IES
Integrated Energy Systems

Overview of Nuclear-Hydrogen Demonstrations supported by INL

National Academies of Sciences: Laying the Foundation for New and Advanced Nuclear Reactors in the United States

August 9-10, 2021

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INL/CON-21-63552

Idaho National Laboratory

Summary of Projects/Demonstrations Supported by INL

- Exelon: Low temperature electrolyzer (LTE) operation for dynamic participation in an organized electricity market
- Davis-Besse: LWR Integrated Energy Systems Development & Demonstration (originally planned as LTE but will likely change to high temperature electrolysis, HTE)
- Xcel Energy: LWR Integrated Energy Systems Development & Demonstration (150 kW HTE)
  - Phase II of Davis-Besse project with Energy Harbor and Arizona Public Service)

Nuclear utility demonstrations ("demand-driven")

- FuelCell Energy: Solid oxide electrolysis (HTE) system demonstration
- Bloom Energy: HTE hydrogen production using nuclear power
- OxEon Energy: Performance validation of a 30 kW reversible HTE system

HTE Tech provider demonstrations ("supply-driven")

- GSE Systems: Modifications to a full-scope, high fidelity full nuclear power plant simulator for thermal power dispatch to support HTE hydrogen production

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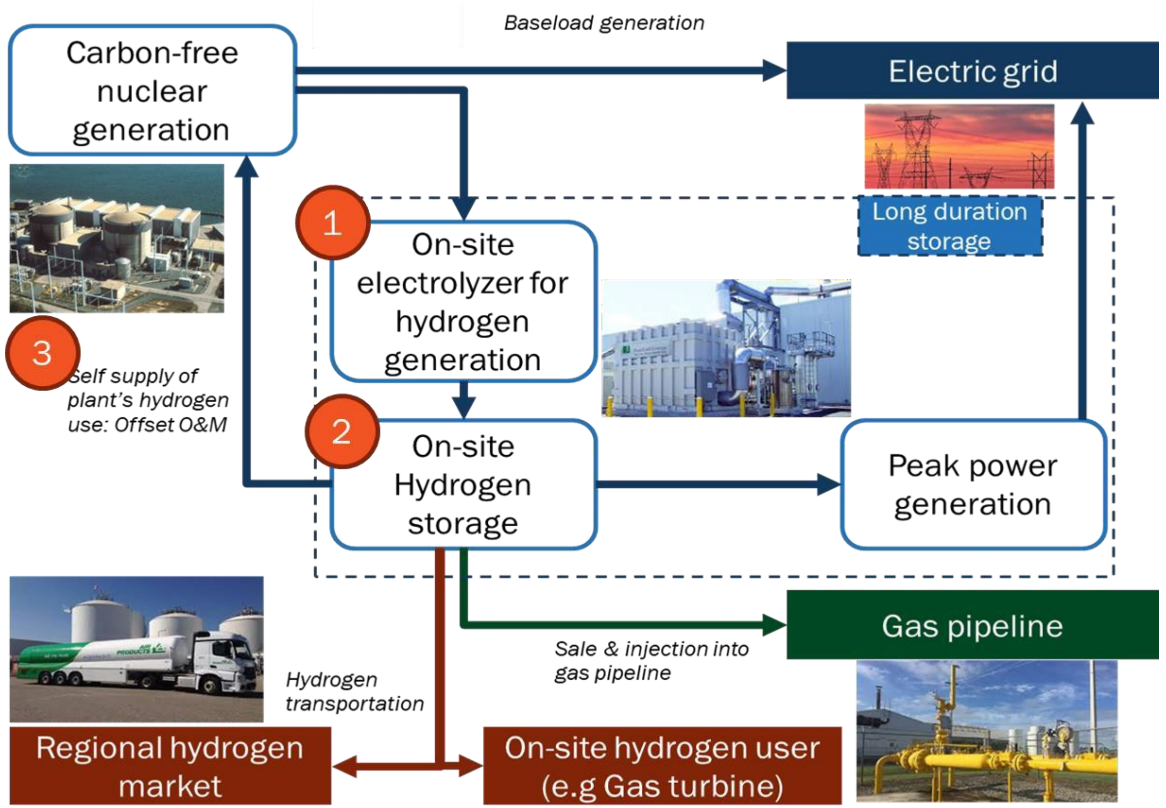
LWR-H2 Demonstration Project: Exelon with Low Temperature Electrolysis

- ***Purpose:***
  - Install a 1 MW Polymer Electrolyte Membrane (PEM) electrolyzer and supporting infrastructure at an Exelon nuclear power plant
  - Provide economic supply of in-house hydrogen consumption at the plant
  - Simulate operation of a larger electrolyzer participating in power markets
- ***Partners:*** Nel Hydrogen, ANL, INL, NREL
- **Progress:** Project has completed first budget period, which included testing a 750 kW prototype electrolyzer at NREL



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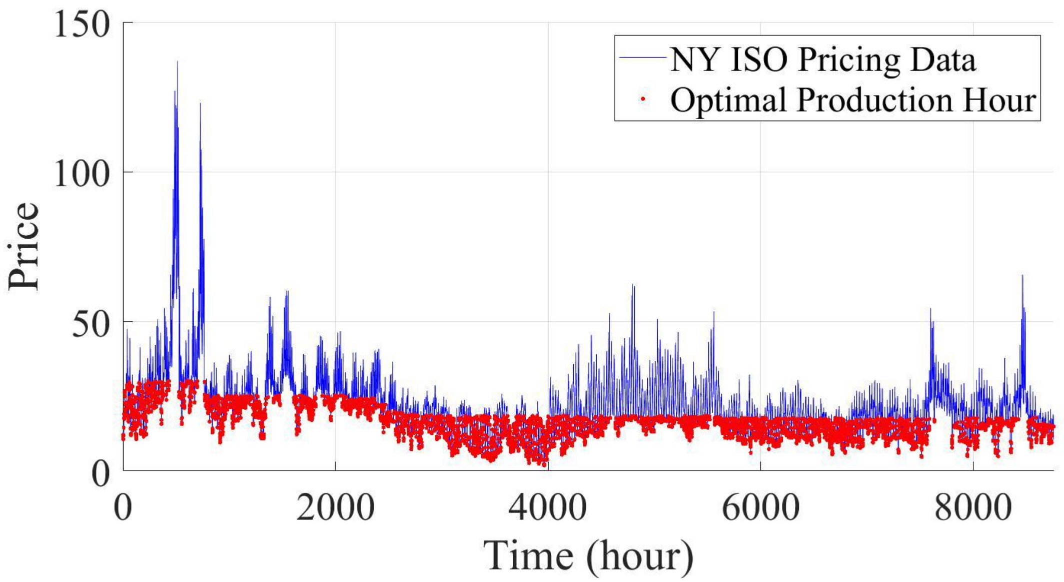
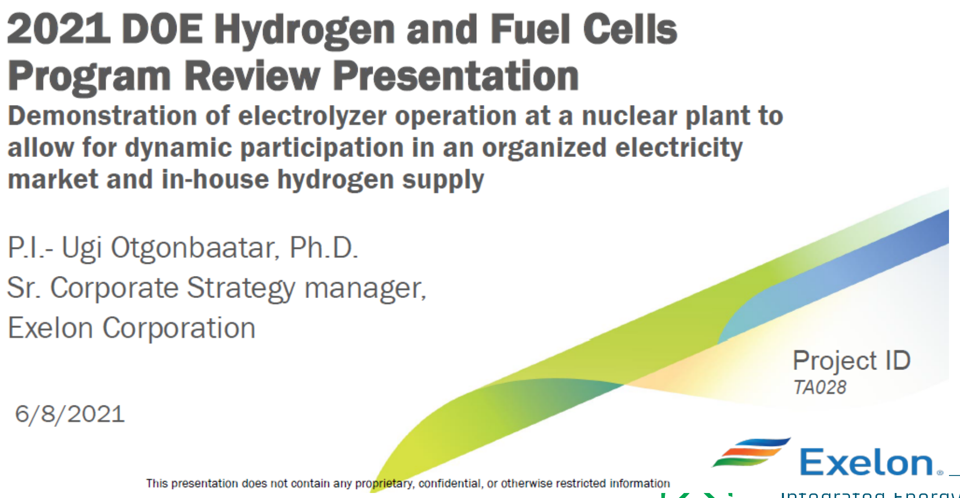
LWR-H2 Demonstration Project: Exelon with Low Temperature Electrolysis

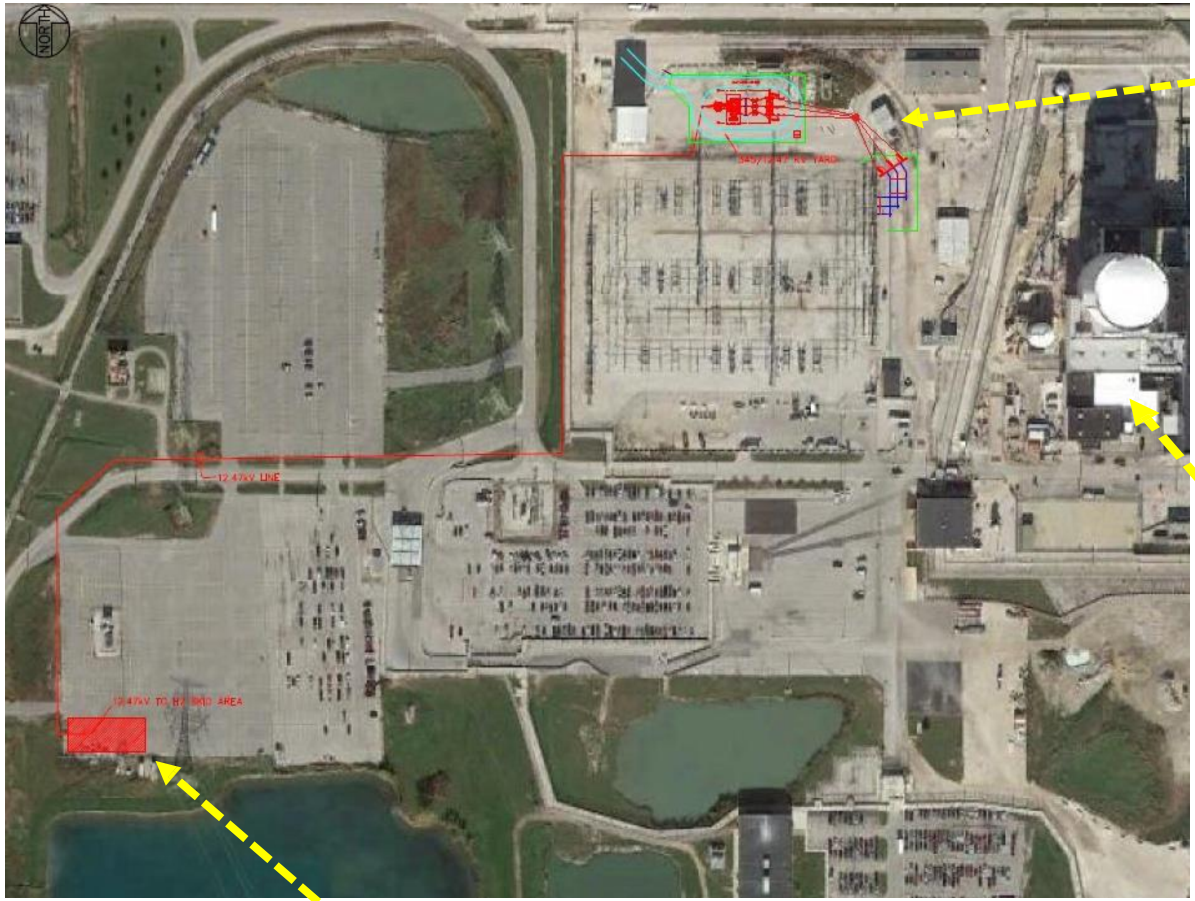
- ***INL's role:***
  - Develop a front-end controller to optimize the operation of the electrolyzer based upon market prices, hydrogen demand, and hydrogen storage constraints
- **Notable outcome:** Electricity price threshold at which electrolyzer turns on varies throughout the year, depending upon daily hydrogen supply/demand/storage capacity ratios
- **Further information:**
  - U. Otgonbataar, 2021 DOE Hydrogen and Fuel Cells Program Review (*https://www.hydrogen.energy.gov/amr-presentation-database.html*)
  - Analysis Report: Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest (*https://www.osti.gov/biblio/1559965-evaluation-non-electric-market-options-light-water-reactor-Midwest*)





LWR-H2 Demonstration Project: Davis Besse Nuclear Generating Station

- ***Purpose:*** Produce hydrogen for first movers of clean hydrogen: fuel-cell buses, heavy-duty trucks, forklifts and industrial users
- ***Industry Consortium:*** Energy Harbor, Xcel Energy, Arizona Public Service, DOE Labs
- Engineering team will design and locate the hydrogen production equipment such that the effect on the design and licensing basis is mitigated (to the extent practical).
- <u>Analysis Report</u>: Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest (https://www.osti.gov/biblio/1559965-evaluation-non-electric-market-options-light-water-reactor-Midwest)
- Project has been delayed but expected to start fall 2021.
- May use a turnkey HTE system that will first be vetted at INL.



LWRS LIGHT WATER REACTOR SUSTAINABILITY

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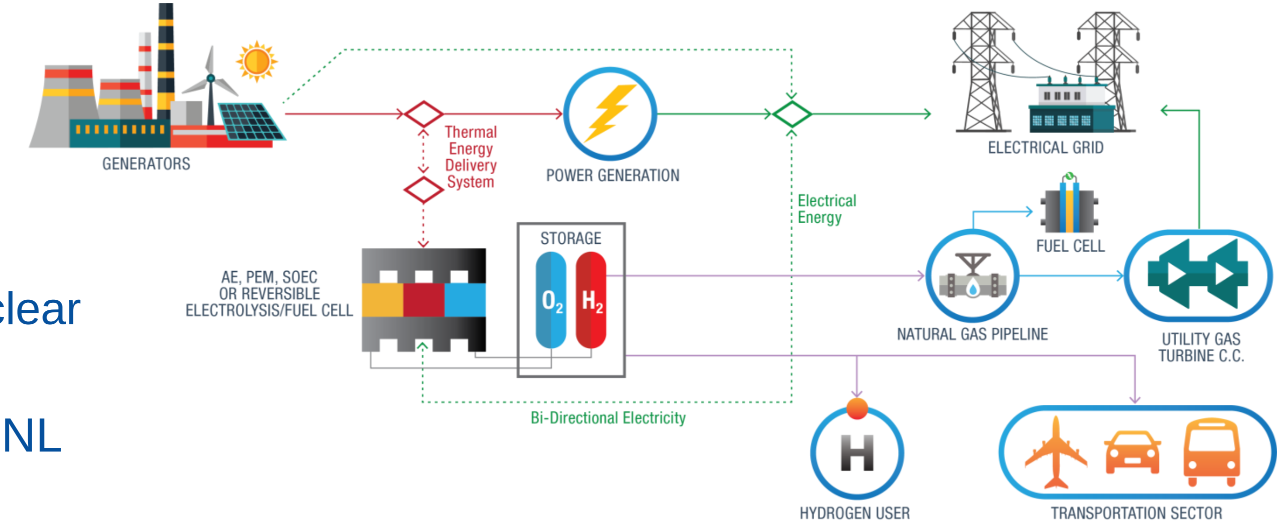
LWR-H2 Demo Project: Xcel Energy with High Temperature Electrolysis

(Phase II of Nuclear Industry Consortium "Davis-Besse" project)

- ***Purpose:***
  - Demonstrate High Temperature Electrolysis (HTSE) at a nuclear plant operated by Xcel Energy
  - Complete engineering design assessment for a bi-directional HTE demonstration at the Palo Verde nuclear plant
- ***Industry Consortium:*** Energy Harbor, APS, ANL, INL
- Project expected to kick off in fall 2021.
- Design and execute thermal and electrical interconnections for the Xcel nuclear power plant HTE system
- Design, test, and build a 150 kWe Solid Oxide Electrolysis Cell (SOEC) system
- INL will commission the HTE system and use it in hardware-in-the-loop tests prior to plant installation



Nuclear power plants can produce green hydrogen at a competitive price with low capital costs

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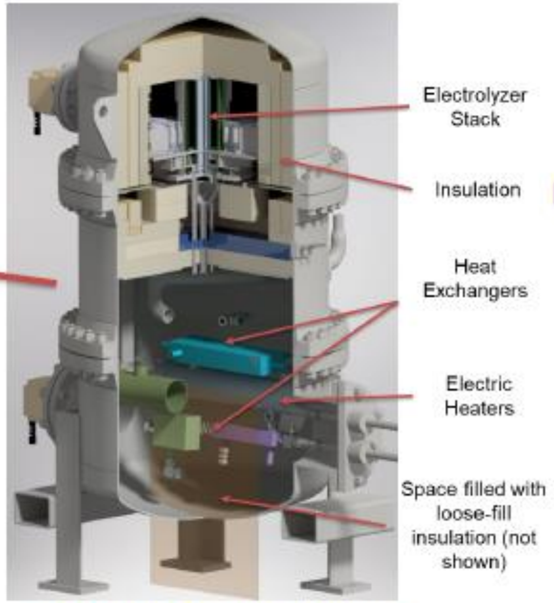
FuelCell Energy: HTE system demonstration

- ***Purpose:***
  - Validate that the integration of HTE technology with nuclear plants will result in high efficiency and low-cost alternative for production of hydrogen utilizing nuclear electricity and heat
- ***Partners:*** FuelCell Energy, INL
- **Approach:**
  - Build and test a 250 kW turnkey solid oxide electrolysis system
  - Perform validation with nuclear power plant emulator at INL
  - Perform technoeconomic analysis for scaled up 500 MW system (~300 tonnes-H_2/day)

SOEC Electrolyzer System



SOEC Electrolyzer Module

Stack Module:
- 125 psig (8.6 barg) design pressure
- Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
- **Three thermal zones:**
  - Hot zone for the electrolyzer stack

- **Further information:**
  - H. Ghezel-Ayagh, 2021 DOE Hydrogen and Fuel Cells Program Review (*https://www.hydrogen.energy.gov/amr-presentation-database.html*)

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Bloom Energy: HTE system demonstration

- ***Purpose:***
  - Test Bloom electrolyzer with nuclear plant emulator and also determine long-term system durability/lifetime
- ***Partners:*** Bloom Energy, INL
- **Approach:**
  - Test a 100 kW Bloom electrolysis system with a nuclear power plant emulator
  - Perform a long-term hydrogen production test (>5,000 hours)
- **Further information:**
  - Delaware facility capable of producing 500 MW of systems (300 tonnes H_2 production)/year and 1 GW within a year
  - *https://www.bloomenergy.com/news/bloom-energy-unveils-electrolyzer/*
  - *https://www.bloomenergy.com/news/bloom-energy-and-idaho-national-laboratory-to-generate-hydrogen-powered-by-nuclear-energy/*

https://www.bloomenergy.com/news/bloom-energy-unveils-electrolyzer/

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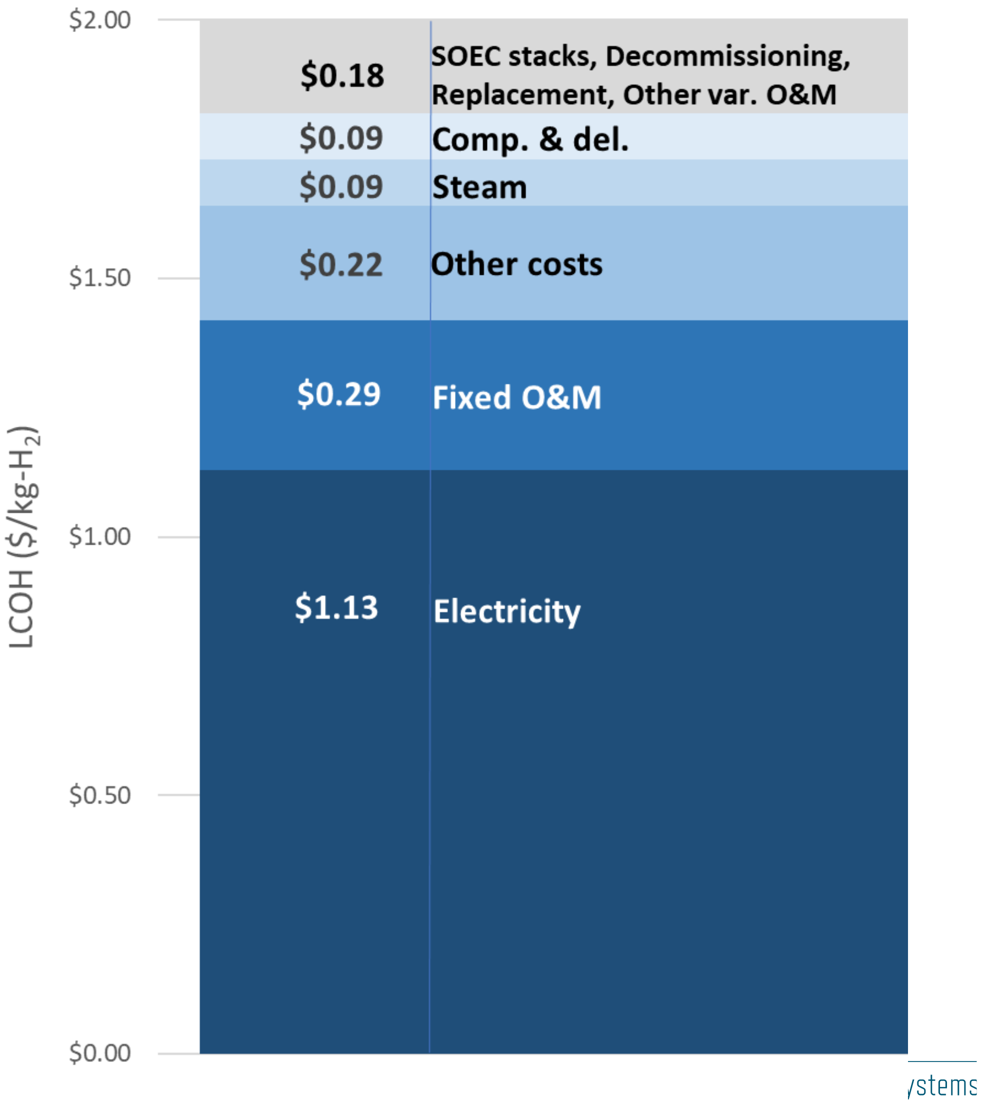
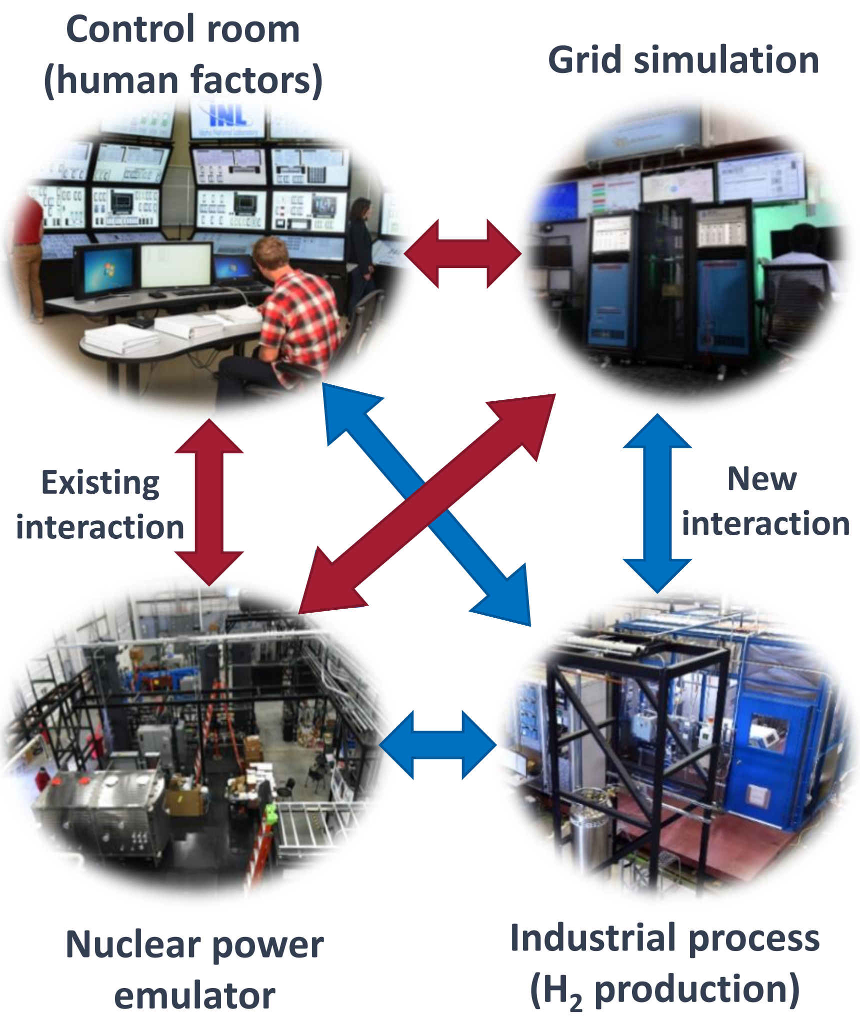
OxEon Energy: Bi-directional HTE system demonstration

- **Purpose:**
  - Validate bi-directional operation of high temperature electrolysis/fuel cell system with 3,000 hrs of operation
  - Bi-directional systems can use the same system components to reduce capital cost and maximize equipment capacity factor
  - May be deployed at small scale to meet needs of diverse users for clean energy utilization, storage, and supply (supports environmental justice)
- **Partners:** OxEon Energy, INL
- **Approach:**
  - Build and test a 30 kW bi-directional system
  - Perform engineering and technoeconomic analyses
    - Show path to achieve >85% system efficiency
- **Further information:**
  - T. Westover, 2021 DOE Hydrogen and Fuel Cells Program Review (*https://www.hydrogen.energy.gov/amr-presentation-database.html*)



INL Demonstration High-level Approach

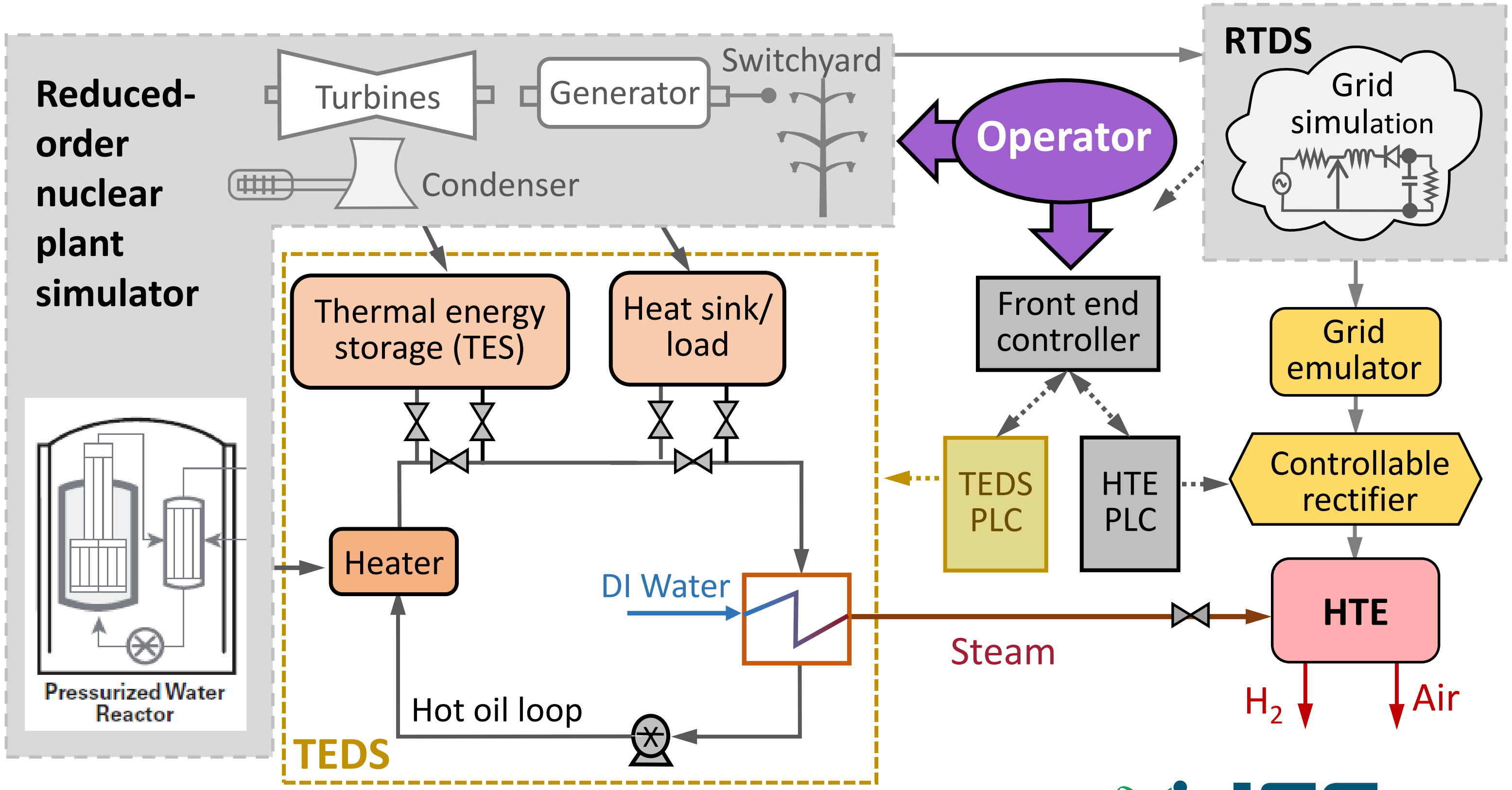
- **Full-scope, high fidelity NPP simulators for coupled thermal and electric power dispatch with human-in-the-loop operations**
  - Support probabilistic risk assessments (PRAs), design-basis accident scenarios investigation, and technoeconomic assessments (TEA);
  - Can capture realistic coupling between NPP and industry partners
  - Full-scope simulators have 1,000+ parameters (difficult to integrate with physical experiments & hardware)
- **Reduced-order simulators for coupled thermal and electric power dispatch with human- and hardware-in-the-loop operations**
  - Hardware-in-the-loop tests probe vital system-system & human-system interactions that can be missed in purely digital simulations;
  - Combines human and hardware factors – essential for coupling to new technology
  - Hardware (pilot-scale) equipment does not match commercial scale – need scaling functions provided by reduced-order simulators



INL Demonstration Capabilities: Hardware-in-the-Loop Testing

- ***Actual process is more complicated than shown in simplified diagrams***
  - *Nuclear reactor & plant*
  - *Electric grid*
  - *Thermal & electric power dispatch*
  - *Thermal & electric power consumer*
  - *Interface controller/optimizer*
- ***Interoperability tests needed in controlled, non-nuclear environment***
  - *Simulated electric grid (Real Time Digital Simulation or RTDS)*
  - *Reduced-order nuclear simulator*
  - *Thermal Energy Distribution System*
  - *Front end controller (optimizer)*
  - *Realistic industrial complex*

Reduced order nuclear plant simulator used to interface with operators and control pilot-scale equipment



Simplified control interface diagram

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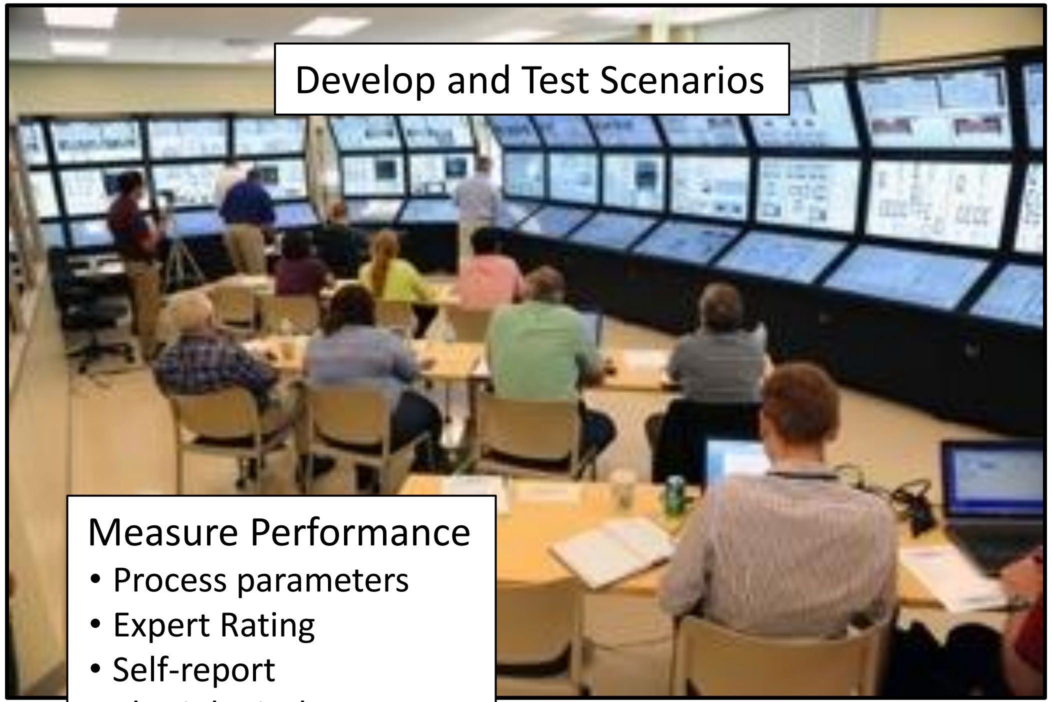
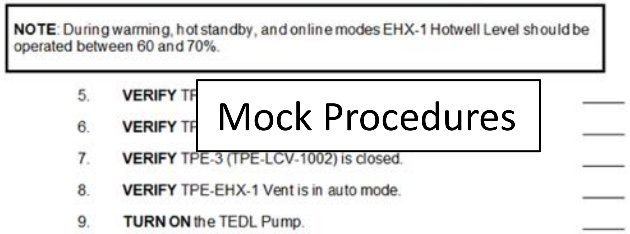
INL Demonstration Capabilities: Nuclear Control Room Simulator

Operator tests using full-scope high-fidelity nuclear power plant simulator modified to enable thermal power dispatch

- *Two former licensed operators*
- *Tested 14 normal and off-normal scenarios*
- *Static "snapshots" or snaps of real simulator data*

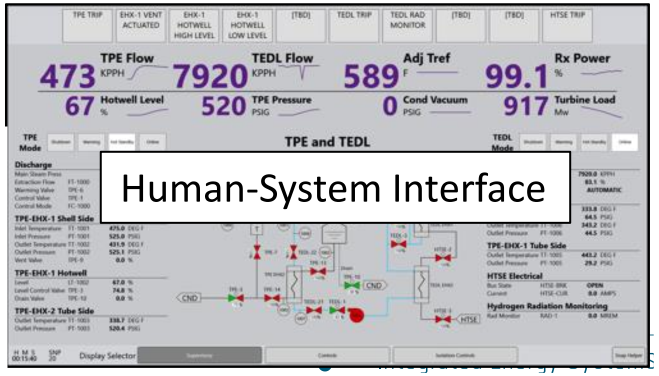
- ***Four basic operating scenarios***
  - *Shutdown->Hot Standby-> Online->Back again*
- ***Findings and Issues***
  - *Operators able to maintain plant in safe condition during all scenarios, although some unacceptable excursions were recorded*
  - *Automatic thermal power dispatch isolation valve is needed for acceptable operations*
  - *Thermal power dispatch can improve plants response to some off-normal events*
  - *Future: need to determine conditions to implement automatic isolation of thermal dispatch system*





NOTE: During warming, hot standby, and online modes EHX-1 Hotwell Level should be operated between 60 and 70%.

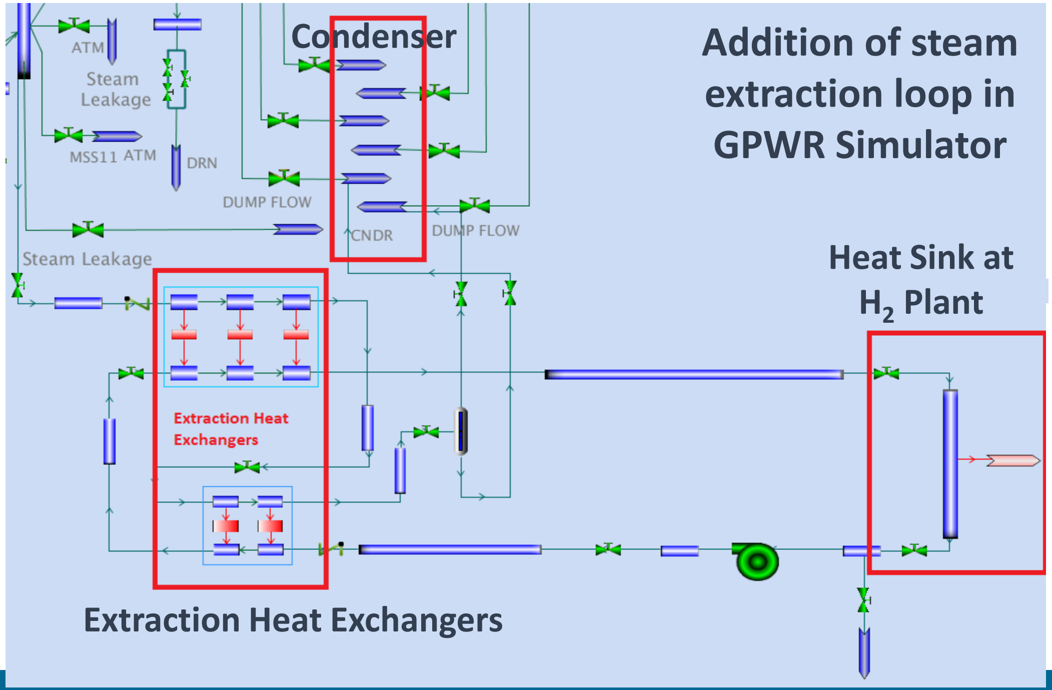
5. **VERIFY** TP
6. **VERIFY** TP
7. **VERIFY** TPE-3 (TPE-LCV-1002) is closed.
8. **VERIFY** TPE-EHX-1 Vent is in auto mode.
9. **TURN ON** the TEDL Pump.

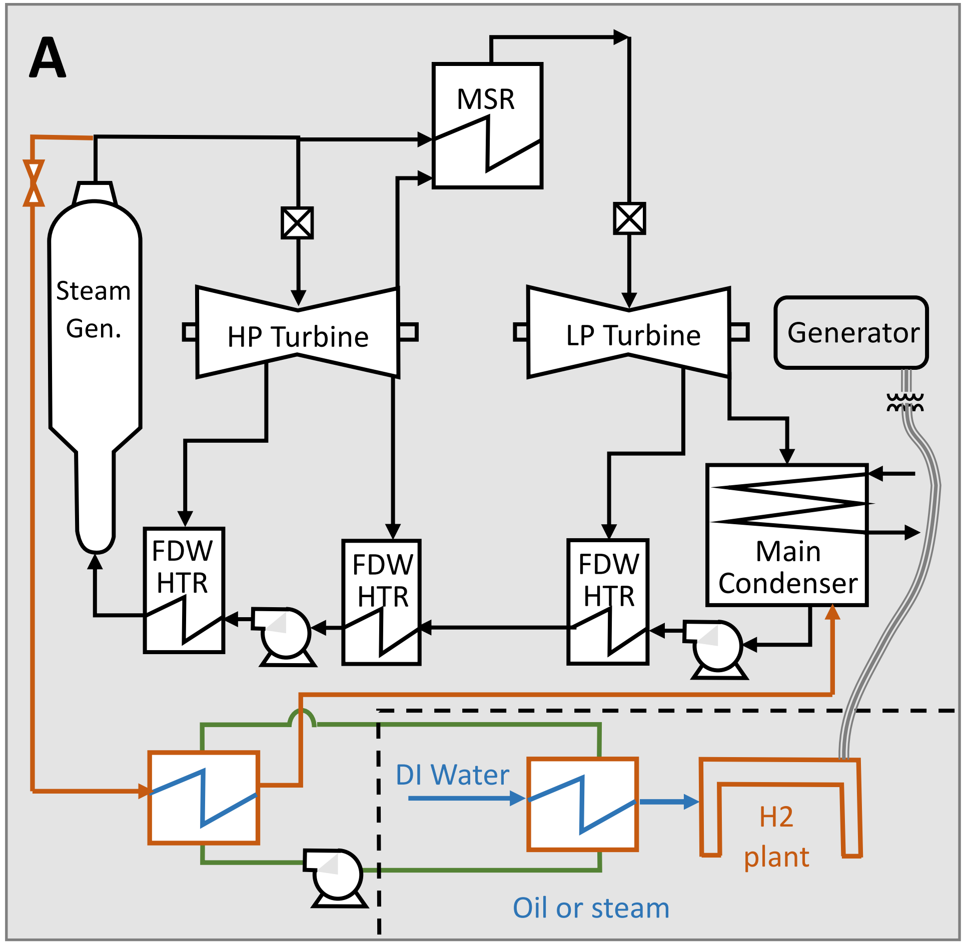


GSE Systems Full-Scope Nuclear Power Plant Simulator Modified for Thermal Power Extraction

GSE Systems® Generic Pressurized Water Reactor (GPWR) Simulator (RELAP 5-HD™)

- High-definition, real-time simulator of 3-loop Westinghouse PWR design (nominal capacity rating of 1000 MW)
- Typically used for training: operator, controls, thermal-hydraulics, fundamentals, reactor neutronics, etc.





FDW HTR: Feedwater Heater
HP: High Pressure
LP: Low Pressure
MSR: Moisture Separator Reheater

Simplified diagram of thermal power dispatch. Steam from main steam line passes through a heat exchanger and then sent to condenser. A tertiary closed loop containing steam or oil provides steam for hydrogen production.

Summary

- Several nuclear utilities are undertaking clean hydrogen demonstration to respond to growing demand
- Domestic and international electrolysis technology providers are rapidly scaling up (LTE to 100’s MW and HTE to 10’s of MW and then 10 100’s of MW)
- A combination of high fidelity, full scope simulators and reduced order simulators coupled to pilot-scale hardware will prepare for integrated nuclear and hydrogen plant operations
- INL is developing the needed capabilities
  - Full scope and reduced order nuclear power plant simulators modified for thermal and electric power dispatch
  - Nuclear power plant emulation
  - Industrial processes that can benefit from nuclear steam and electricity
- Several integrated energy system demonstrations have been announced and more are being planned (at scales up to 20 MW)

Extra Slides

New Technology for Energy Transport, Conversion & Storage

- ***Integrated Energy Systems Involve:***
  - Thermal, electrical and process intermediates integration
  - More complex systems than co-generation, poly-generation, or combined heat and power
  - Economics of coordinated energy systems
  - May provide grid services through demand response (import or export)
- ***Technology Development Needs & Opportunities:***
  - New energy storage technologies (thermal, chemical, electrical)
  - Thermo-Electrical chemical conversion processes
  - Modern advanced informatics and decision systems for massive data
  - Embedded sensors for health monitoring and cyber security

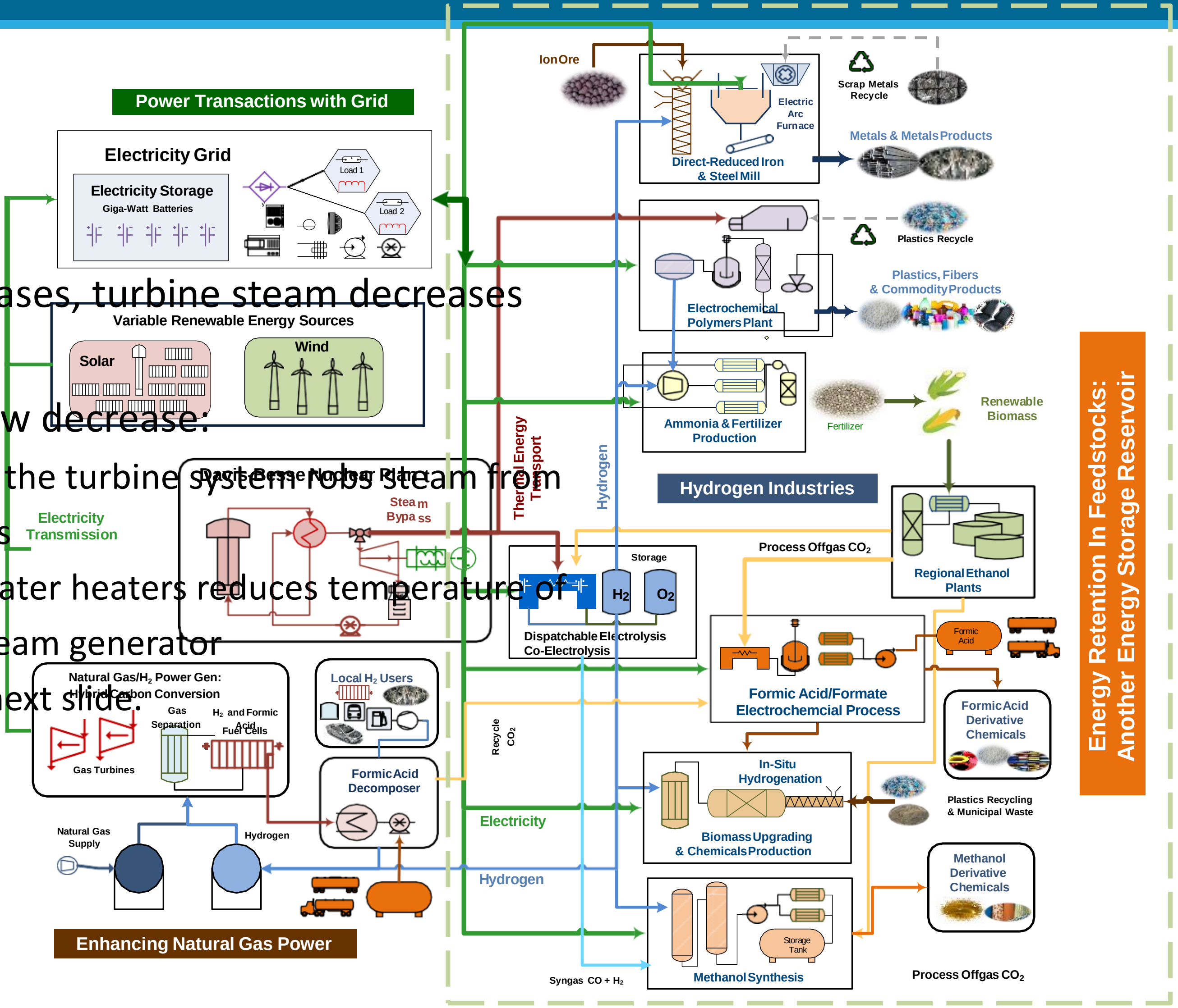
As TPE steam flow increases, turbine steam decreases (conservation of mass)

Cause of main steam flow decrease:

Diverting steam from the turbine system robs steam from the feedwater heaters

Loss of heat to feedwater heaters reduces temperature of water entering the steam generator

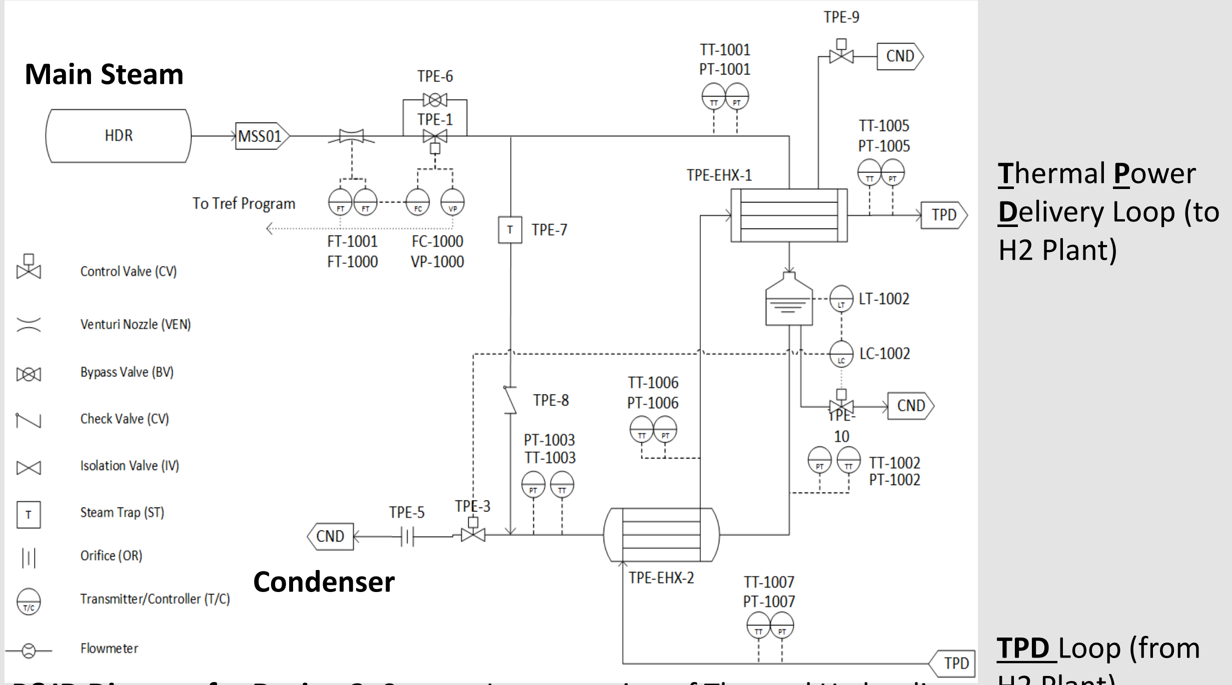
More on this on the next slide.



GSE Systems Full-Scope Nuclear Power Plant Simulator Modified for Thermal Power Extraction

6 Scenarios Evaluated

- *1 Scenario verified with RELAP5-3D*
- *1 scenario analyzed for both oil and steam in Thermal Power Delivery Loop (TPDL)*
- *Other scenarios simulated at steady-state with HYSYS*



P&ID Diagram for Design 2. Source: Incorporation of Thermal Hydraulic Models for Thermal Energy Dispatch into an LWR... INL/EXT-20-58766

Scen-ario	Thermal dispatch power	Thermal dispatch distance	Software & model extent
1	150 MW	1.0 km	RELAP5-3D for Steam Extraction Line & TPDL; HYSYS for TPDL only
2	150 MW	0.5 km	HYSYS for TPDL only
3	150 MW	0.1 km	HYSYS for TPDL only
4	15 MW	0.1 km	HYSYS for TPDL only
5	200 kW	0.1 km	HYSYS for TPDL only
6*	200 kW	0.1 km	HYSYS for TPDL only

- **Oil vs. Steam in Thermal Power Delivery Loop (TPDL)**
  - Oil is much simpler for analysis and matches INL's Thermal Energy Distribution System (TEDS)
  - Pump power for oil is ~20x greater than for steam
  - Max. pressure greater for steam (2.7MPa vs. 0.4kPa)
  - Mass flow greater for oil: 1,000kg/s vs. 72kg/s
  - Oil has additional contamination and flammability hazards

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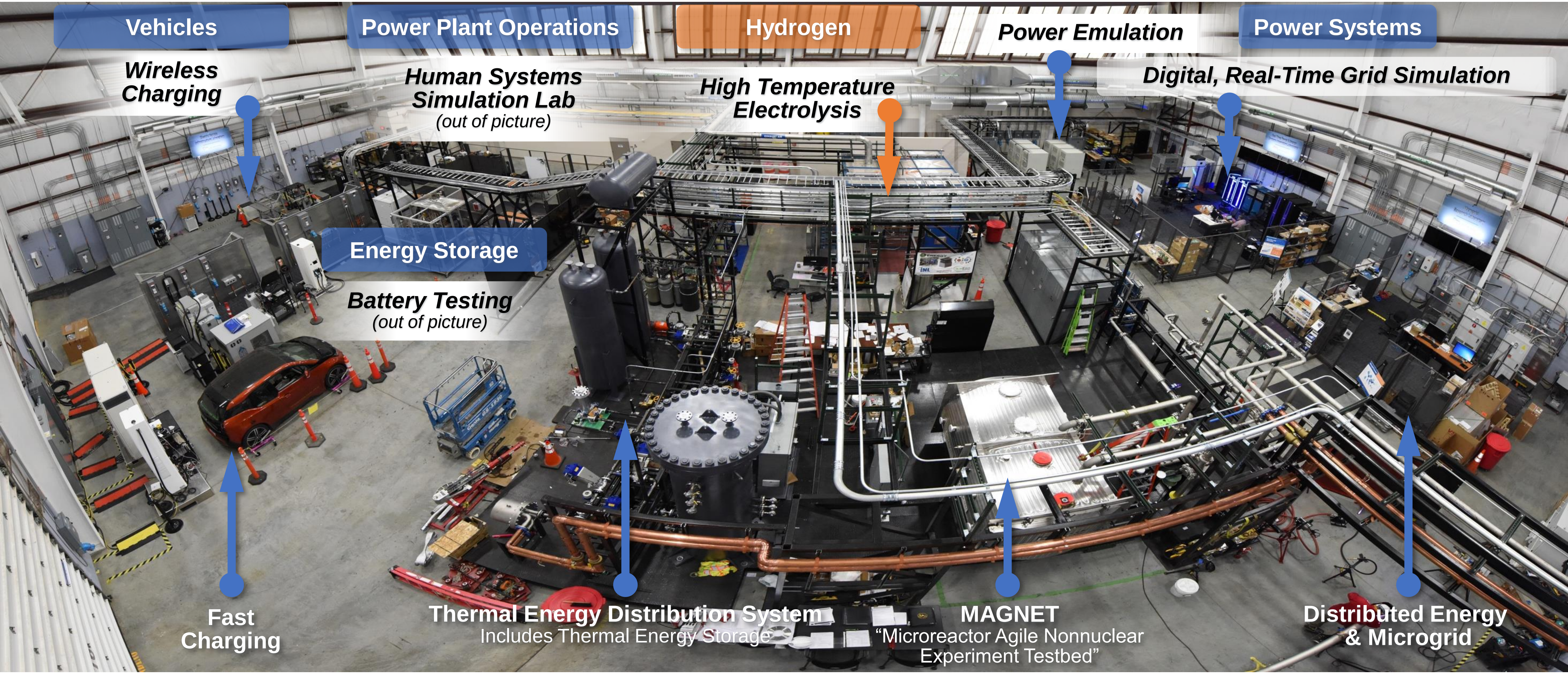
Energy Systems Laboratory IES Capability



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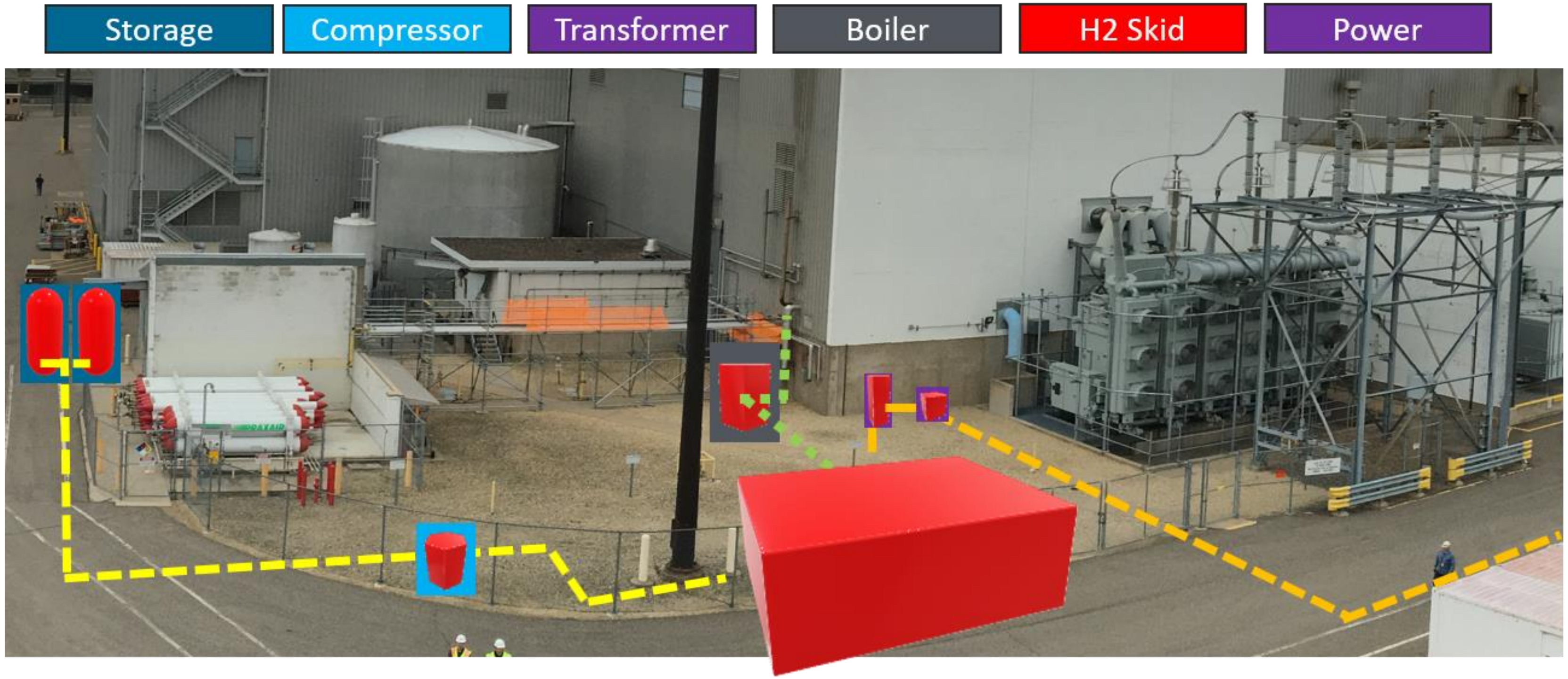
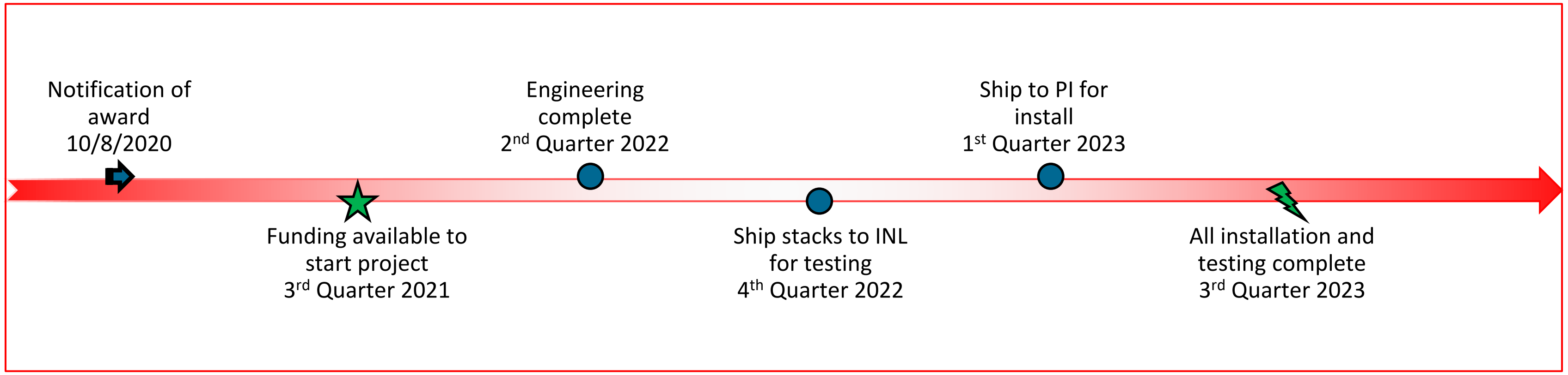
Xcel Energy HTE Demo at a Nuclear Power Plant

SENSITIVE DATA
- DO NOT SHARE -

- Design and install 150 kWe HTSE at nuclear plant
  - Mechanical and electrical connections
  - Controls, operation, maintenance





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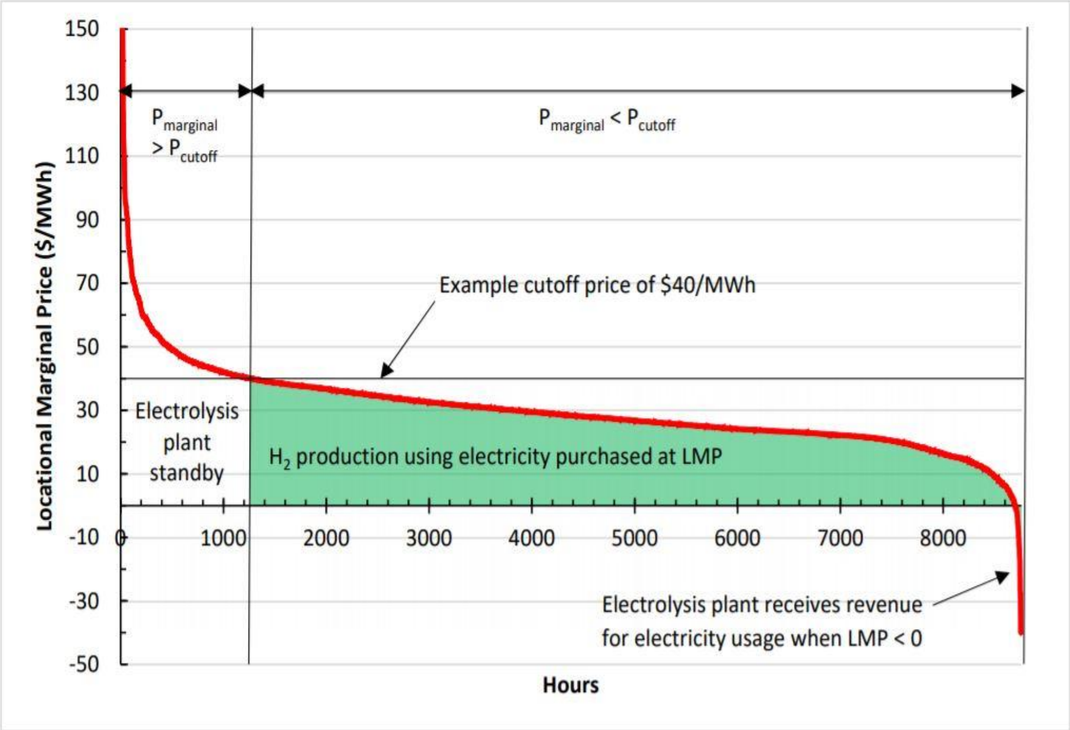
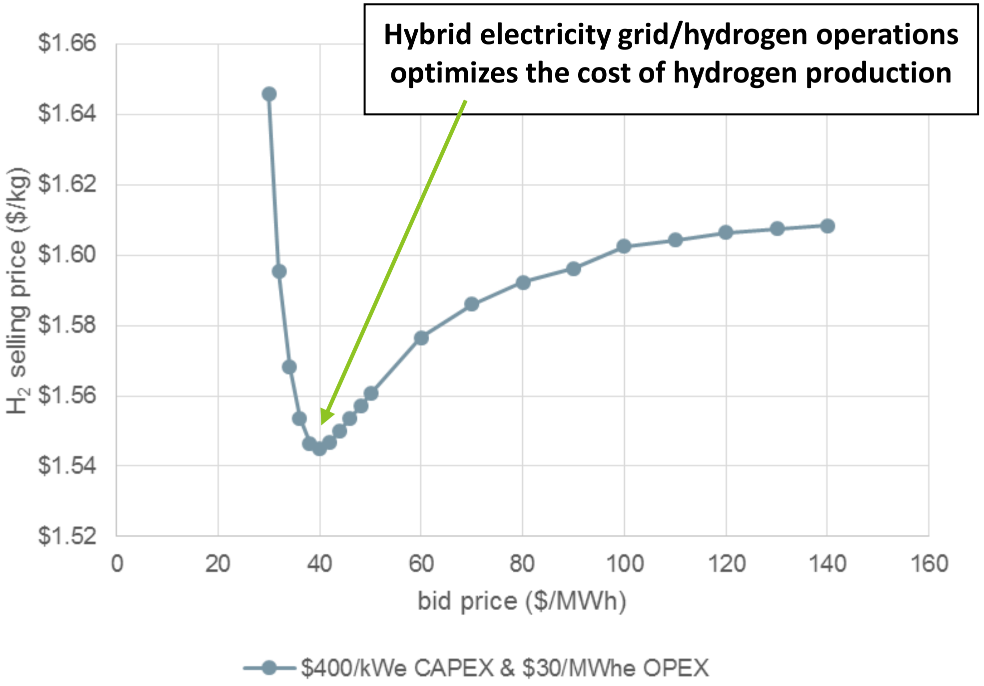
Finding Hybrid IES Solutions for Nuclear



Project analysts developed an algorithm to determine the cut-off price that activates hydrogen production to optimize the revenue of a hybrid power/hydrogen production plant.



Minimum hydrogen production costs versus cut-off selling price for producing/selling electricity

INL/LTD-19-55247: Region-Specific Merchant Hydrogen Market and Techno-Economic Assessment of Electrolytic Hydrogen Generation, March 2020

Southern Company Exelon. Xcel Energy