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Light Water Reactor Sustainability Program

Co-simulation of Hydrogen Production with Nuclear Power Plants

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ABSTRACT

Within the Light Water Reactor Sustainability (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 electricity grid. Recent events have added greater motivation to these efforts. For example, the recent Inflation Reduction Act (IRA) passed by the United States (U.S.) federal government offers substantial tax incentives for producing clean hydrogen.

FPOG activities include the development and testing of new operating concepts to verify that energy co-generation operations can be done efficiently and safely. Producing hydrogen with maximum efficiency using nuclear power requires dispatching both electrical and thermal power from the nuclear plant to the hydrogen plant. Nuclear power plants (NPPs) are licensed by the U.S. Nuclear Regulatory Commission (NRC). This license is based on the Final Safety Analysis Report (FSAR), which specifies the operating conditions of the NPP. NPPs rely on trained operators and control systems that recognize and respond to plant operating conditions to maintain the reactor in a safe condition.

This report documents the implementation of a data link between the Idaho National Laboratory (INL) Human Systems Simulation Laboratory (HSSL) and the INL Energy Systems Laboratory (ESL) connecting a small-scale high-temperature electrolysis (HTE) pilot plant and an electricity grid simulation capability. This connection enables virtual/physical co-simulation of an NPP to help develop operating concepts and control systems that will enable nuclear plant operators to dispatch thermal energy and electrical power between a close-coupled hydrogen plant, the electricity grid, or energy storage buffers that can be used for power arbitrage.

The data connection between the physical hardware and the human operator systems was tested and proven suitable to support the development and testing of the interoperability of controls and communications between human operators, control systems, and physical equipment more realistically than can be tested using virtual models alone. A scenario was tested to verify that devices and models at the HSSL and ESL respond appropriately during a co-simulation. In this scenario, a co-simulation was performed in which a HTE plant was cycled from normal operation to hot standby and back to normal operation again. The steam flows in both the NPP and HTE simulators responded as expected, and the rquired technical functionality of the data connection was verified.

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ACRONYMS

API	application programming interface
BWR	boiling water reactor
CRADA	Cooperative Research and Development Agreement
DOE	U.S. Department of Energy
DRTS	Digital Real-Time Grid Simulation
EIL	Energy Innovation Laboratory (Human Systems Simulation Laboratory)
ESL	Energy Systems Laboratory (Physical Testbeds and Real-Time Data Simulator)
FORCE	Framework for Optimization of ResourCes and Economics
FPOG	Flexible Plant Operations and Generation
FSAR	Final Safety Analysis Report
GPWR	generic pressurized water reactor
HMI	human-machine interface
HOIL	human-operator-in-the-loop
HSI	human-system interface
HSSL	Human Systems Simulation Laboratory
HTE	high-temperature electrolysis
HWIL	hardware-in-the-loop
I&C	instrumentation and control
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
IRA	Inflation Reduction Act
kW_e	kilowatt electric
LDRD	Laboratory-Directed Research and Development
LWR	light water reactor
LWRS	Light Water Reactor Sustainability Program
MCR	main control room
MW	megawatt
MWe	megawatt electric
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OMCF	Open Meta Calculation Framework
PEPSE	thermal-hydraulics modeling software developed by Curtiss-Wright Nuclear
PLC	programmable logic controller

PWR	pressurized water reactor
R/O	reduced-order
R/O-TPD-PWR	reduced-order model for thermal power dispatch from a pressurized water reactor
RTDS	Real Time Digital Simulation
SOEC	solid oxide electrolysis cell
SSH	secure socket shell
TCP	transmission control protocol
TEDS	Thermal Energy Delivery System
TEMS	Thermal Energy Management System
TES	Thermal Energy Storage
TPD	thermal power dispatch
TRL	technology readiness level
U.S.	United States

CO-SIMULATION OF HYDROGEN PRODUCTION WITH NUCLEAR POWER PLANTS

1. INTRODUCTION

Within the Light Water Reactor Sustainability Program (LWRS), 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. Specific research objectives of the FPOG Pathway include:

1. Developing design and cost estimates for thermal and electric power dispatch from a representative pressurized water reactor (PWR) and representative boiling water reactor (BWR) to tertiary industrial loads at different levels ranging from 10–70% of the total rated reactor power.
2. Developing concepts of operation for dispatching thermal and electric power from representative LWRs to the electric grid and tertiary industrial loads.
3. 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 United States (U.S.) Nuclear Regulatory Commission (NRC) for specific plants and for sharing with stakeholders to assist in hardware integration. Nuclear power plants (NPPs) are licensed by the U.S. Nuclear Regulatory Commission (NRC). This license is based on the Final Safety Analysis Report (FSAR), which specifies the operating conditions of the NPP.
4. Testing proposed concepts of operation and integrated system performance using human operator-in-the-loop (HOIL) and hardware-in-the-loop (HWIL) tests. These tests will employ reduced-order (R/O) and full-scope simulators, as needed, to demonstrate the feasibility of dynamic operations in normal and off-normal events.

Recent events have added greater motivation to these efforts. For example, the recent Inflation Reduction Act (IRA) passed by the U.S. federal government offers substantial tax incentives for producing clean hydrogen. In addition, water-splitting electrolysis can produce both clean and pure hydrogen. One advantage of electrolysis is the ability to ramp production up and down in a short period of time. This feature allows a nuclear power plant (NPP) to quickly switch the electricity supply between the grid and the electrolysis plant. Fortunately, the technology readiness level (TRL) of dispatchable and high-efficiency hydrogen production has dramatically increased in a short amount of time.

This report documents progress toward Objective 4 using HOIL and HWIL. It is expected that the concepts of operations for the various designs of thermal and electric dispatch will require custom PWR and BWR simulators. In 2023, the work will focus on two activities. First, modeling and simulation will continue to study coupling PWRs to 500 megawatt electric (MWe) high-temperature electrolysis (HTE) plants. In the latter half of 2023, the focus will shift to dispatching up to 30% of the thermal power from the reactor for various industrial applications beyond HTE. In 2024, these tasks will include developing similar simulators for dispatching thermal and electrical power from BWRs.

In the past two years, modular prototype HTE systems have been installed at the Idaho National Laboratory (INL) Energy Systems Laboratory (ESL). By connecting NPP simulators to these test units, realistic control response characteristics can be used to verify operator dispatch concepts—in lieu of relying on the fidelity of the electrolysis plant models. Relevant capabilities of INL's Human Systems Simulation Laboratory (HSSL), which is located in the Energy Innovation Laboratory (EIL), and ESL are summarized in Section 2 and Section 3 of this report, respectively. Section 4 contains the description of the data connection between the HSSL and the ESL and includes details of an initial use case in which an R/O NPP simulator at HSSL was coupled to a simulation of a HTE facility in the ESL for dynamic co-simulation testing. Section 5 provides conclusions from the work.

2. THE HUMAN SYSTEMS SIMULATION LABORATORY (HSSL)

The HSSL 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-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 1. 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 because there are more pixels providing 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 1. HSSL with virtual touch screens used to reproduce virtual analog control panels to support thermal power dispatch (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 control (I&C) units on touchscreen displays that mimic the control boards of actual NPP control rooms. Because the control boards are virtual, new digital human-system interfaces (HSIs) can be rapidly introduced and reconfigured following the same approach adopted by NPPs performing digital updates to their control rooms.

The HSSL is supporting the FPOG pathway in evaluating 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 meeting NUREG-0700 regulatory standards (O'Hara et al., 2012; O'Hara, 2012). These changes may be undertaken concurrently with plant modernization activities to incorporate human factors methods in both efforts simultaneously.

3. THE ENERGY SYSTEMS LABORATORY (ESL)

3.1 ESL Overview

The ESL was established to help develop the interfaces necessary for an NPP to dispatch thermal and electrical power between a hydrogen plant and the electrical grid. The ESL contains hardware for testing HTE stacks, as well as integrated testing capabilities for other applications—including wireless battery testing, thermal energy storage, NPP emulation, distributed microgrids, and digital real-time simulations, as shown in a panoramic photograph in Figure 2. Additional facilities for testing HTE systems and other power systems are located in the ESL's north yard with thermal, electric, and control connections to equipment inside the ESL.

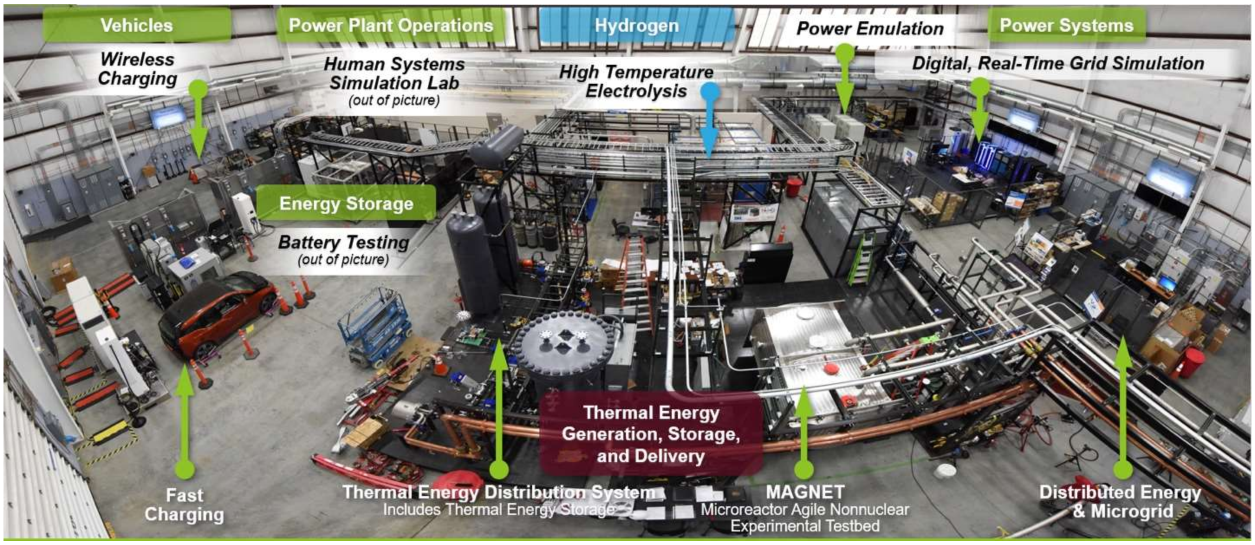

Figure 2. Panoramic of test facilities inside the ESL.

The ESL offers a holistic representation of an electrical grid, with real-time grid simulation and real-time power emulation to test NPP-hydrogen plant environments. A distributed energy microgrid provides the real-time signals of wind and solar power production, while random or programmed electrical vehicle charging events and thermal energy storage can be added to the grid environment. For the purposes of the FPOG activities, the goal is to tie into the Digital Real-Time Grid Simulation (DRTS) stations and the HTE electrolysis test modules located outside the building area shown in Figure 2. The Thermal Energy Generation, Storage, and Delivery System is programmable and can be used to supply thermal energy to the HTE modules.

3.2 ESL Solid Oxide Stack or Module Testing

INL supports commercial developers with designs, operations, and performance validation of fully integrated HTE systems. Within a Cooperative Research and Development Agreement (CRADA), INL has tested a Bloom Energy 100 kW_{eDC} solid oxide electrolysis cell (SOEC) system for over 3,000 hours (https://www.businesswire.com/news/home/20220809006052/en/). Steam and power for this test is provided by High Temperature Electrolysis (HTE) Support Facility, which includes five CE+T America 30C3 power converters and a Chromalox CSSB-100 steam generator, as shown in Figure 3.

Figure 3. HTE Support Facility (used to support testing of the Bloom 100 kW_e SOEC system).

FuelCell Energy and INL have teamed together on a U.S. Department of Energy (DOE) cost-shared proposal to test a 250 kW_{eDC} modular test unit (https://www.energy.gov/ne/articles/us-department-energy-announces-269-million-advanced-nuclear-technology). This unit is expected to arrive at INL in the spring of 2023 and will be connected to a hydrogen product gas conditioning station to supply hydrogen to two to four fuel cell electric motor coach buses that will operate on bus routes between INL's dispersed facilities. INL is prepared to support other HTE modules for testing. Infrastructure planning of the buildout to accommodate additional test skids and associated pilot plants is in progress.

4. DATA CONNECTION BETWEEN HSSL AND ESL

4.1 Purpose and Approach

The primary purpose of the connection between the HSSL and the ESL is to allow real-time simulator tests to also 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 using a simulation of a representative power grid—including renewable energy generation—to understand integrated operations in a hybrid nuclear/renewable energy environment. Figure 4 shows the coordination of simulated and physical equipment in the HWIL tests. The NPP and other energy resources—including variable renewable energy sources and hydrogen resources—will be modeled as a part of the electric grid using the DRTS. The hydrogen plant and the system that extracts heat from the NPP 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 the 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.

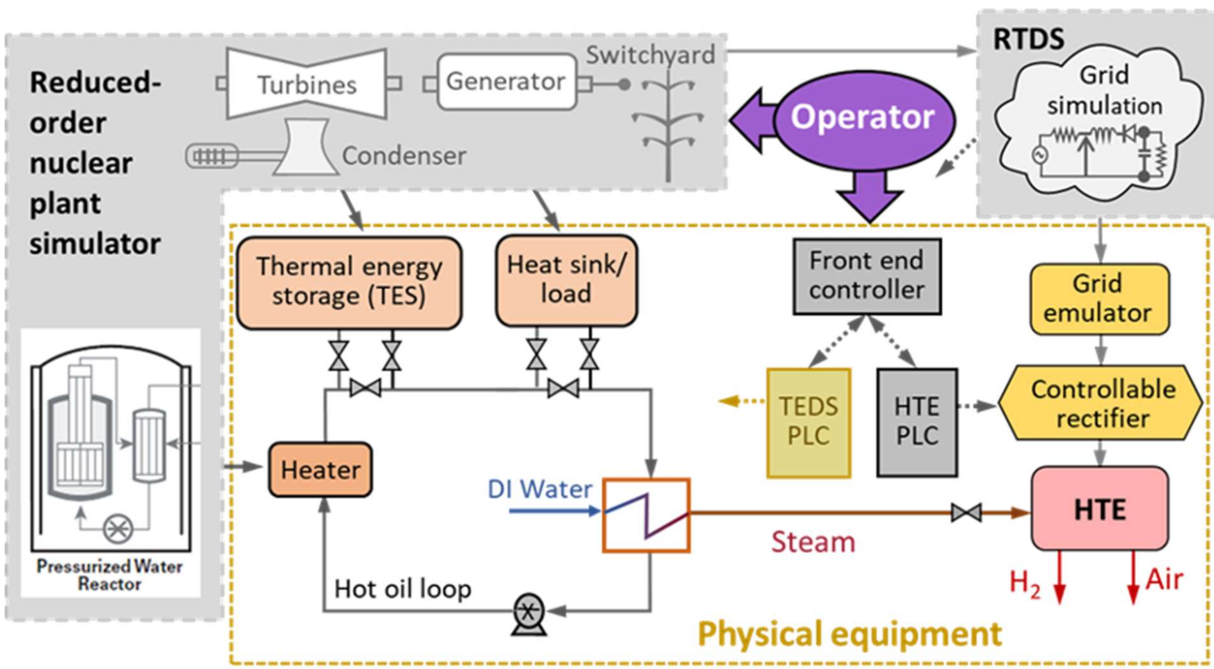

Figure 4. Schematic of simulated and physical equipment for HTE HWIL tests. *(NOTE: HTE – High-Temperature Electrolysis Module; TEDS – Thermal Energy Delivery System; TES – Thermal Energy Storage; RTDS – Real-Time Digital Simulator; PLC – Programmable Logic Controller.)*

The Concept-of-Operation testing—including the HOIL and HWIL testing—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 Open Meta Calculation Framework (OMCF) that houses the modeling tools and provides the required exchange of information. For example, PEPSE—the thermal-hydraulics modeling software developed by Curtiss-Wright Nuclear—is used to analyze the thermal power transport and storage of power plant components, including the turbine system in the NPP, but it only provides steady-state modeling capabilities. For the dynamic HOIL and HWIL tests, the PEPSE results will need to be translated to NPP transient operations models (i.e., a training simulator with appropriate dynamics and control capabilities).

The first step in this effort has already been completed by developing an R/O NPP simulator that assumes constant turbine flow coefficients. 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 the 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. In addition to the NPP simulators, models and simulations are also needed for the coupled industrial processes, such as hydrogen production facilities, the electric power grid, and energy storage.

4.1.1 SOEC Hydrogen Production Facility Model

The hydrogen plant model is based on a dynamic model developed in a separate project and is being 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.

4.1.2 Electrical 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 Institute of Electrical and Electronics Engineers (IEEE) reference bus test system (Pai, 2012) with added renewable solar or wind generation. INL has developed a comprehensive Thermal Energy Management System (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. The TEMS and representative electric grid models developed in prior work are available to support the simulations in these planned activities.

4.1.3 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 the 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.

4.2 HSSL & ESL Data Connection Communication Architecture and Protocols

The NPP simulators located in the HSSL communicate with RTDS in the ESL using transmission control protocol (TCP) socket communication. TCP socket communication is a low-level two-way networking protocol where a client and server exchange data with three-way handshakes to acknowledge message transmissions. The architecture has RTDS act as a server and the NPP simulators connect as clients. The communication requires the parameter exchange to be specified and configured on both the clients and server. The communication protocol has been implemented with dry run tests using Python 3.9’s standard socket library to communicate with RTDS. The protocol starts with the R/O establishing a socket connection with RTDS. The client then sends packs and parameters at 1 Hz frequency as big-endian 32-bit floating point numbers and receives back a byte string from RTDS in acknowledgment of the request. The client then unpacks the parameters.

Figure 5 shows the initial experimental configuration that is used to share information between the emulated control room in the HSSL and the physical hardware in the ESL. A bridge program has been constructed to act as a relay between the NPP simulators and the RTDS. The bridge program exchanges data with the simulators using application programming interfaces (APIs, such as GSE's s3 Gii protocol) and use transmission control protocol (TCP) socket communication as previously described to communicate with the TDS. In a prior effort, a bridge program was successfully used to provide two-way communication between GSE's generic pressurized water reactor (GPWR) and Argonne National Laboratory's Parameter-Free Reasoning Operator for Automated Identification and Diagnosis (PRO-AID) prognostic diagnosis system. The bridge program was implemented using Microsoft's .NET framework. The connection between HSSL and ESL mimics the approach used in that prior project.

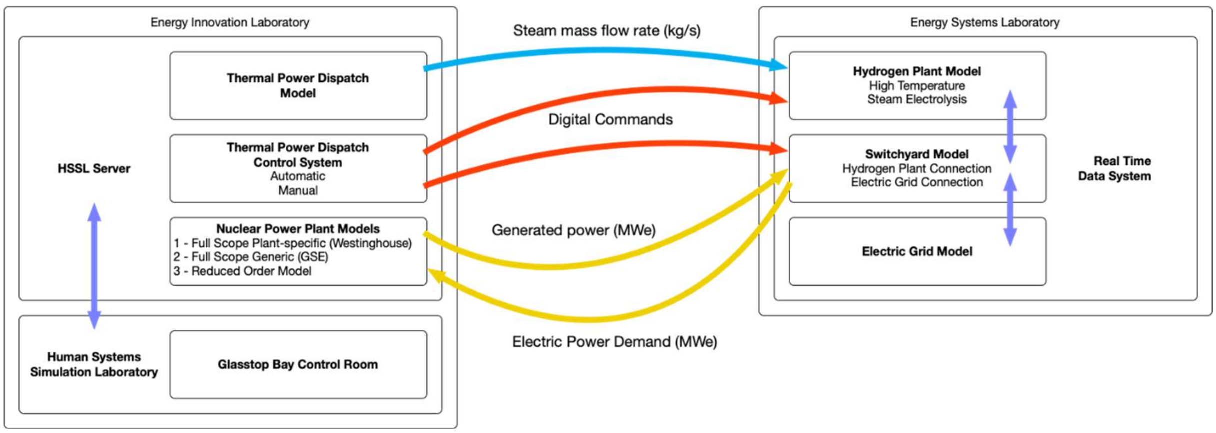

Figure 5. Simulation elements and their configuration to support the scenario-based HOIL testing. The relationships between the different systems are shown with arrows.

Physical network modifications have been made to provide a fiber connection with sufficient speed to support the communication between the HSSL with the NPP control room simulator and the ESL that houses the RTDS racks, RTDS server, OPAL-RT/Simulink/Matlab resources, and the hardware systems. To support the communications, specific software solutions and protocols have been developed. Figure 6 shows a detailed connection diagram. A preliminary network test was performed in the summer of 2022 to ensure the various devices were able to communicate across the network to exchange a single variable without any API solutions developed specifically for the various models. A simple Python script was used to perform the variable exchange.

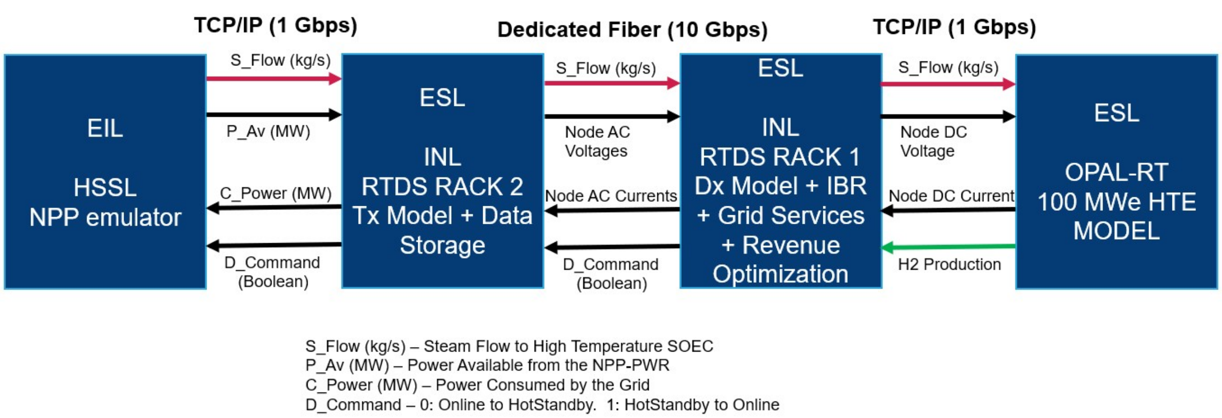

Figure 6. Detailed connection diagram mirroring the HSSL-ESL connection elements.

4.3 Auxiliary Test Support

Graphical HMIs for the HOIL and HWIL tests are designed and implemented with human factors considerations. Overview displays present shared information for key parameters depicting the interfaces between the NPP, electric grid, and industrial plant. TPD requires organization between the NPP operators, electric grid dispatchers, and 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 is useful because it can accommodate the small suite of parameters used during the tests. The overview display and interfacility communication will be evaluated using representative operators from each facility in the integrated simulation framework. 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.

4.4 Data Connection Validation

The HSSL/ESL data connection was validated using a co-simulation that involved different models at HSSL and ESL operating together. An R/O PWR TPD model was used as the HSSL NPP simulator because this is the simplest available simulator model and the most straightforward to test. Future work will address integrating full-scope plant simulators to support similar capabilities. The NPP and hydrogen plant models were modified to support integration by developing APIs with functions that can receive inputs across the network and execute commands on their respective models. As briefly mentioned in the previous section, the initial network configuration to suppport communication was tested in the summer of 2022. More rigorous testing was performed in November 2022, as summarized below.

A co-simulation performed in November began with single variable exchange to ensure basic communication was established and that the APIs were receving valid inputs in the correct format. After the data connection was verified, a full scenario was performed to verify that the models responded appopriately for all connected devices at HSSL and ESL. In this scenario, the HTE plant was cycled from normal operation to hot standby and back to normal operation again. A console-based HMI was used for the reduced-order model for thermal power dispatch from a pressurized water reactor (R/O PWR TPD) simulator, while the HMI was implemented with a third party textual user interface library (textual library by textualize.io) for Python, as observed in Figure 7. The HMI provides system monitoring and operational controls. Multiple HMIs for a single simulator instance can be deployed in multiple locations, including the HSSL bays and remote locations, through secure socket shell (SSH) terminal sessions using terminal multiplexing (tmux).

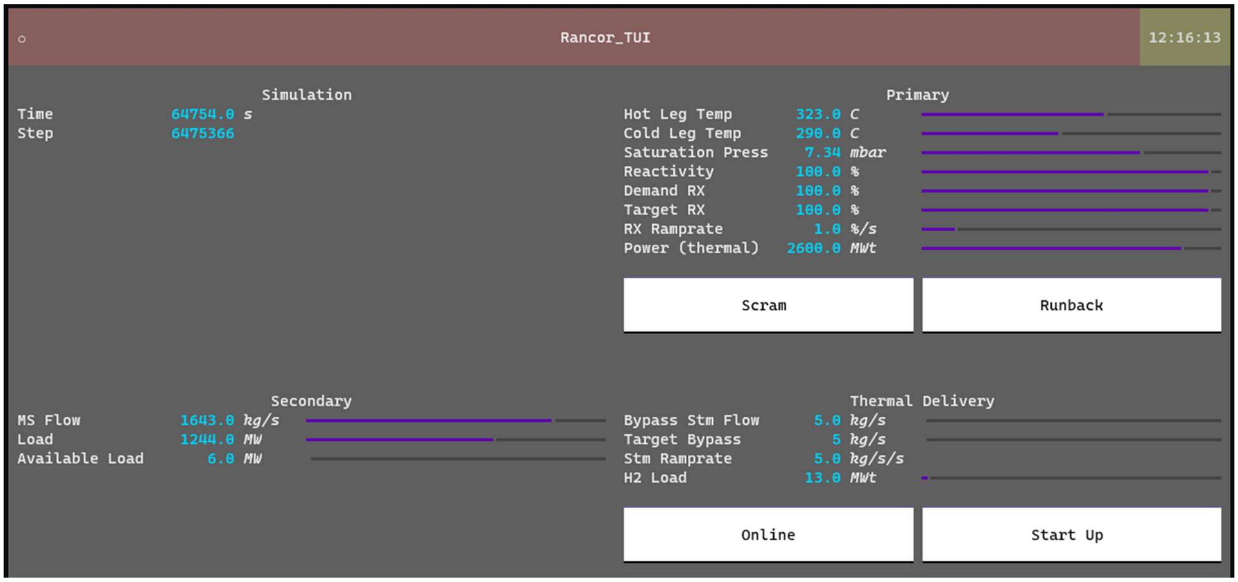

Figure 7. HMI for the R/O simulator used to monitor plant response during the testing.

During normal operation, the extraction of steam from the main steam line to the thermal power dispatch heat exchanger is 555 kg/s. During hot standby, the steam flow rate from the main steam line decreases to 5 kg/s. The change in the steam flow rate during the scenario is shown in Figure 8, which also includes the power output of the turbine. In this engineering example, the time of the transition was artificially accelerated, so that the data connections and device responses could be verified rapidly. With the accelerated procedure, the entire cycle was completed in less than 400 seconds. As shown in Figure 8, as the steam flow to the HTE plant decreased, the power output from the turbine increased from 601 megawatts to 1248 MW. As expected, the power output of the turbine system is inversely related to the steam flow to the HTE plant. The simulators in HSSL and ESL successfully exchanged the commands and updated their respective models correctly.

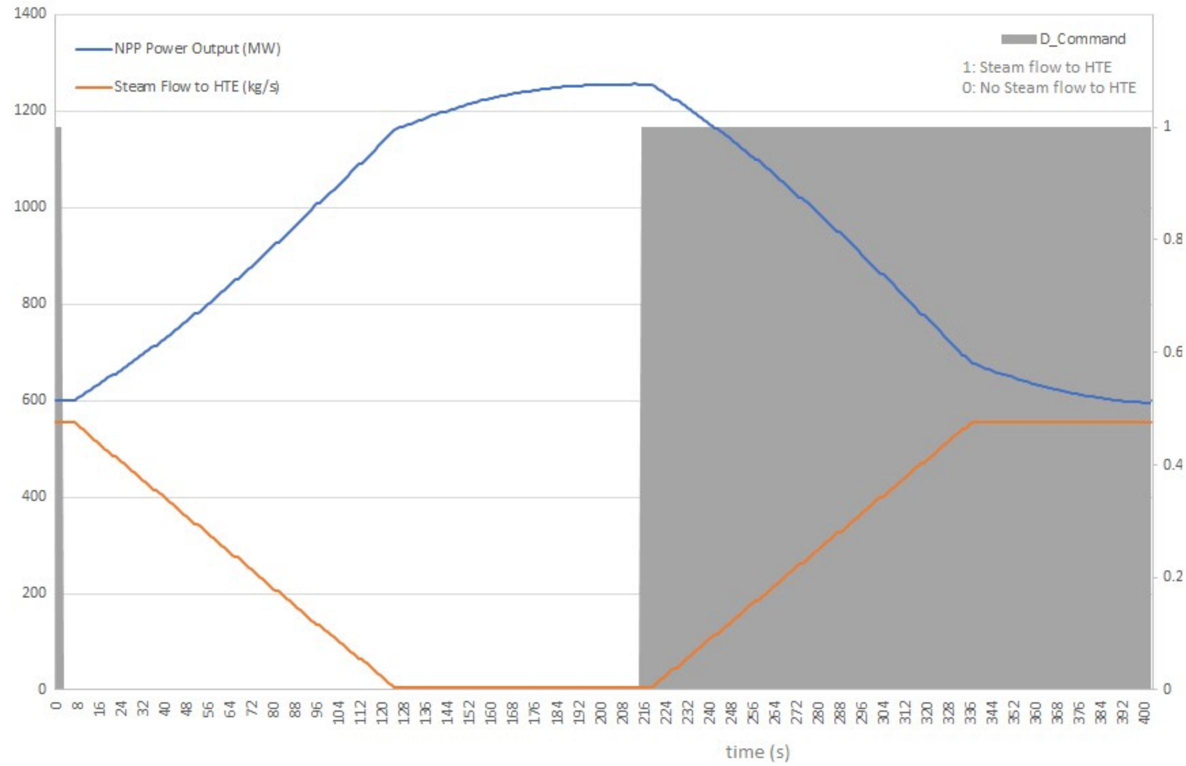

Figure 8. Results of variables and commands exchanged across the HSSL-ESL connection reflected as process variables of NPP Power Output (MW) and thermal power dispatch steam flow rates.

5. CONCLUSIONS & PLANS

A high-speed data connection between the HSSL and ESL has been established and verified. A scenario was performed to verify that devices and models at the different laboratories responded appopriately during a co-simulation. In this scenario, a co-simulation using a R/O-TPD-PWR simulator at HSSL and an HTE plant simulator at HTE was performed in which the HTE plant was cycled from normal operation to hot standby and back to normal operation again. The steam flows in both the NPP and HTE simulators responded as expected, and the operation of the data connection was verified.

Coupling the power generation deck of a NPP to a hydrogen production facility introduces new possibilities for operational transients that must be addressed. In particular, the startup and shutdown procedures 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 newly developed NPP operating procedures and grid power dispatch schedules working in harmony with hydrogen plant operators and grid power coordinators.

For complex systems in which human operators perform control actions at multiple levels within the controls systems, such as NPPs 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.

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.

Future 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 HWIL tests.

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