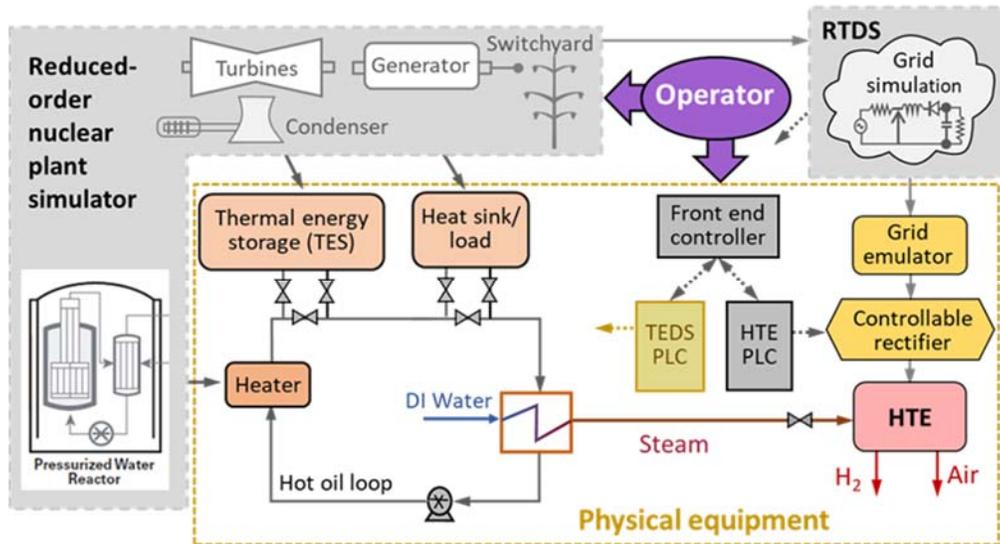


Figure 5. Schematic of simulated and physical equipment for HTE HWIL tests.

Combined HOIL and HWIL tests provide opportunities to verify interoperability of controls and communications between human operators, control systems, and physical equipment more realistically than can be tested using virtual models alone. HOIL and HWIL tests will include normal and off-normal scenarios that are comparable to those that have been tested in previous FPOG pathway research (Ulrich et al., 2021). Normal operation scenarios will focus on starting and stopping the hydrogen production facility or other tertiary loads over specified time intervals, such as 10- and 30-minutes, as would be required for supplying spinning and non-spinning grid reserves. Off-normal scenarios will include steam line rupture events, sudden loss-of-load events, and surprise events that are undefined in advance to test the ability of human operators to respond to unplanned situations, including tests with HWIL tests).

Future HOIL and HWIL testing will include additional scenarios. For example, a larger amount of TPD may pose greater challenges to operator responses to faults within the existing plant systems and faults specifically within the TPD system. Consequently, additional abnormal fault scenarios may be evaluated. Previous tests employed a manual control system that was observed to induce excessive workload when performing rapid TPD operating mode transitions to meet 10-minute and 30-minute grid non-spinning reserve requirements. The excessive workload was observed during key steps that required prolonged operator attention focused on the TPD system while also monitoring other NPP systems. Future tests will seek to demonstrate automated control systems that reduce operator mental load.

System performance will be measured through a variety of metrics following the same approach used in the prior TPD HOIL studies (Ulrich et al., 2021). The measures align with NUREG-0711 requirements and are established metrics providing accepted evidence to demonstrate due diligence in meeting industry best practices for addressing human factors. Utilities can follow the approach to facilitate safe and effective TPD operations. The details for the metrics can be found in Ulrich et al., 2021. In brief, simulator logs record process parameters for relevant systems and key plant parameters during scenarios. Human performance is evaluated during the scenarios with expert observers to evaluate task completion and situational awareness. Eye tracking provides alternative metrics for operator attention and workload as they complete diverse scenarios. After each scenario, the operator debriefs capture issues, recommendations, and a self-evaluation of their performance across a variety of cognitive metrics. The analysis of the human performance measures is then combined with an evaluation process parameters from the plant to provide overall metrics of system performance to serve as evidence to compare existing operations to automatic and manual TPD operations for normal and abnormal scenarios. The ultimate goal of these comparisons is to establish equivalency with existing operations to indicate whether additional risk introduced by TPD operations is significant or not.

2.6 OMCF for Dynamic Testing

The Concept-of-Operation testing, including HOIL and HWIL tests, requires dynamic simulators. As noted above, comprehensive testing will include thermal modeling, electric power modeling, dynamic grid simulations, hardware and HMIs. These different models or tools will either be coupled in co-simulations with simulators provided by vendors or they will be interfaced through an OMCF that will house the modelling tools and provide the required exchange of information. For example, PEPSE, which is used to analyze thermal power transport and storage of power plant components, including the turbine system in the NPP, only provides steady-state modeling capabilities. For dynamic HOIL and HWIL tests, the PEPSE modeling results will need to be translated to a NPP transient operations model (i.e., a training simulator with appropriate dynamics and control capability). The first step in this effort has already been completed by developing a reduced order (R/O) NPP simulator that assumes constant turbine flow coefficients, as described in Section 3.3. This R/O simulator was summarized in a previous report (Westover, et al., 2021). The next step in that effort is to modify the R/O simulator to accommodate transient modeling and incorporate nonlinear flow effects from PEPSE heat balance models. The updated, dynamic R/O simulator will be housed in a OMCF that will also include a dynamic hydrogen plant model (adapted from a model developed in separate work), a dynamic real-time grid simulation, a dynamic energy storage model, and an HMI.

2.6.1 SOEC Hydrogen Production Facility Model

The hydrogen plant model will be based on a dynamic model developed in a separate project and will be modified to closely match the plant design described by Prosser et al. (Prosser, et al. 2022). The plant model includes power transformers, power rectifiers, low and high-temperature heat recuperators, electrochemical cell hydrogen production, and product hydrogen gas post-processing to realistically model both transient electrical and thermal loads as the hydrogen plants ramps up and down to respond to commands from the integrated grid dispatch. Previous analyses lumped the hydrogen plant's electric loads for simplicity. Future work in this project will take a more rigorous approach by separating the electric load types to accurately capture electric induction and capacitance effects to realistically predict dynamic electric load profiles.

2.6.2 Electric Grid Model

A representative dynamic electric grid model will be coupled to the nuclear/hydrogen plant simulations. This dynamic electric grid model will likely be based on the New England IEEE reference bus test system (Pai, Mangalore, 2012) with added renewable solar or wind generation. INL has developed a comprehensive TEMS based on integrated nuclear, solar, wind, and natural gas generation as well as flexible hydrogen

production and other grid loads supported with battery energy storage systems, as described in Section 2.4. The TEMS and representative electric grid models developed in prior work are available to support the simulations in these planned activities.

2.6.3 Energy Storage Model

These activities will include energy storage in the simulations planned for future efforts. Thermal and electric energy storage models are available from separate previous efforts, including Laboratory Directed Research and Development (LDRD) projects and Framework for Optimization of Resources and Economics (FORCE) (<https://ies.inl.gov/SitePages/FORCE.aspx>). These models will be adapted for the simulations in these activities as needed.

2.7 Human Factors Program Review Model Approach (NUREG-0711)

The NRC provides requirements utilities must follow to maintain or modify their current license when undertaking a significant plant modification to ensure any changes meet stringent safety requirements and uphold the U.S. nuclear industry safety record. Modifications that require a license amendment request (LAR) beyond the 10 CFR 50.59 review process must also meet Human Factors Engineering Program Review (NUREG-0711). An important consideration, though, is that TPD systems, which have new functionality for integrating existing LWRs with industrial heat loads, require human factors development and evaluation activities that may go beyond what is prescribed in existing guidance. For example, NUREG-0711 was not originally intended for novel systems but rather modifications to systems that maintained existing plant functionality. The research team has authored supplemental guidance for NUREG-0711, such as GONUKE (Boring, Ulrich, & Lew, 2015; Boring, Ulrich, & Lew, 2021). GONUKE was written to provide evaluation techniques not explicitly defined but nonetheless implied as required elements under NUREG-0711. Still, even the GONUKE guidance does not fully capture all activities that are required for the development and evaluation of novel systems.

The research team's prior work to demonstrate and evaluate a conceptual TPD concept of operations in a dynamic HOIL study used the NUREG-0711 approach (Ulrich et al, 2021). Future work will continue to follow the NUREG-0711 approach. Indeed, the simulator-driven, scenario-based testing approach with HOIL evaluating the physical systems, instrumentation and controls, HMI, and procedures all represent different types of elements captured in a formal NUREG-0711 process. Also, the iterative and graded nature of the proposed research activities with incrementally increasing complexity is a fundamental aspect of the NUREG-0711 process and follows systems engineering best practices.

Research outcomes from these activities include guidance on the human factors processes to modify existing plant operations to support TPD operations as well as regulatory guidance that can reduce the risk for utilities pursuing TPD capabilities. This research plan addresses additional needs for the development and evaluation of thermal power dispatch systems. A particular emphasis is placed on the elevated importance of the integrated human operator- and hardware- in-the-loop (HOIL & HWIL) simulation-based evaluations for coupling NPPs to hydrogen production facilities and other industrial heat loads.

3. RESEARCH ACTIVITY DESCRIPTIONS

This work is separated into five research activities:

1. Thermal Power Dispatch Modeling
2. Electric Power Dispatch Modeling
3. Human Operator- and Hardware- in-the-Loop (HOIL & HWIL) Testing with Reduced/Order (R/O) Simulators
4. HOIL Testing with Generic Full-Scope Modified NPP Simulators
5. HOIL Testing with Plant-Specific Full-Scope Modified NPP Simulators

The first two activities will develop tools that will be used in an OMC that will integrate TPD modeling, electric dispatch modeling, hardware, and HMI development. The OMC and underlying models and HMI tools will be used in the third activity to perform HOIL and HWIL tests that will verify the concept of operations, including human factors. The fourth activity will employ generic modified TPD-NPP simulators from an NPP simulator vendor as described briefly above in Section 2.5 and in more detail below in Section 3.4. The fifth activity will employ plant-specific modified TPD-NPP simulators from an A/E firm for high-fidelity tests that will thoroughly address NRC requirements for specific plant configurations.

Modified full-scope TPD simulators developed in the fourth activity are expected to have slightly lower predictive fidelity than those in the fifth activity. The primary advantage of simulators developed and tested in the fourth activity is that the control algorithms will be made publicly available, and the simulators themselves will be available to select partners who have access to licenses for the generic simulators. R/O simulators developed in the third activity will have lower fidelity than those of the fourth and fifth activities (approximately 10% less predictive accuracy); however, the complete R/O simulator codes will be available to all partners and the lower number of parameters will make it possible to track more closely the physical mechanisms that are responsible for component performance to better explain cause-and-effect relationships between parameters.

The key planned deliverables in the research activities are summarized in Table 2 for DOE fiscal year (FY) 2023 (Oct. 1, 2022, to Sept. 30, 2023) and in Table 3 for DOE FYs 2024-2025. Detailed descriptions of each activity are provided in the subsections below.

Table 2. Planned research milestones for TPD research activities during FY2023. Milestones marked “DOE” are formally reported to DOE, and milestones marked “Publication” are project internal milestones to support planned peer-reviewed publications for stakeholders.

Milestone/Accomplishment (supported activity numbers in parenthesis)	Date	Notes
Complete a plan for developing and verifying human-machine interface and simulators to test operator/machine performance of close-coupled nuclear/electrolysis plants (All activities)	30-Sep-2022	DOE. This document.
Coupling PWRs to 500-MWe HTE Hydrogen Plants		
Complete connection of hydrogen electrolysis pilot plant operations and electricity grid simulator to nuclear power plant simulators installed at the HSSL (Act. 3-5)	15-Dec-2022	DOE. Needed to connect physical equipment and grid simulations to NPP simulators.
Install and demonstrate a vendor-developed simulator on the HSSL for dispatch of LWR electrical power to a close-coupled electrolysis plant (Act. 5)	22-Dec-2022	DOE. The simulator will be provided by an A/E firm with deep NPP controls expertise. Intellectual Property (IP) will not be shared.
Complete pre-conceptual design of PWR thermal and electrical power delivery systems to a 500 MWe high-temperature electrolysis plant (Act. 1)	30-Apr-2023	DOE.
Provide a preliminary design and cost estimate, including technical design criteria, for nuclear power plant switching between the electricity grid and a nominally 500 MWe electrolysis plant (Act. 2)	30-Jun-2023	DOE. Electrical power dispatch model and cost estimate.
Develop a generic, full-scope TPD PWR simulator with automated controls. Verify standard operations can be performed automatically while maintaining the PWR in normal operating conditions (Act. 4)	30-Jun-2023	Publication. Will build on the existing full-scope, PWR simulator that has manual controls. Will help guide and validate work in Activity 3 (R/O models).

Milestone/Accomplishment (supported activity numbers in parenthesis)	Date	Notes
Develop R/O TPD PWR simulator with automated controls. Complete HWIL tests using a 25+kW SOEC system to verify inter-operability of controls and communications between the SOEC system and simulator (Act. 3)	30-Jul-2023	Publication. Will build on the existing R/O simulator. The complete simulator will be shared with partners.
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 (Act. 3, 5)	07-31-2023	DOE. TPD requirements will be verified using a generic full-scope simulator. TPD combined with electric power dispatch will be verified with R/O simulator.
30% TPD from PWRs		
Complete a pre-FEED study for 30% TPD from a nominally rated 1,000 MWe PWR power plant for temporary storage (Act. 1)	30-Jun-2023	DOE.
Develop plant-specific, full-scope TPD PWR simulator with automated controls. Verify standard operations can be performed automatically while maintaining the PWR in normal operating conditions (Act. 4)	30-Jun-2023	Publication. Will help guide and validate work in Activity 3 (R/O models).
Develop R/O TPD PWR simulator with automated controls. Perform HWIL tests using a 25+kW SOEC system to verify inter-operability of controls and communications between the SOEC system and simulator (Act. 3)	30-Jul-2023	Publication. Will build on the existing R/O simulator. The complete simulator will be shared with partners.
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 (Act. 3, 5)	07-31-2023	DOE. Will be based on a plant-specific simulator. A full-scope simulator is preferred; however, a R/O simulator will suffice if necessary.
Complete an evaluation and verification of PWR operator capability to switch thermal and electrical power between a full-scale hydrogen plant and the grid for meeting non-spinning reserve requirements (Act. 3, 4, 5)	30-Sep-2023	DOE. Will use R/O simulator and plant-specific, full-scope simulator, if possible.
Complete screening of FPOG impacts on the overall efficiency of thermal energy extraction for up to 30% thermal energy extraction (Act. 1)	30-Sep-2023	DOE. Will use analysis and simulators.

Table 3. Planned research milestones for TPD activities during FYs 2024 and 2025. Milestones marked “DOE” are formally reported to DOE, and milestones marked “Publication” are project internal milestones to support planned peer-reviewed publications for stakeholders.

Milestone/Accomplishment (supported activity numbers in parenthesis)	Date	Notes
50-70% TPD from PWRs		
Complete a pre-FEED study for 50-70% TPD from a nominally rated 1,000 MWe PWR power plant for temporary storage (Act. 1, 2)	28-Feb-2024	DOE. The level of TPD depends on plant impacts. FEED will seek practical application within regulatory limits.
Develop plant-specific, full-scope TPD PWR simulator with automated controls. Verify standard operations can be performed automatically while maintaining the PWR in normal operating conditions (Act. 4)	31-Apr-2024	DOE
Develop R/O TPD PWR simulator with automated controls. Perform HWIL tests using a 25+kW SOEC system to verify interoperability of controls and communications between the SOEC system and simulator (Act. 3)	31-Apr-2024	Publication.
Coupling BWRs to 500-MWe HTE Hydrogen Plants		
Complete pre-FEED of BWR thermal and electrical power delivery systems to a 500 MWe high-temperature electrolysis plant (Act. 1)	30-Aug-2024	DOE.
Develop plant-specific, full-scope TPD BWR simulator with automated controls. Verify thermal and electrical power can be dispatched between a 500 MWe hydrogen plant and the bulk grid to meet non-spinning reserve requirements (Act. 4)	30-Sep-2024	DOE. Will help guide and validate work in Activity 3 (R/O models).
Develop a generic, full-scope TPD BWR simulator with automated controls. Verify standard operations can be performed automatically while maintaining the PWR in normal operating conditions (Act. 4)	30-Sept-2024	Publication
Develop R/O TPD BWR simulator with automated controls. Perform HWIL tests using a 25+kW SOEC system to verify interoperability of controls and communications between the SOEC system and simulator (Act. 3)	31-Oct-2024	Publication. Will build on the existing R/O simulator. The complete simulator will be shared with partners.
30-70% TPD from BWRs		
Complete pre-FEED study or studies for 30-70% TPD from a nominally rated 1,000 MWe BWR power plant for temporary storage (Act. 1)	30-Apr-2025	DOE.
Develop plant-specific, full-scope BWR simulator with automated controls for 30-70% TPD (Act. 4)	30-Apr-2025	DOE. Will help guide and validate work in Activity 3 (R/O models).
Develop R/O TPD BWR simulator with automated controls (Act. 3)	30-Apr-2025	Publication.
Complete screening of FPOG impacts on the overall efficiency of thermal energy extraction for up to 70% thermal energy extraction (Act. 1)	30-Sep-2025	DOE.
Complete operator testing of simulator featuring nominally rated 1,000 MWe PWR with 50-70% TPD and temporary energy storage (Act. 3)	30-Sep-2025	DOE. Demonstrate the concept of operations for high levels of TPD and energy storage with a PWR.

3.1 Activity 1 – Thermal Power Dispatch Modeling

The first activity is thermal power dispatch modeling, which follows the approach described in Section 2.2. As shown in Figure 1, modeling in 2023 will focus on TPD from PWRs for hydrogen production and other industrial uses that require relatively low amounts of TPD (less than 7% of the total rated reactor thermal power). In the second year of the project, operator and grid simulation tests will be conducted with a different industrial plant with a TPD in the range of 30% to 70% of the rated reactor thermal power. The specific amount of TPD will be determined based on predicted NPP plant impacts. It is expected that natural TPD thresholds will be found for specific TPD designs. For example, TPD from cold reheat piping will likely be limited to approximately 100 MWt. Larger amounts of TPD will require extracting steam directly from the main steam line, which will have greater impacts on the operation of the HP turbine. As the amount of TPD increases, the size of the extraction steam lines will increase and modifications to automated controls systems will be greater, resulting in potentially more severe increases in risks to the NPP and increased analysis to support potential license amendments or justifications to avoid a license amendment. It is anticipated that the bulk of the detailed TPD modeling for specific design concepts will be performed by a nuclear A/E firm, although INL will perform some modeling for conceptual exploratory purposes and to support R/O simulators for HOIL and HWIL testing.

3.2 Activity 2 – Electric Power Dispatch Modeling

Electric power dispatch modeling will be performed to match the TPD modeling efforts as described in Section 2.3. Electric power dispatch modeling will start at relatively high levels, such as approximately 500 MWe for a nominal 500 MWe HTE plant in 2023. In the second year of the project, as the amount of TPD increases to the range of 30% to 70% of the total rated reactor thermal power, the amount of electric power dispatch must decrease to maintain constant reactor power. Consequently, the effort in electric power dispatch modeling will decrease in future years, although the complexity of the automated control system is expected to increase with increasing TPD.

3.3 Activity 3 – HOIL & HWIL Testing with R/O Simulators

The OMCF will house the thermal and electric power models as well as modeling tools for other energy systems, such as hydrogen plant models and energy storage models. The OMCF will also provide the required exchange of information with dynamic grid simulations, hardware and HMIs. The thermal, electric and other power systems models will be based on reduced order (R/O) models, rather than full-scope, high-fidelity models due to several R/O model benefits. First, R/O simulators with fewer than 100 parameters are much simpler to adjust to match available hardware for HWIL tests. Identifying and accommodating system connection requirements to physical industrial equipment will be more practical and lower risk using R/O simulators than full-scope NPP simulators. Second, R/O NPP simulators can be shared with and even used by partner technology vendors, such as hydrogen production 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.

Comparing simulated plant responses predicted by R/O simulators with those from high-fidelity, full-scope simulators has great value to both modeling efforts. In addition to verifying the accuracy of the R/O simulator, the validation process also greatly assists in explaining and validating the predictions of the full-scope simulators. Due to a large number of parameters in the full-scope simulators and high level of complexity, small errors in code development, compilation or execution can produce incorrect results that can be very difficult to identify, diagnose, and correct. The R/O simulators contain fewer parameters by nearly two orders of magnitude so identifying and correcting errors is much easier. Achieving agreement between models with such different levels of complexity increases confidence in prediction results. R/O simulators are also well suited for proof-of-concept testing when integrating multiple complex systems by reducing the potential failure points involved with integrating complex physical and virtual systems. The simplified nature of R/O simulators allows the models to be efficiently modified and scaled for different

integrated system applications. Their simplified nature also yields computational advantages allowing them to be run in faster than real-time simulations as well as real-time to support HOIL and HWIL testing.

A recent effort focused on developing and validating an RO-TPD-PWR simulator for TPD operations. The model followed the approach taken by Poudel, Joshi, and Gokaraju (2020) by incorporating a reactor pressure vessel at constant pressure (perfect pressurizer control) and a lumped kinetics model with a single precursor group to approximate core neutronics. The steam generator is a simplified three-lump model with primary coolant, tube metal, and secondary coolant. The secondary coolant circuit follows that developed by Ibrahim, Ibrahim, Attia (2014). The secondary side includes two HP turbines, three low pressure (LP) turbines, a moisture separator and reheater (MSR), a deaerator, two HP feedwater heaters (HP-FWHs), three LP feedwater heaters (LP-FWHs), a condenser, one LP pump, and one HP pump. The model also includes a steam bypass line from the main steam line to the condenser as typically featured in PWRs. Figure 6 shows a nodal representation of the R/O simulator. Replacement of specific components or submodels with improved versions is relatively straight-forward, such as incorporating nonlinear turbine modeling results from PEPSE. The R/O model also has automation to control reactivity, secondary load, and steam flow to the industrial process.

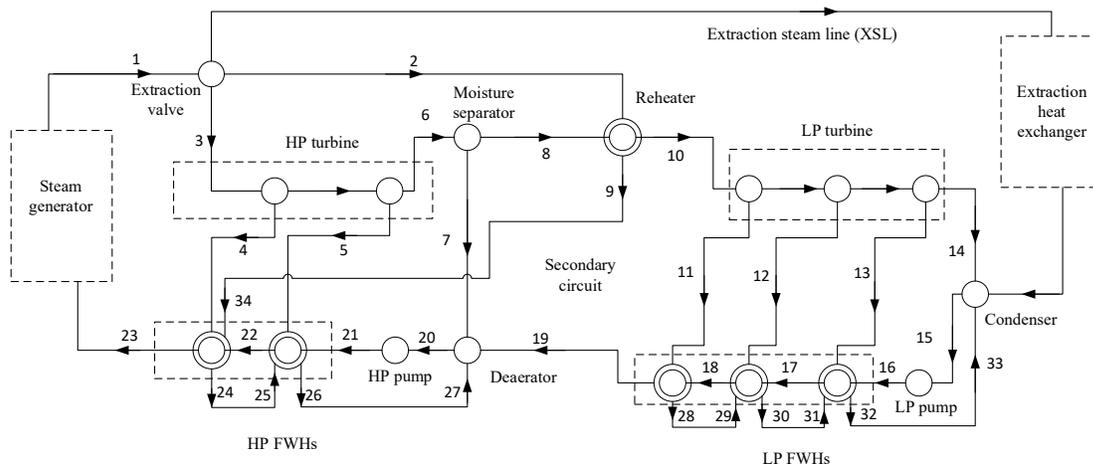


Figure 6. Nodal representation of PWR secondary coolant circuit in a R/O model.

The capabilities in the RO-TPD-PWR simulator will be utilized in the OMCf with other models and tools described in Section 2.6, including a SOEC plant model, energy storage models, and electric grid model powered by digital real-time simulation. The OMCf will also make use of tools that are available in INL's Rancor Microworld Simulator, including an advanced gamified HMI, Web API, historian for logging and plotting simulator data, serialization functionality for saving and loading plant initial condition states as well as a link to the steam2 Numba library to accelerate accessing steam properties. These tools allow R/O models to compute faster than real-time, even on light-weight single core virtual machines (VMs) with minimal random-access memory (RAM).

The physical equipment that will be used in HWIL tests is located in INL's Energy Systems Laboratory (ESL). The Human Systems Simulation Laboratory (HSSL) that contains the glass top virtual panels that mimic NPP control room is located nearby in INL's Energy Innovation Laboratory (EIL). The HSSL hosts a VM for running the RO-TPD-PWR simulator and other modeling tools in the OMCf. A virtual local area network (VLAN) has been established to connect the VM in the HSSL to the physical equipment at ESL. The VLAN is a demilitarized zone (DMZ) network isolated from other intranet and internet traffic, except for dedicated connections and servers in the HSSL and ESL. Initial testing verified the VLAN is functional and that two-way communication of multiple variables and datatypes can be exchanged between the different labs.

In 2023, the industrial plant considered in the HOIL and HWIL tests will be an HTE hydrogen plant that requires a relatively small thermal power dispatch (less than 7% of the rated reactor thermal power). In the second year, 2024, HOIL and HWIL tests will be conducted with a different industrial plant consuming thermal power in the range of 30% to 70% of the rated reactor thermal power. The specific amount of TPD will be determined based upon modeling in Activity 1 that identifies an appropriate TPD target to meet electric grid and hydrogen economics.

Graphical HMIs for the HOIL tests will be designed and implemented with human factors considerations. Overview displays will present shared information for key parameters depicting the interfaces between the NPP, electric grid, and industrial plant. TPD requires organization between the nuclear power plant operators, the electric grid dispatchers, and the industrial plant (i.e. a hydrogen production facility for the first tests planned in 2023). Thermal storage use cases will potentially require other operators that oversee the accumulation, storage, and distribution of thermal energy. As such, coordinated control actions between these organizations are important and may require common information displays in each facility. A prototype real-time overview display will be developed and evaluated to identify general and organization-specific needs to support effective coordination. This display will also prove useful for R/O testing since it can accommodate the small suite of parameters exchanged to develop the simulator and hardware integrations. The overview display and interfacility communication will be evaluated using representative operators from each facility in the integrated simulation framework under Activities 4 and 5 (described in Sections 3.4 and 3.5, respectively). The prototype informational display will contain detailed information, such as:

- Current grid power demand
- Forecast grid power demand
- Net generation
- Electric power flow from the NPP to the grid
- Steam and electrical power flow to the tertiary power user(s)
- Industrial processes state (online, shutdown, dumping steam, etc.)
- Scheduled transitions with ramp profiles.

Figure 7 shows the initial experimental configuration sharing information between the emulated control room in the HSSL and the physical hardware in the ESL. Physical hardware integration will occur through the real-time data system, as depicted in Figure 5. The overview displays will be used in the full-scope activities as well.

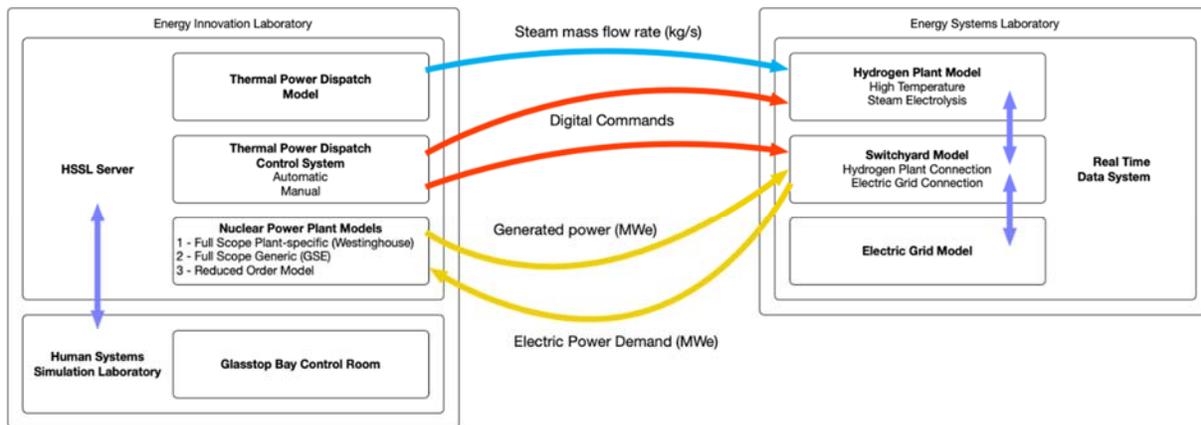


Figure 7. Simulation elements and their configuration to support the scenario-based operator-in-the-loop testing across the various research simulator activities. The relationships between the different systems are shown with arrows and the interfaces of these parameters form the basis for the common overview display.

3.4 Activity 4 – Full Scope Generic Simulator

In prior work under the FPOG pathway, INL modified GSE Systems’ generic pressurized water reactor (GPWR) simulator to enable dispatching steam from the main steam line to an industrial user (Hancock, Westover2021). HOIL workshops were conducted to validate the model and demonstrate that operators could manually operate the plant and thermal delivery system (Ulrich et al., 2021). However, the lack of automated controls for transitioning the steam delivery was identified as a shortcoming and recommended for future examination.

This fourth activity will work with a full-scope NPP simulator vendor to develop and test additional full-scope NPP simulators that include dynamic TPD to a tertiary industrial load. These simulators will have simplified automated control systems for which complete descriptions will be published. 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. This fourth activity 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 TPD and tested for performance. A few universities already have access to full-scope simulators, and this activity will provide opportunities for collaboration and future independent research by universities. The full-scope NPP simulators will focus on relatively low levels of TPD (less than 10% of rated reactor thermal power) and will employ simplified electric power dispatch models compared to the simulators developed with an A/E firm in Activity 5 (described below). It is expected that simulator vendors will be able to modify and test their generic full-scope simulators relatively quickly, so this activity will support the development of an automated control system for the R/O simulator developed in Activity 3. INL will work closely with a simulator vendor so that the automated control system designs used by both simulators will be comparable. In that way, results from the different simulators with widely differing levels of complexity can be used to increase confidence in the predictions and explain the observed nuanced system behaviors. Based on prior comparisons (Hancock, Westover2021), it is expected that the results from full-scope and R/O simulators will agree within 10% for key metrics, such as steam pressures, enthalpy flows, and power generation.

3.5 Activity 5 – Full Scope Plant-specific Simulator

Full-scope simulators are complex and require special knowledge and skills to modify while still guaranteeing the simulator functions properly. In addition, modifications to control systems that potentially affect the safety operations of NPPs are subject to NRC regulations, as noted in Section 2.7 [USNRC 10 CFR 50.54(i)]. Nuclear A/E firms have experience in meeting these requirements and can provide crucial guidance in this effort. INL is setting up a corporate research and development agreement (CRADA) with an A/E firm to develop and test a high-fidelity, full-scope NPP simulator that will be modified for coupled thermal and electric power dispatch. This simulator will be based on a specific four-loop PWR and will include dynamic thermal and electric power dispatch to a tertiary industrial load. The A/E firm will provide the modified full-scope simulator, with a dynamic model and automated control system. INL will support testing the simulators in HOIL tests using the HSSL. 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 a representative bulk transmission grid connected to the NPP, similar to the grid simulations that will be developed for the R/O model simulations and tests performed in Activity 3. The HOIL tests will include realistic digital and human communications between the nuclear power plant, the tertiary industrial load, and the grid coordinator. Similar to Activity 3, in the first year of the project, the tertiary industrial load will be an HTE hydrogen plant that requires a relatively small amount of TPD (less than 7% of the total rated reactor thermal power). In the second year of the project, operator and grid simulation tests will be conducted with a different industrial plant with TPD in the range of 30% to 70% of the total rated reactor thermal power.

It is expected that the automated control systems developed and used by the architectural engineering 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 for detailed on-site testing. HOIL tests using the simulator with an automated control system provided by the A/E firm will verify that NRC requirements can be met for TPD applications and will also show the expected optimized performance of such integrated energy systems.

4. CONCLUSIONS

This report presents a multi-facility coordinated research plan for fiscal years 2023 through 2025 for analyzing integrated electric and thermal power dispatch from commercial light water reactors (LWRs) to tertiary industrial loads. A Westinghouse 4-loop reactor has been selected as being representative of PWRs in general. During the second and third years of the project, a single representative BWR will also be selected for analysis. Analyses will include detailed thermal-hydraulics modeling, electric power modeling, and utilization of reduced-order and full-scope NPP simulators, as described in Section 2. PRAs and license amendment reviews will be covered in separate work. The analyses will include +/- 30% cost estimates for modifications that will be needed for the proposed operations.

Analyses will include pre-FEED studies as well as the development of different types of corresponding simulators. Those simulators will be used to verify proposed concepts of operation for integrating dynamic thermal and electrical power dispatch from PWRs to the grid and to potentially multiple tertiary industrial loads. Each of the simulator types serves a different purpose. Plant-specific, full-scope simulators have the highest fidelity but are proprietary such that only the simulation results can be shared. Generic, full-scope simulators also offer good fidelity and realistic HMIs, but the engineering analyses supporting the TPD is not as rigorous as that of plant-specific, full-scope simulators. Reduced order (R/O) simulators tend to have slightly lower fidelity but their full details, including control system designs, can be openly shared with stakeholders to facilitate teaming and hardware integration. The lower number of parameters also make them more amenable for general use, such as coupling to hardware.

For complex systems in which human operators perform control actions at multiple levels within the controls systems, such as nuclear power plants performing TPD, there are key benefits from conducting

tests in which the human operators interact with the control system as “in-the-loop” control elements to ensure the system stability and safety (Samad, 2020). In this project, those tests are referred to as HOIL tests. Also including physical hardware in selected tests, referred to as HWIL tests, provides additional confidence that the concept of operations is robust against issues encountered with realistic physical equipment, such as thermal inertia, thermal losses, unexpected component failures, and non-ideal valve operations. Combined HOIL and HWIL tests provide opportunities to verify interoperability of controls and communications between human operators, control systems, and physical equipment more realistically than can be tested using virtual models alone. The physical equipment will be actual high-temperature SOEC hardware or other thermal power loads at approximately 100 kW scale.

Efforts in the first year of the project (2023) will focus primarily on coupling PWRs to a HTE hydrogen production facilities at a nominal scale of 500 MWe(DC). Work in 2023 will also focus on a different, unspecified tertiary load that consumes as much as 1,100 MWt (approximately 30% of the total rated thermal power of a 4-loop Westinghouse PWR). Toward the end of 2023, attention will shift to higher levels of TPD between 50% and 70% of the total rated reactor power from PWRs. The exact level of TPD will depend upon plant impacts predicted by thermal and electric power analyses as well as potential regulatory restrictions. In 2024, work will commence on thermal and electric power dispatch from a representative BWR, following the research pattern established for PWRs.

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