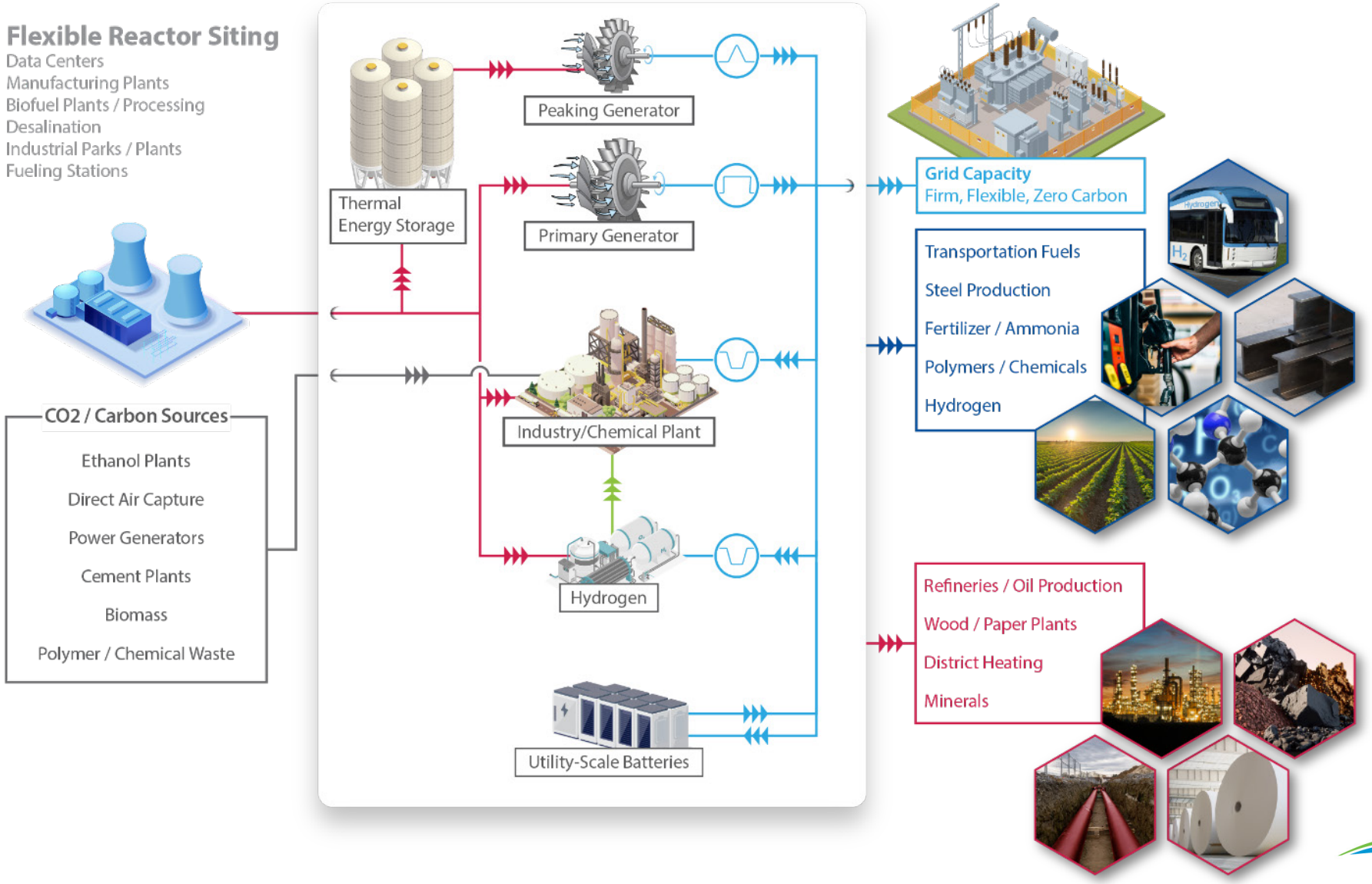
LWRS Spring Review

Flexible Plant Operation and Generation (FPOG)

Richard Boardman, Pathway Lead

April 30, 2024

FPOG enables diversification of light-water reactors to produce non-electrical products



FPOG Research Emphasis

- **Technical & economic assessments**
  - Hydrogen production using water-splitting electrolysis
  - Hydrogen markets; current and emerging
  - Thermal energy extraction, storage, and delivery to Industry
- **Dynamic energy offtake and delivery to the second user**
  - Steam diversion and transport to a close-coupled industry
  - Electrical energy offtake in front of the grid
  - New control concepts and human factors
- **Safety hazards and regulatory review research**
  - Fire and explosion hazards analysis
  - New risk initiating events
  - Probability risk assessments
  - Operating license review

Levelized cost of hydrogen is competitive for markets that value clean energy products; power, fuels, chemicals, steel

Nuclear plants can contribute to meet DOE's goal of producing H_2 for <$2/kg

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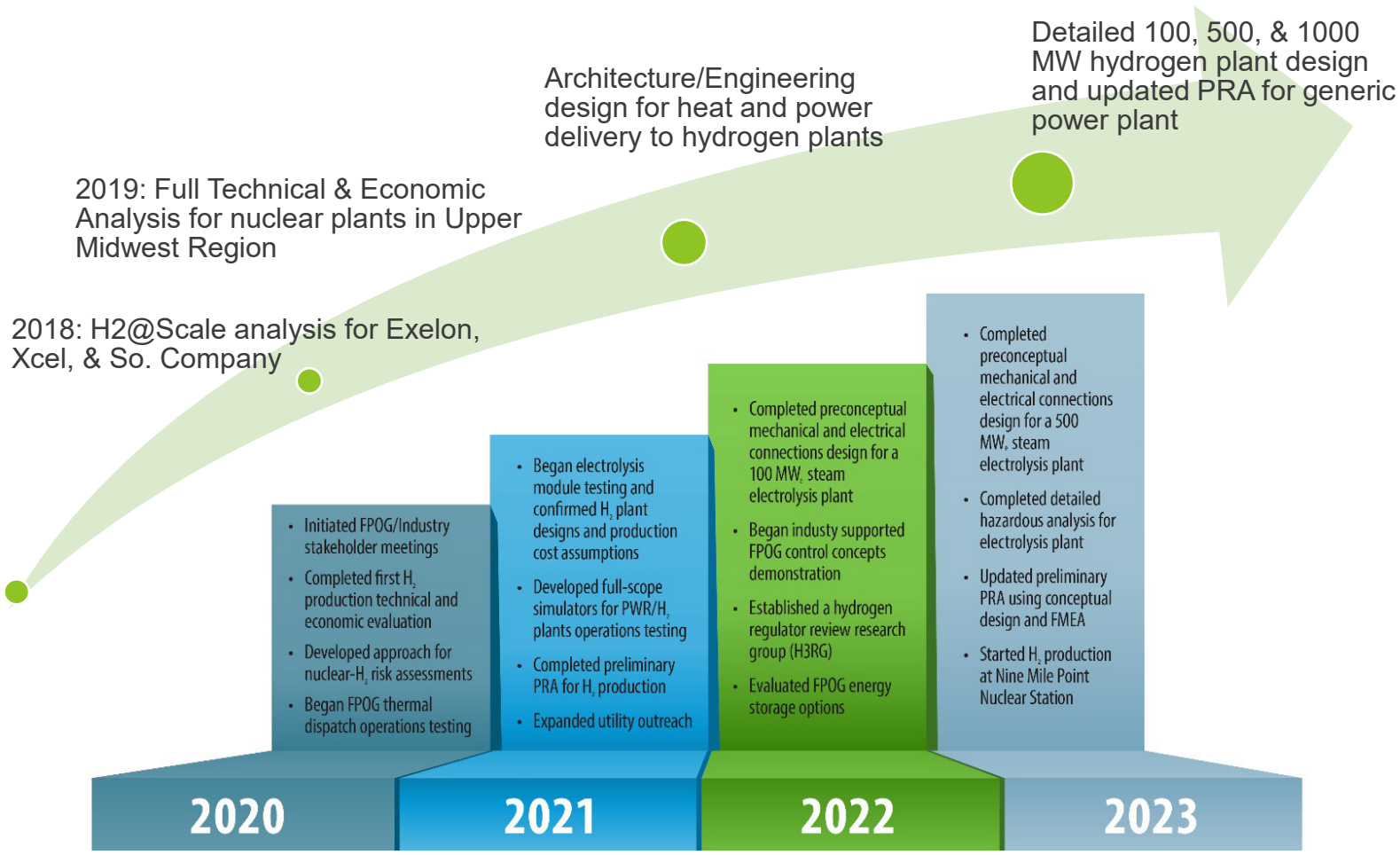
FPOG Progressive R&D Stages



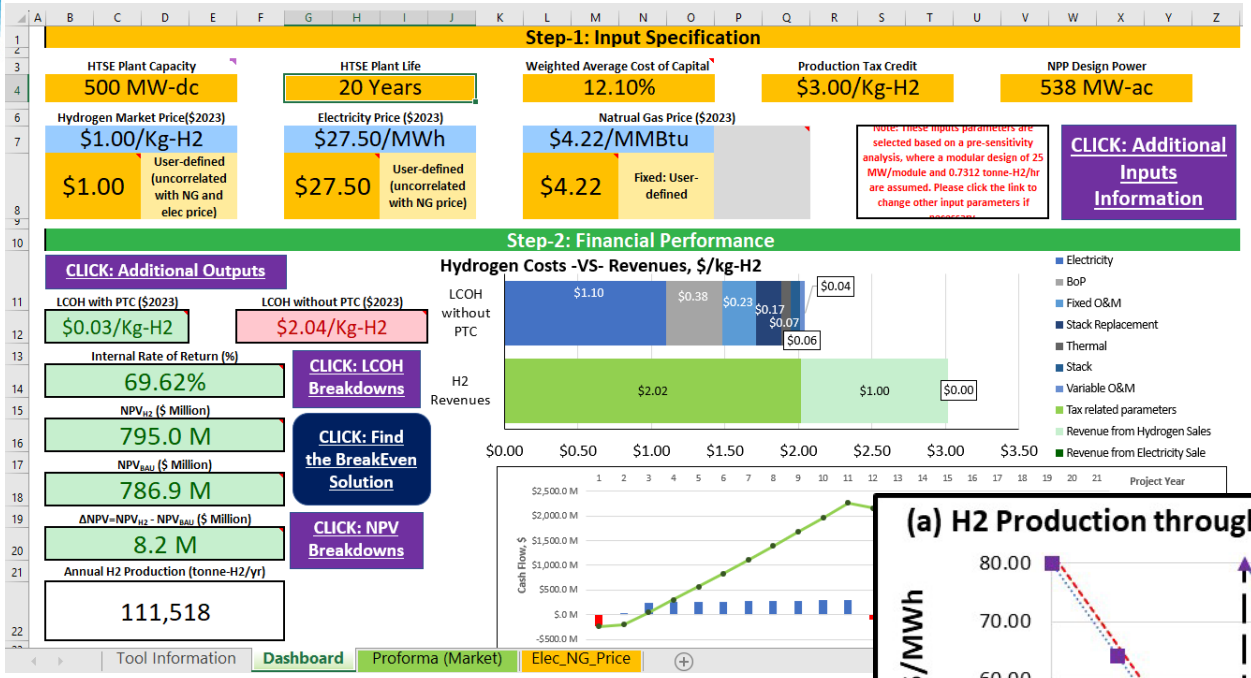
FY-24 Task Highlights:

- ❑ Capstone on hydrogen production with nuclear power plants
- ❑ Assessment of Gulf Shore hydrogen and thermal markets
- ❑ Prospector tool for screening FPOG markets
- ❑ Value of nuclear power plants relevance to grid reliability & resilience
- ❑ 30-50-70% thermal energy offtake designs and concepts of operations

Industry Engagement

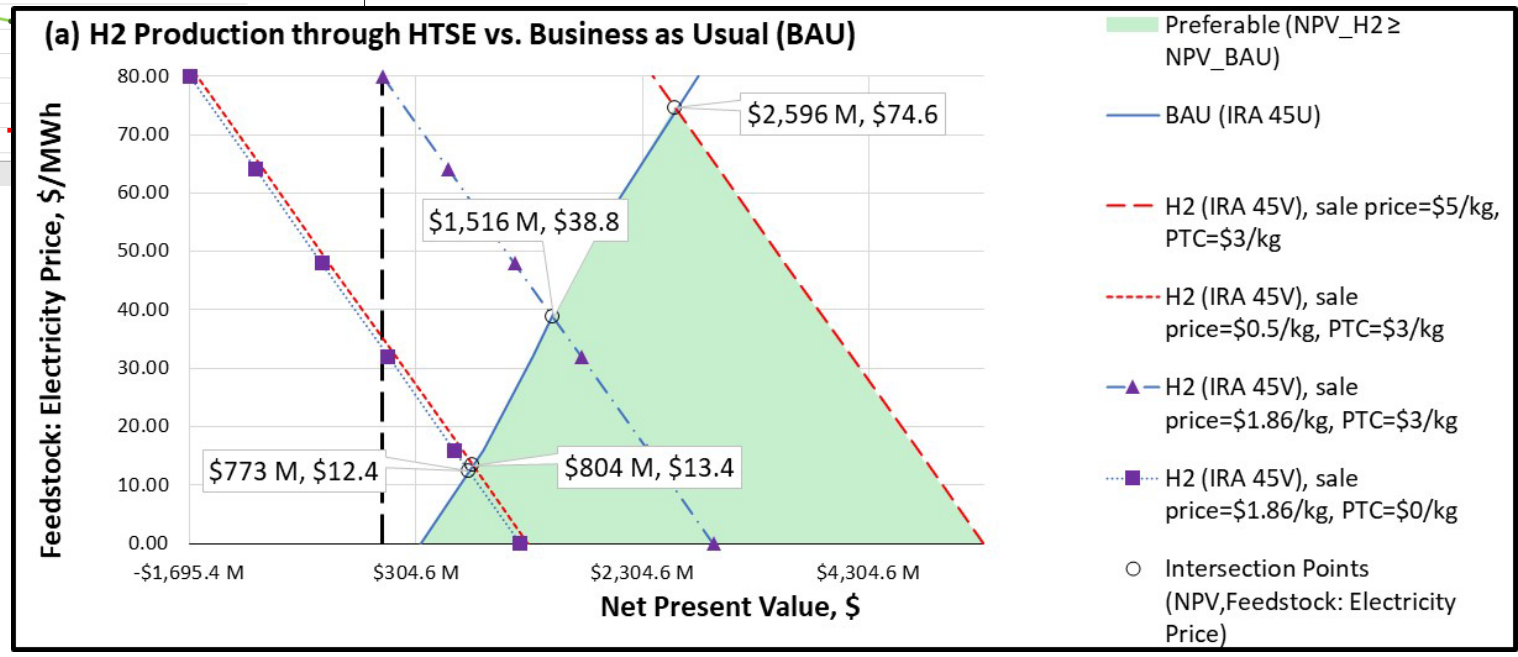
- Electric Power Research Institute / Nuclear Beyond Electricity
- Cost-shared Industry Funded Research
  - Hydrogen market studies
  - Electrolysis hydrogen demonstration projects
  - Co-electrolysis technology testing
  - Control systems and thermal energy offtake development
  - Full-scope simulator development for nuclear-hydrogen coupled plants
  - Bloom Energy electrolysis module testing, including flexible ramping up and down from 10% to 95% of full power
- Hydrogen Hub Projects

Calculator for utility-scale hydrogen production market potential analysis



- Developed for light water reactors (LWR) owners
- Dashboard provides user with hydrogen project and gird market parameters
- Calculates levelized cost of hydrogen, net present value, internal rate of return on investment

- Compares profit of hydrogen versus the grid market
- Value of production tax credits calculated
- Hydrogen plant scalable to 500 MWe electrolysis module



Foundational Laboratory R&D Efforts

Controls systems and user interfaces

Human factors development and operator performance testing

Full-scope licensed operator simulation in Human System Simulation Lab (HSSL)

Real hardware and grid simulations

GSE SYSTEMS

Westinghouse

Bloomenergy

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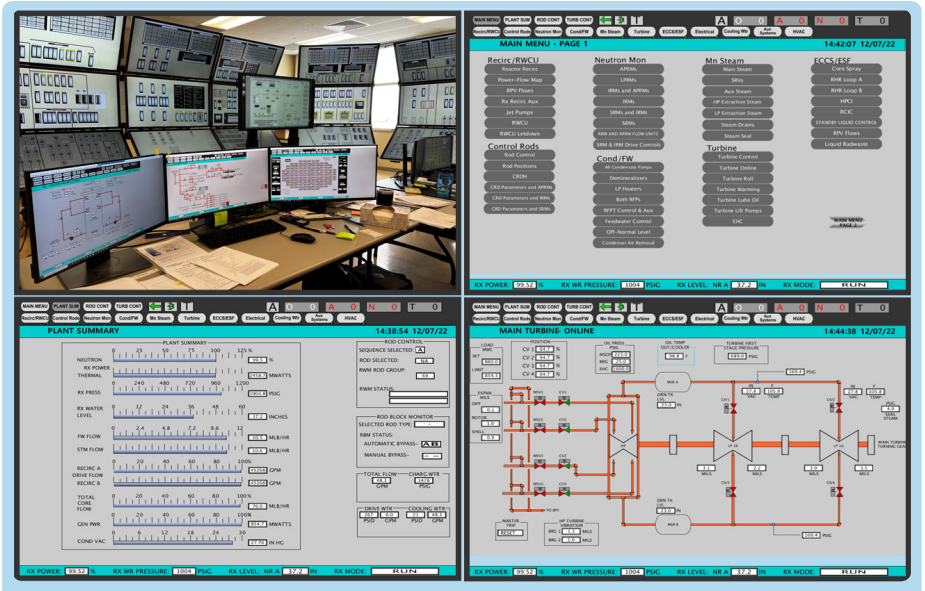
Nuclear Power Plant Simulators Ready for Development of Operating Concepts for FPOG

- LWRS leads completed the installation and verification of full-scope simulators of a nuclear plant coupled to a high temperature steam electrolysis plant.
  - GSE was contracted to modify a simulator for a pressurized-water reactors and a boiling water-reactors based on an architecture/engineering preconceptual design for thermal and electrical coupling to a hydrogen plant
  - Westinghouse Cooperative Research and Development Agreement and contract supporting development of operating concepts and full-scope simulators based on a pressurized-water reactor
  - A dynamic model for the electrolysis plant was added to the plant simulator to provide realistic feedback to plant operators regarding the status of the hydrogen plant
  - Both simulators were installed and verified at the INL Human Systems Simulation Laboratory
- The modified simulators are being used to test operating concepts, address human factors, and prove NPP operators can reliably and safely dispatch thermal and electrical power to a hydrogen plant



GSE Systems Inc. Modified Boiling Water Reactor in the Human Systems Simulation Laboratory

Contact thomas.ulrich@inl.gov or tyler.westover@inl.gov for more information

Conceptual Design Development

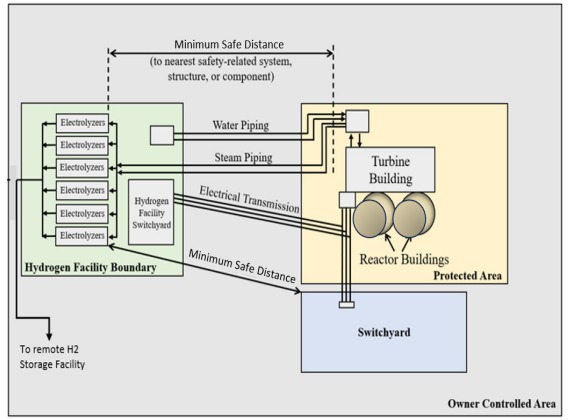
Sargent & Lundy

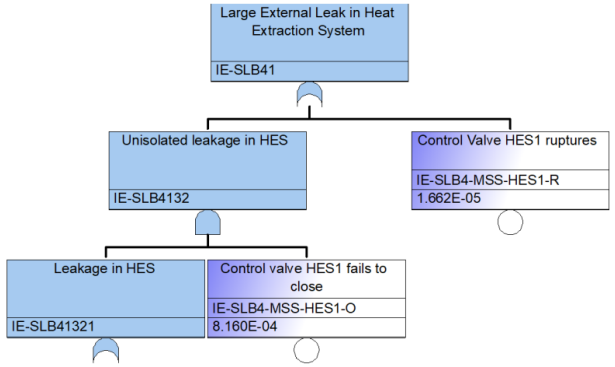
Electrical and thermal integration modeling of co-located HTE at a Standard 1200 MW NPP

Traditional engineering methods used to limit uncertainties on design and operational impacts

Failure Modes and Effects Analysis (FMEA) input to risk modeling

Generic design evaluated under 10 CFR 50.59 process





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Risk Analysis Approach Progression

Early simplified probabilistic risk assessment (PRA) approaches

Initiating events, fault trees, FMEA addressed

Steam rupture, fire, explosion, and other hazards evaluated for plant operating modes

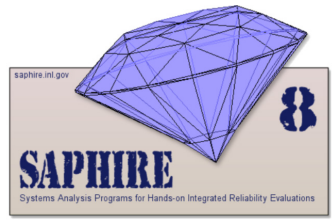
Qualitative hazards assessment for potential community and utility business risks

Evaluation of offset distances to H2 plant from NPP critical infrastructure

Sandia National Laboratories

HyRAM+ Hydrogen Plus Other Alternative Fuels Risk Assessment Models

INL Idaho National Laboratory



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Computer-Aided Fault Tree Analysis (CAFTA)

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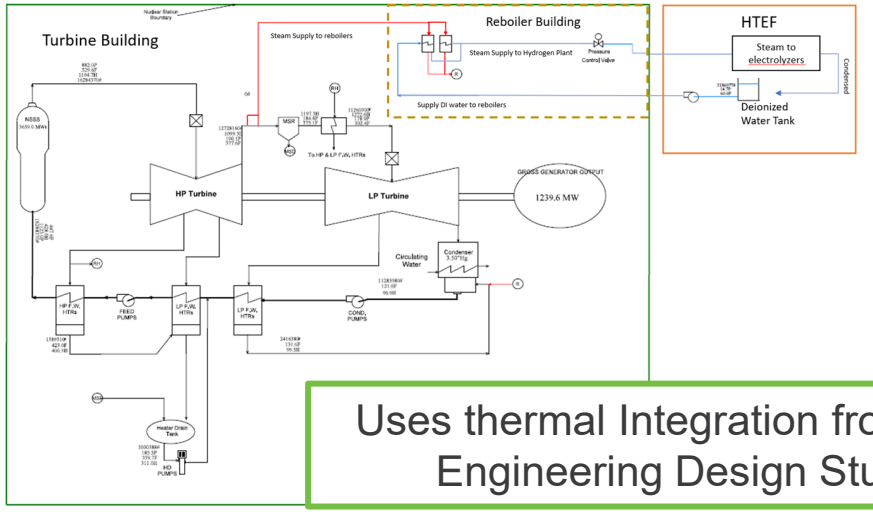
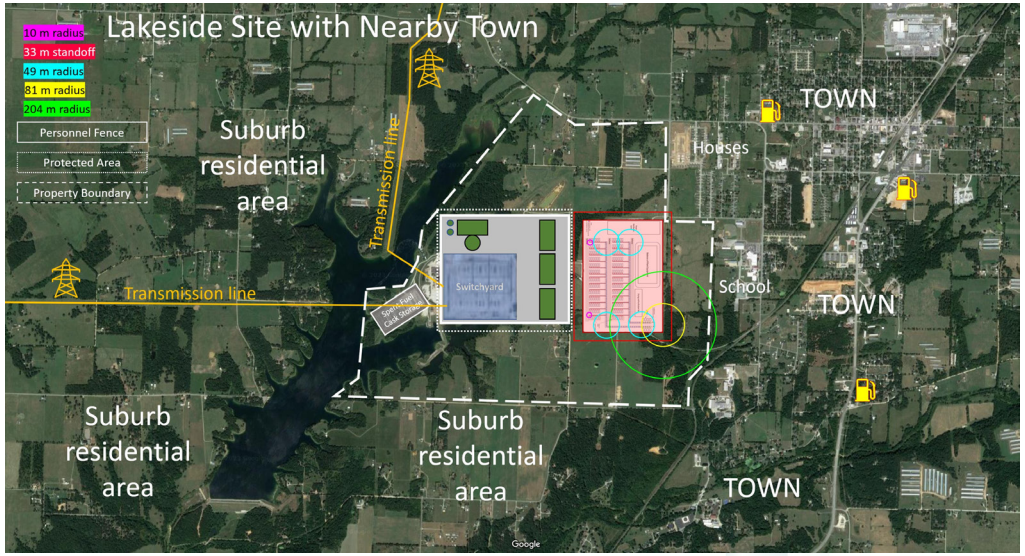
Hazards and Probabilistic Risk Assessments of a LWR Coupled with Electrolysis Utility-Scale Hydrogen Production Plants

INL/RPT-23-74319 issued August 30, 2023

- Detailed 100, 500, and 1000 MW_{nom} HTE hydrogen production facilities
- Defined thermal extraction systems for each size of hydrogen plant
- Determined safe unbarriered standoff distances for each section of the plant
- Applied facility layouts and standoff distances to common generic sites of nuclear power plants
- PRA model calculated the increased initiating event frequencies and other metrics required for NRC licensing acceptance



Uses thermal Integration from S&L Engineering Design Study



Hypothetical Nuclear-Powered Hydrogen Plant located near community area

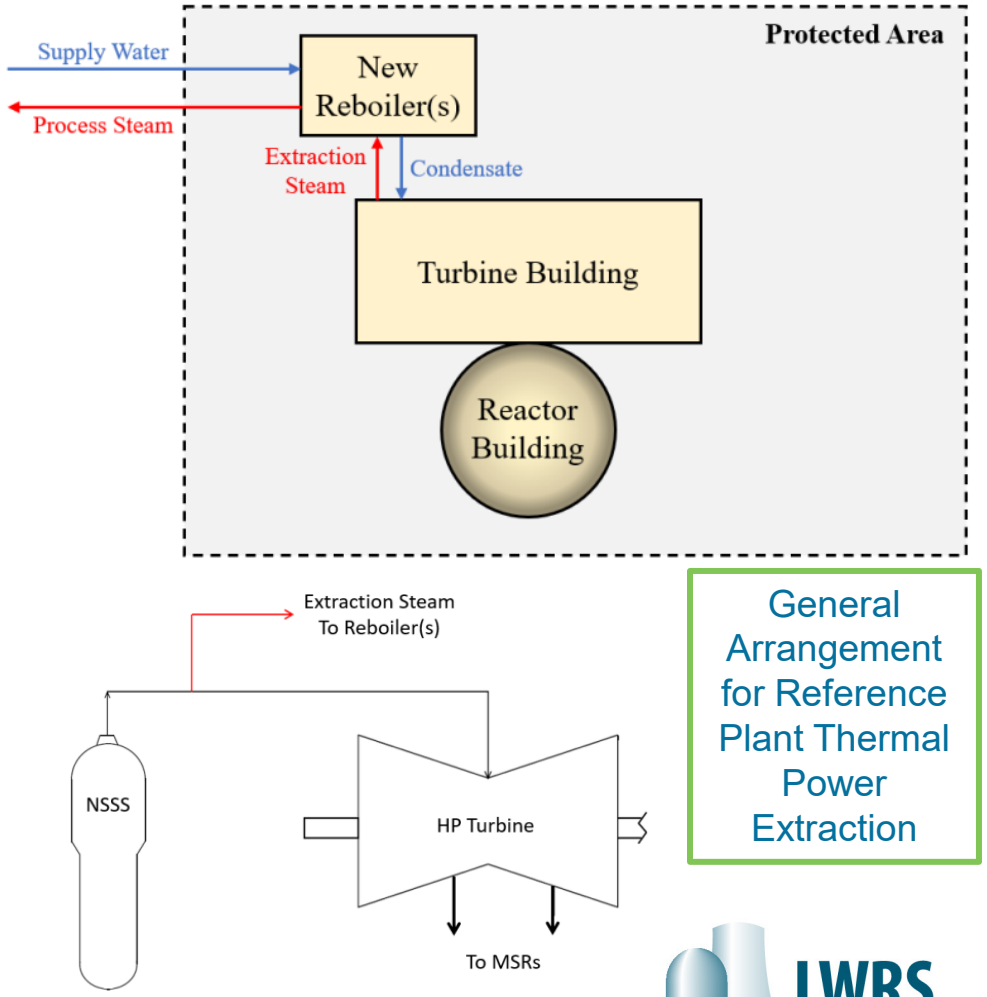
Heat Balance Model Analysis and Equipment Assessment for 30%, 50% and 70% Thermal Power Extraction from a Nuclear Plant

INL/RPT-24-772067 issued March 2024

- Engineering assessment of the impacts to the PWR secondary system based on PEPSE model results for the respective thermal power delivery scenarios.
- Evaluate impacts of thermal and mechanical stresses associated with thermal power extraction on nuclear plant components:
  - High- and low-pressure turbines, main condenser, power train pumps, moisture separator reheaters, drain systems, feedwater heaters, and extraction steam equipment, etc.

Conclusions:

- A nuclear plant can reasonably accommodate up to 50% thermal power extraction without significant impact
- 70% thermal energy extraction presents challenges for the secondary plant and the nuclear steam supply system



General Arrangement for Reference Plant Thermal Power Extraction

Pilot Plant Hydrogen Production Demonstration Projects

- **Technical:**

  Addressed by beta prototype and systems verification testing

- **Economic / Business:**

  Beta prototype testing for Front-End Engineering Design study; Engineering & Plant Construction Design, Capital & Operating Costs; Warranty

- **Permitting:**

  Safety hazards; Emissions verification; Risk assessments; NRC Licensing

Constellation:
Nine-Mile Point Plant

- H_2 production began in 2023
- Nel proton electrolyte membrane (PEM) electrolysis module

Xcel Energy:
Prairie Island Plant

- H_2 production beginning in 2024
- Bloom Energy high temperature solid-oxide electrolysis cell (SOEC) module

Vistra :
Davis-Besse Plant

- H_2 production beginning in 2024
- PEM or SOEC electrolysis unit

EERE R 540.112 02: Technology Readiness Levels (TRLs)

TRL-6. System/process model or prototype demonstration in a relevant environment-Beta prototype (system): Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high-fidelity system applications in an environment relevant to the end user.

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Sustaining National Nuclear Assets

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