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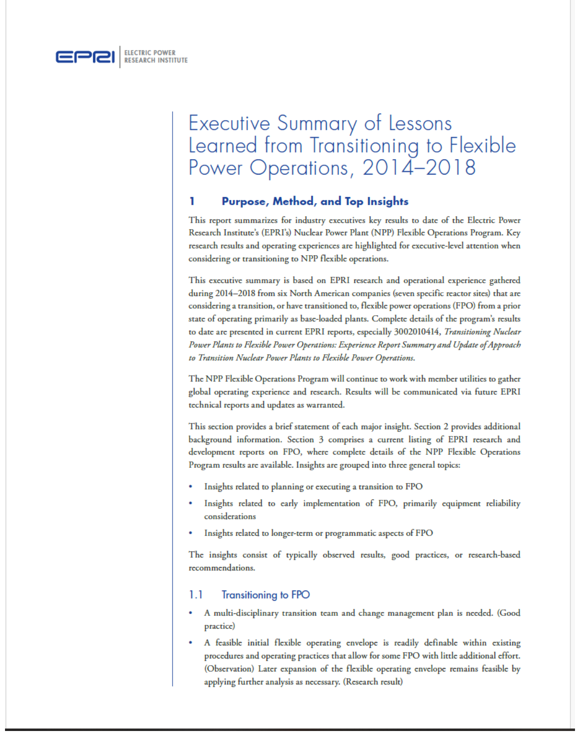
Flexible Plant Operation and Generation (FPOG) Pathway Overview

Problem Being Addressed

- ➢ Nuclear power plants risk curtailment as grid markets continue to change
  1) Increasing buildout of utility-scale wind and solar generation
  2) Impact of low-cost natural gas
  3) Local congestion of the power transmission system
  4) Rising power demand for data centers

- ➢ Flexible plant operations can have adverse impacts on nuclear plant thermal/power systems and fuel burnup conditions
- ➢ The best option is to keep nuclear plants running at their full capacity



EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Executive Summary of Lessons Learned from Transitioning to Flexible Power Operations, 2014–2018

1 Purpose, Method, and Top Insights

This report summarizes for industry executives key results to date of the Electric Power Research Institute's (EPRI's) Nuclear Power Plant (NPP) Flexible Operations Program. Key research results and operating experiences are highlighted for executive-level attention when considering or transitioning to NPP flexible operations.

This executive summary is based on EPRI research and operational experience gathered during 2014–2018 from six North American companies (seven specific reactor sites) that are considering a transition, or have transitioned to, flexible power operations (FPO) from a prior state of operating primarily as base-loaded plants. Complete details of the program's results to date are presented in current EPRI reports, especially 3002010414, *Transitioning Nuclear Power Plants to Flexible Power Operations: Experience Report Summary and Update of Approach to Transition Nuclear Power Plants to Flexible Power Operations.*

The NPP Flexible Operations Program will continue to work with member utilities to gather global operating experience and research. Results will be communicated via future EPRI technical reports and updates as warranted.

This section provides a brief statement of each major insight. Section 2 provides additional background information. Section 3 comprises a current listing of EPRI research and development reports on FPO, where complete details of the NPP Flexible Operations Program results are available. Insights are grouped into three general topics:

- Insights related to planning or executing a transition to FPO
- Insights related to early implementation of FPO, primarily equipment reliability considerations
- Insights related to longer-term or programmatic aspects of FPO

The insights consist of typically observed results, good practices, or research-based recommendations.

1.1 Transitioning to FPO

- A multi-disciplinary transition team and change management plan is needed. (Good practice)
- A feasible initial flexible operating envelope is readily definable within existing procedures and operating practices that allow for some FPO with little additional effort. (Observation) Later expansion of the flexible operating envelope remains feasible by applying further analysis as necessary. (Research result)

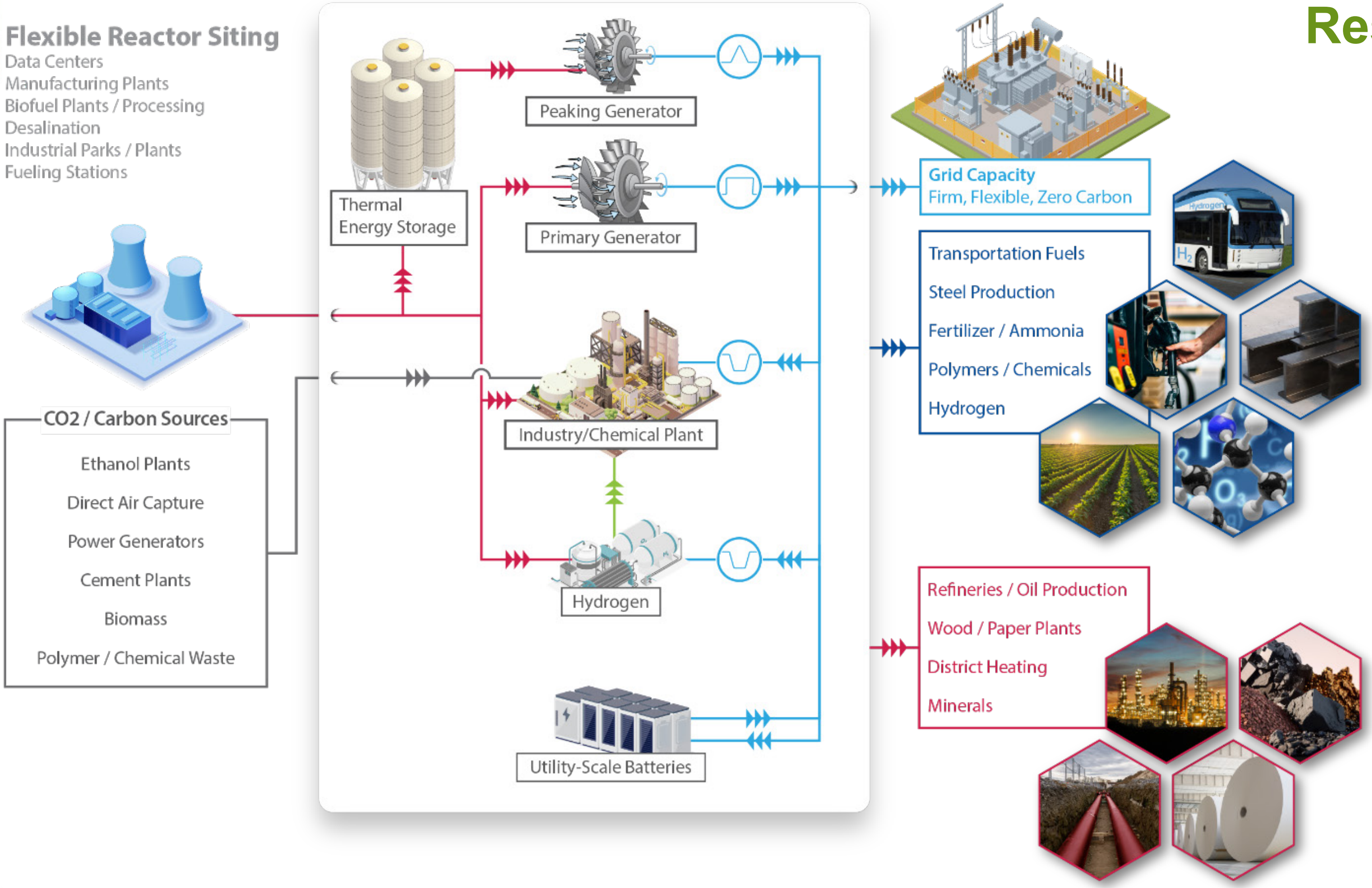
EPRI 2018 Report on FPO: Lessons Learned from Transitioning to Flexible Plant Operations

https://restservice.epri.com/publicdownload/000000003002013086/0/Product

The need for this FPOG research was confirmed in the March 2025 Stakeholder Engagement Meeting

LWRS LIGHT WATER REACTOR SUSTAINABILITY

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



Research Focus Areas:

1) Technical and economic assessments
2) Thermal energy offtake and delivery to the second user
3) Controls & Human Factors
4) Safety hazards and regulatory review research

Stakeholder Engagement Meeting, March 18-19

- Convened a two-day Teams® virtual LWRS Program Stakeholder Engagement meeting
- Approximately 150 participants, averaging 75 -120 over the two-day program
- Discussed nuclear utility challenges and emerging market opportunities
- Reviewed assessments of the technical feasibility and market possibilities for flexible nuclear power plant operation
- Summarized LWRS and EPRI R&D and guidance supporting nuclear utilities hydrogen production implementation
- Reviewed 10 CFR Part 1 45V tax credits for hydrogen production

Utility Reports – Operating Forecasts, Operational Flexibility Needs, and Market Opportunity

- Duke Energy
- Dominion Energy
- Evergy
- Constellation Energy
- Xcel Energy

Industry Reports – Chemical and Refinery Hydrogen and Thermal Energy Requirements

- ExxonMobil
- Argonne National Lab

Hydrogen Implementation Guidance for Pressurized-Water and Boiling-Water Reactors

- EPRI
- Sargent & Lundy
- Westinghouse Electric Company

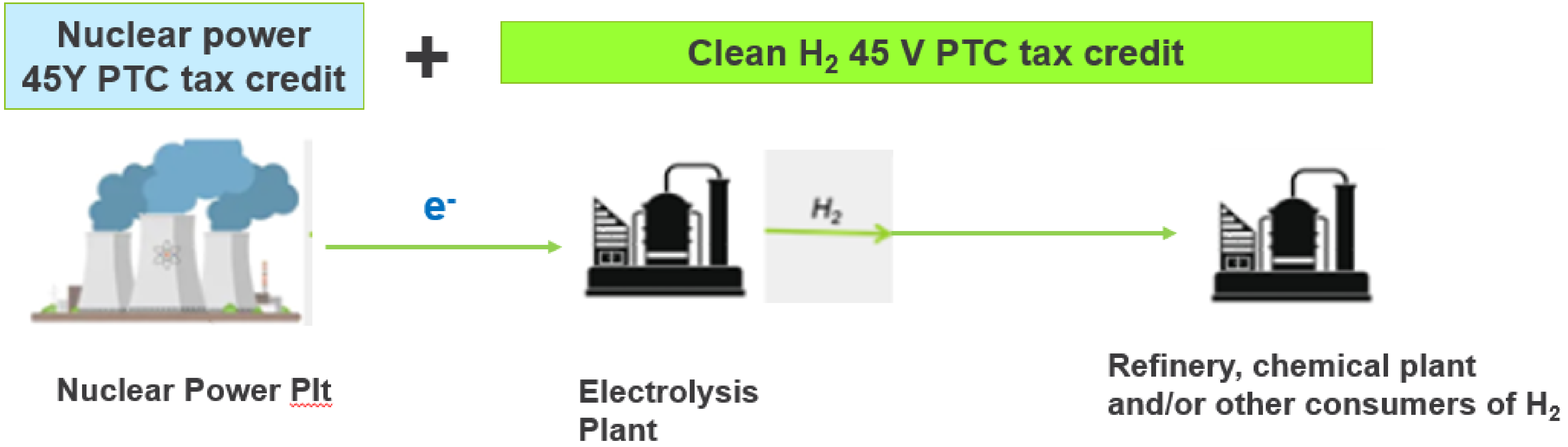
Industry Reports – SOEC/HTSE Technology Vendor Status

- FuelCell Energy
- Bloom

Key Outcomes:

- **Given current and future grid market transitions and uncertainties, FPOG continues to be an impactful research area for nuclear utilities**
- **FPOG is also important to nuclear expansion and increased utilization as a dependable, efficient, and affordable energy source**

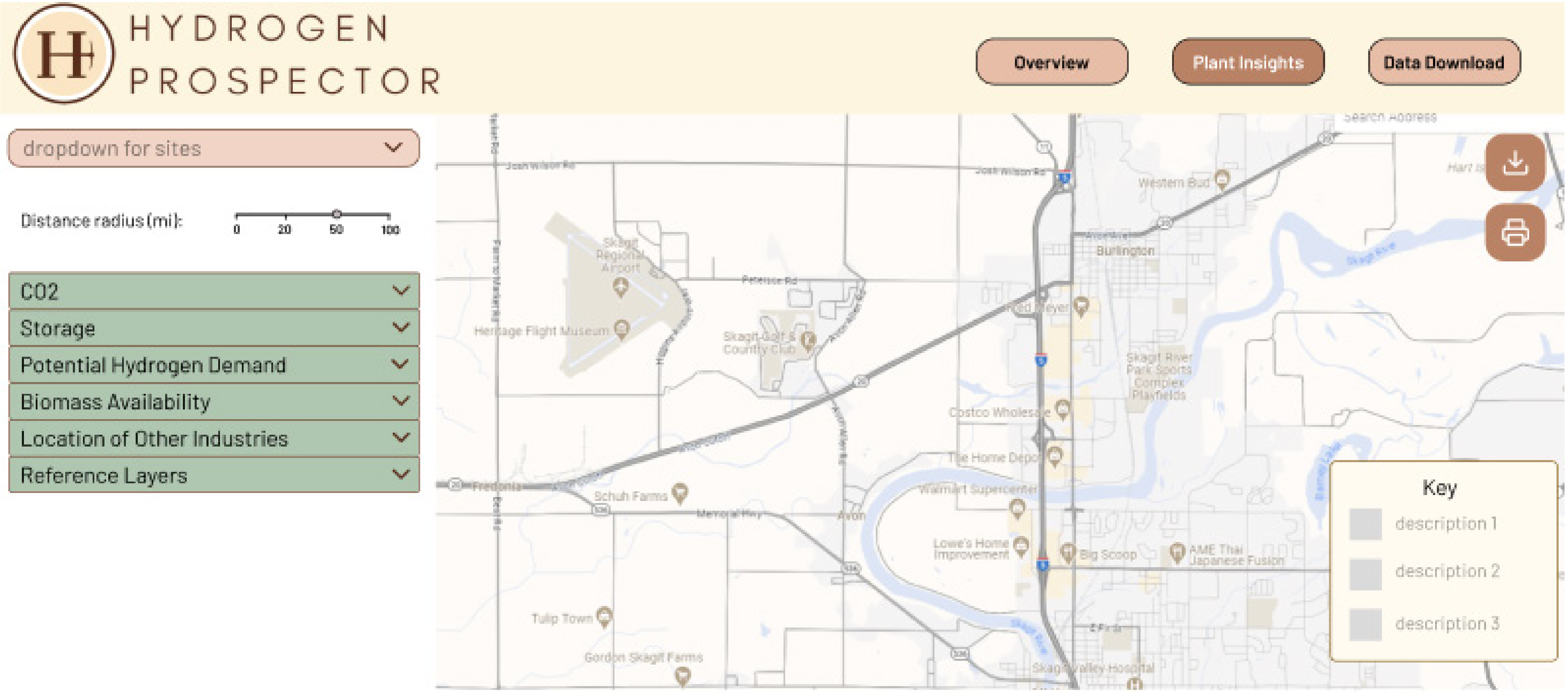
45V Plant-Specific Hydrogen Economics Study (2025 Activity)



Determine credible NPP candidates for hydrogen production based on:

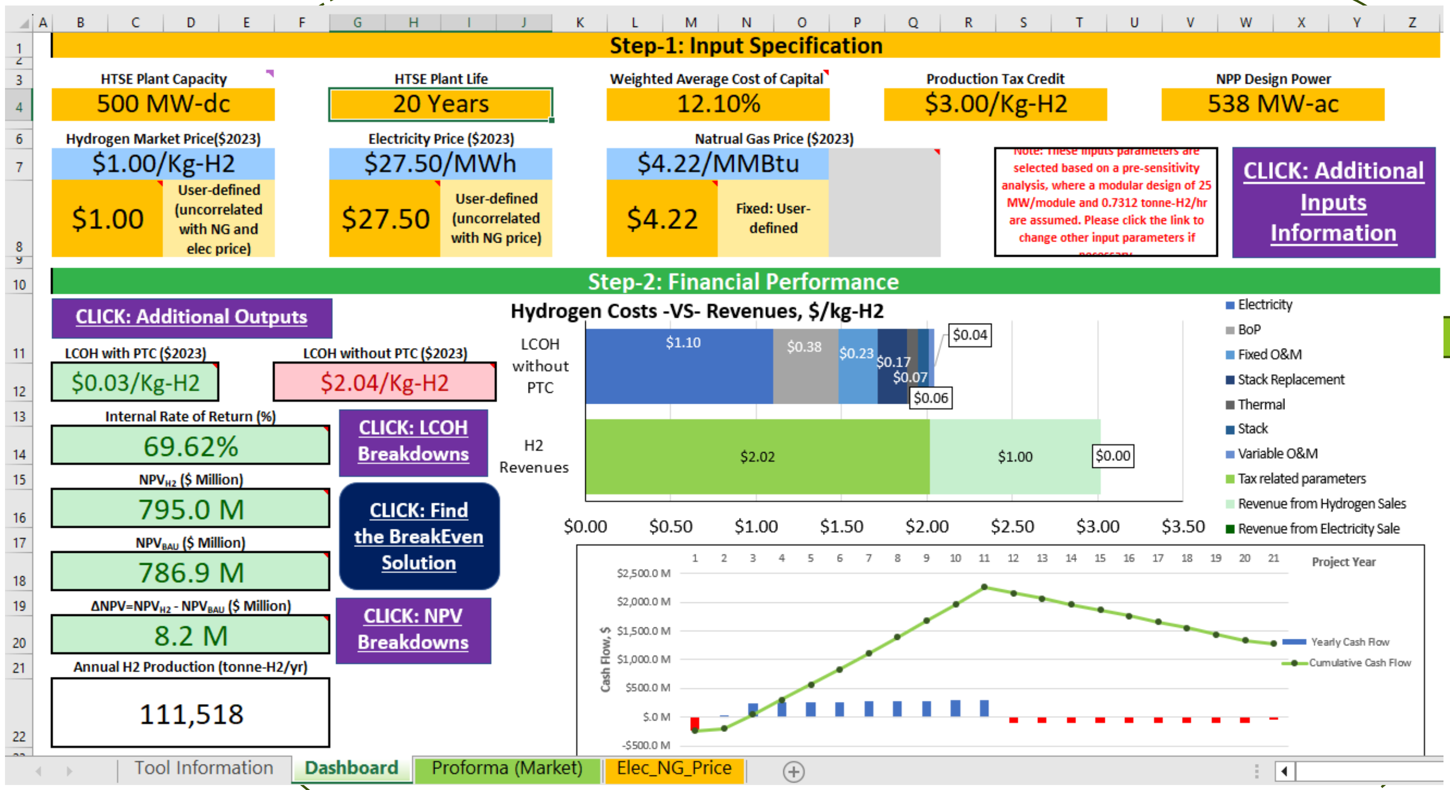
- Regional industrial user hydrogen needs
- Techno-economic analysis of existing generation limits of tax code 45V
- Evaluate the economic feasibility of new generation dedicated to hydrogen through NPP power uprates and restarts

Identify Potential Hydrogen Demand



Hydrogen Market Analysis Calculator

Process



TEA

H_2 Cost Analysis

Outputs

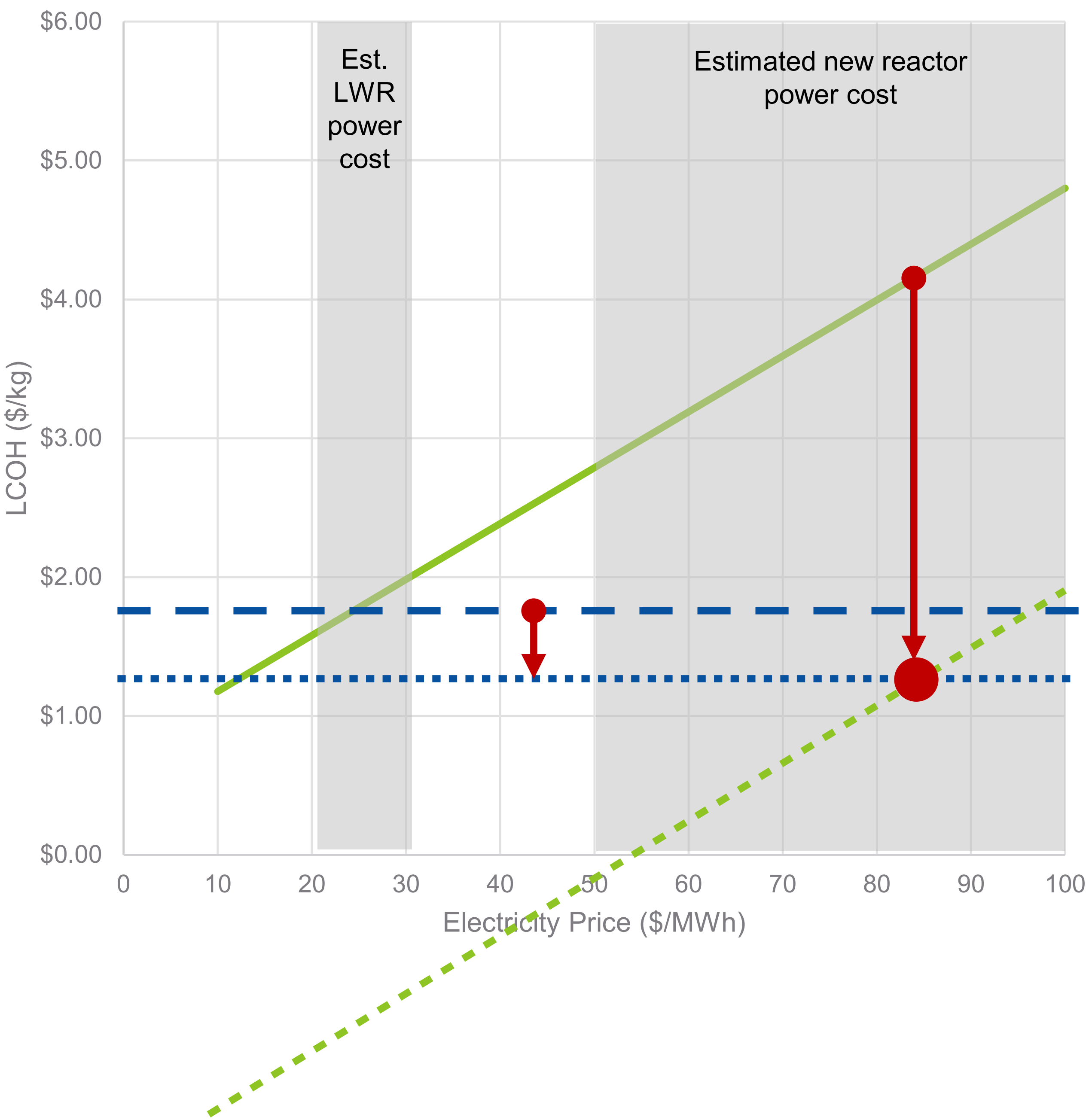
- -LCOH
- -H_2 production rate
- -IRR
- -NPV_{H2}
- - NPV_{BAU*}
- -Sensitivity Analysis
- -Preference Analysis
- -Competitive Analysis

*BAU: Business as Usual

Hydrogen Production Cost Comparison

Blue H_2 without 45V Tax Credit

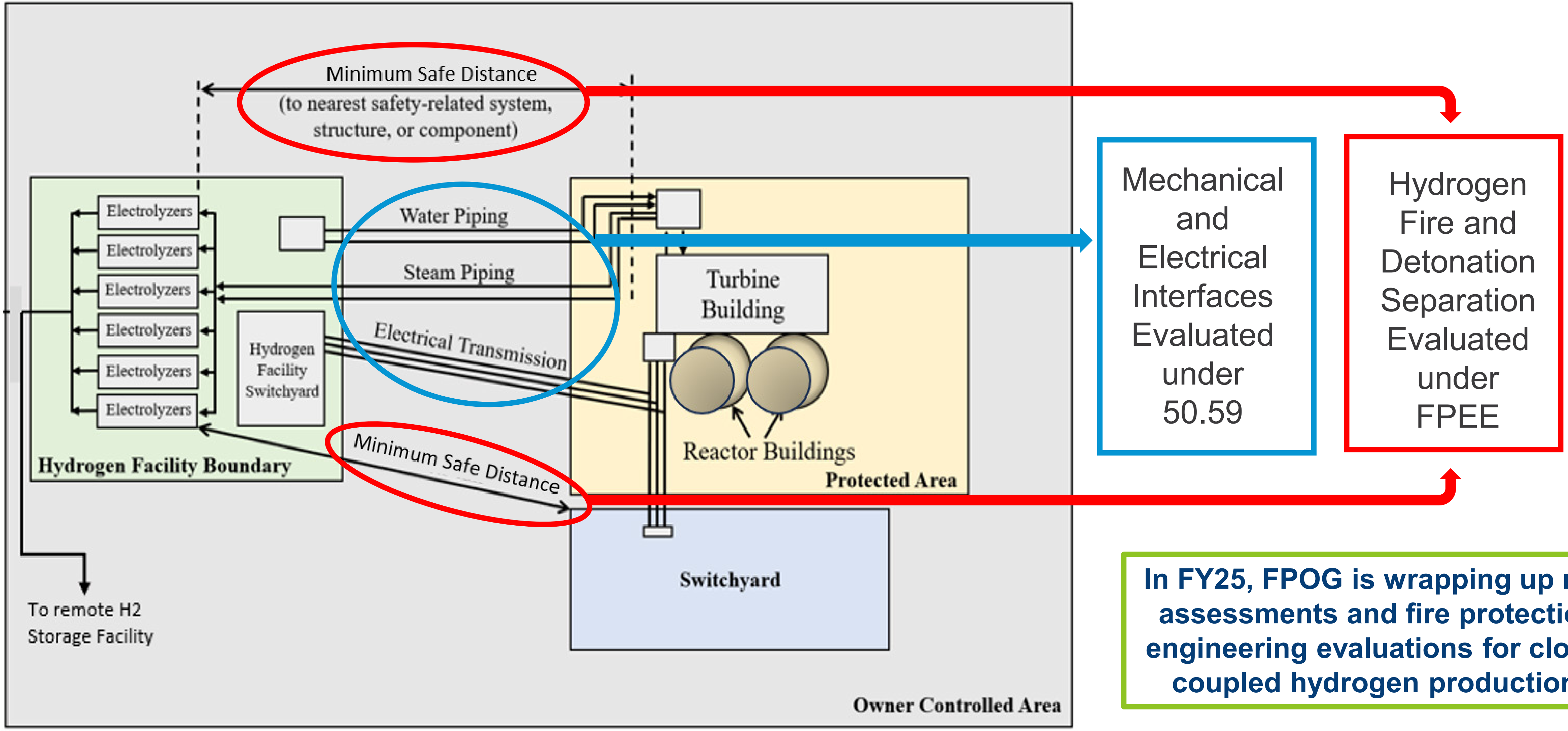
Up to $0.6/kg-$H_2$ for Blue Hydrogen



Nuclear/Electrolysis

Up to $3/kg-$H_2$ for Nuclear

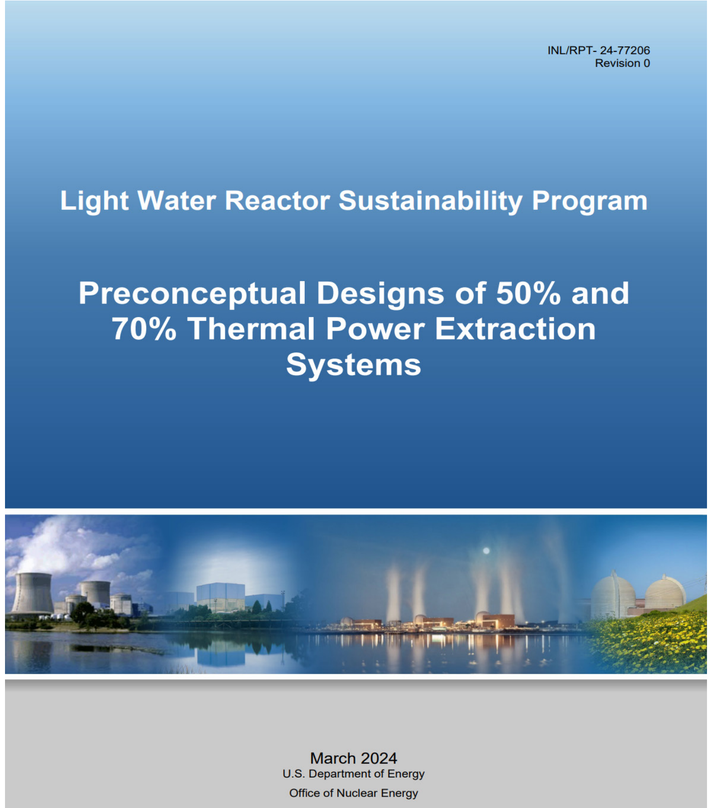
Comparative HTEF - Licensee Evaluation Approaches



In FY25, FPOG is wrapping up risk assessments and fire protection engineering evaluations for close-coupled hydrogen production.

Nuclear Thermal Power Dispatch (TPD) Studies

- **Completed**
  - **Integrated 4-loop PWR* – 100 MW_{DC} H_2 facility**
  - **Integrated 4-loop PWR – 500 MW_{DC} H_2 facility**
  - **Integrated BWR* – 500 MW_{DC} hydrogen facility**
  - **30% TPD from 4-loop PWR (~1,100 MW_t)**
  - **50% TPD from 4-loop PWR (~1,800 MW_t)**
  - **70% TPD from 4-loop PWR (2,550 MW_t)**
- **Participant Roles**
  - INL: Statement of work and PRA
  - S&L: preconceptual design
  - Westinghouse: Design basis for control system


INL/RPT- 24-77206
Revision 0

Light Water Reactor Sustainability Program

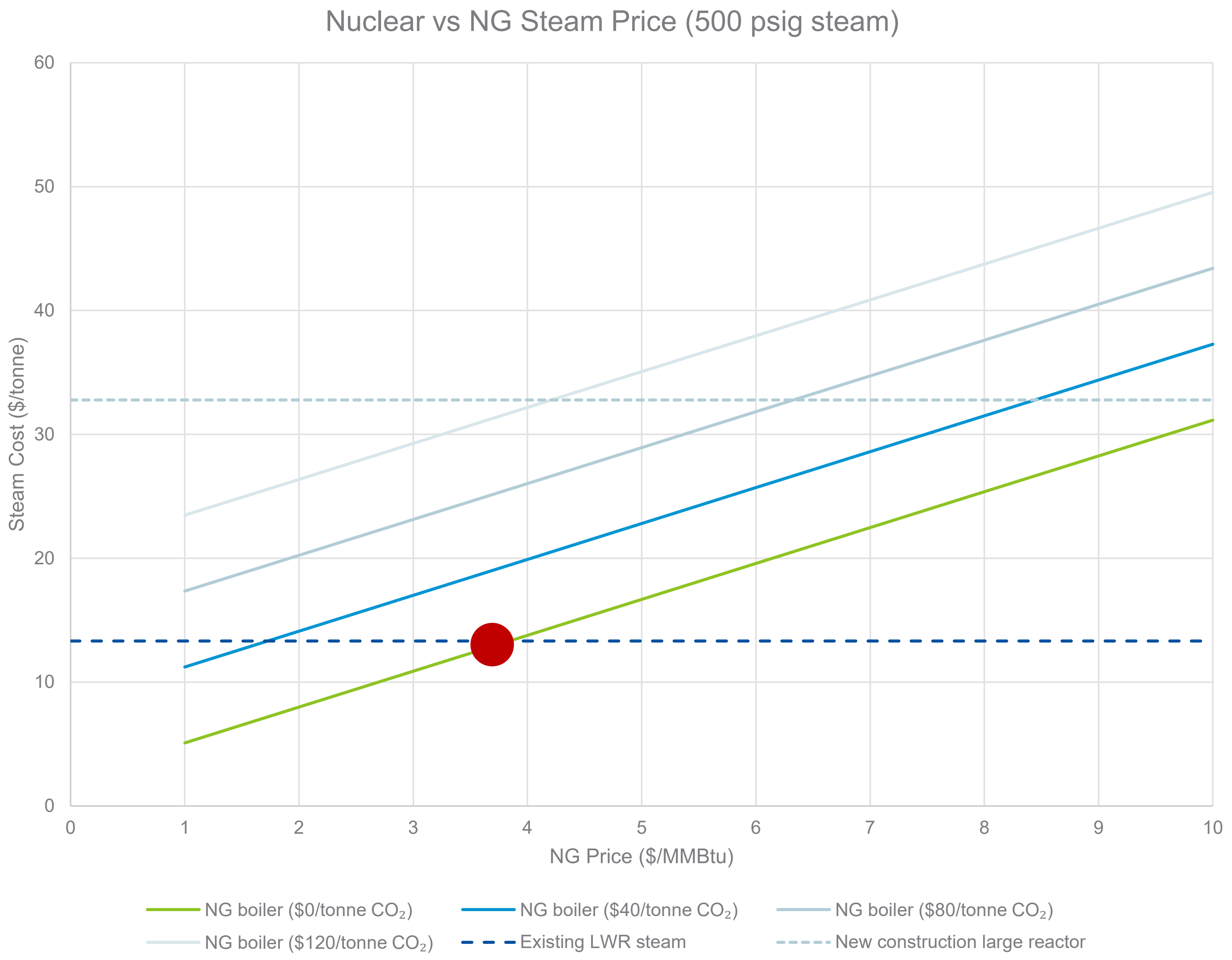
Preconceptual Designs of 50% and 70% Thermal Power Extraction Systems

March 2024
U.S. Department of Energy
Office of Nuclear Energy

https://lwrs.inl.gov/content/uploads/11/2024/10/Preconceptual_Designs.pdf

**PWR: pressurized water reactor; *BWR: boiling water reactor*

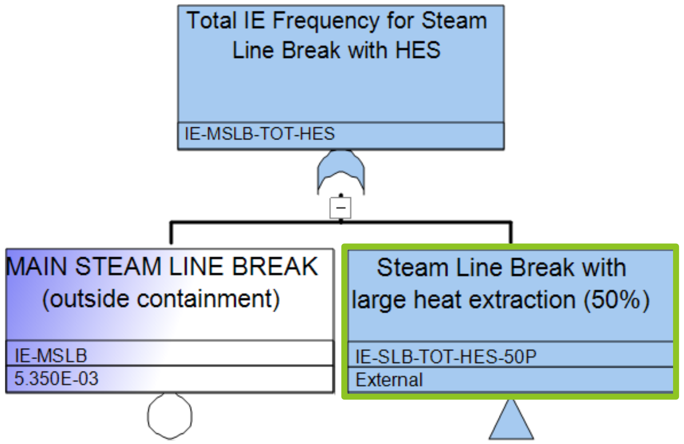
Comparison of Steam Generation Costs

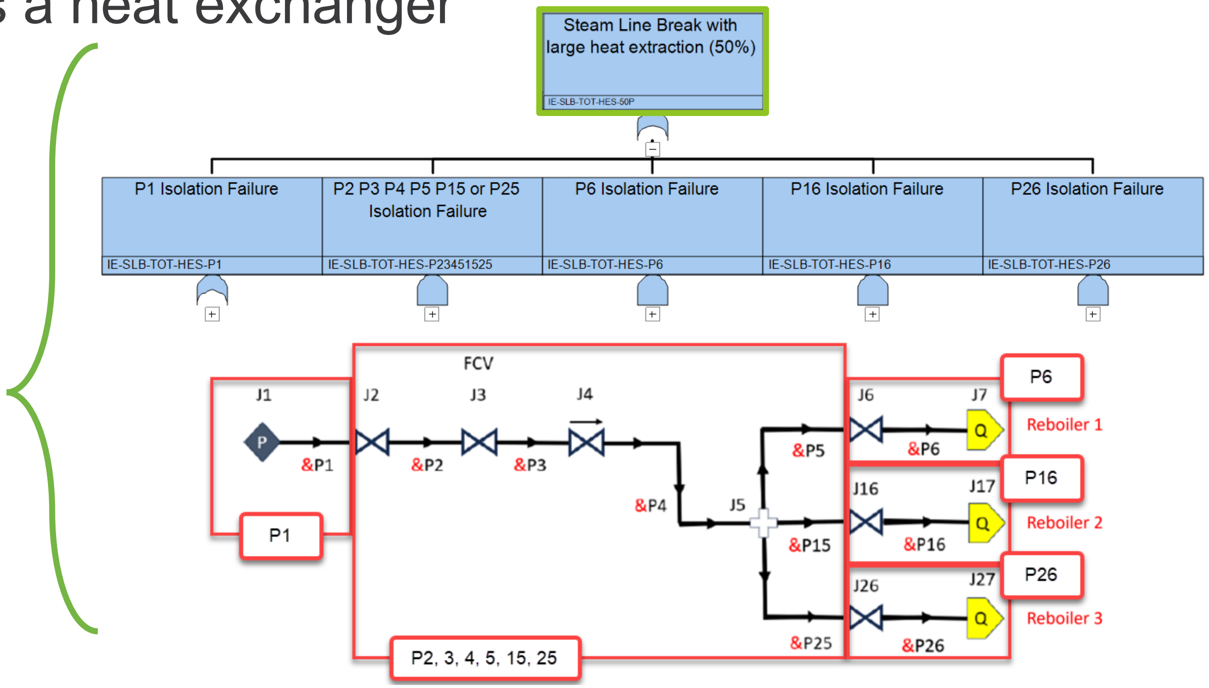


Probabilistic Risk Assessment (PRA)

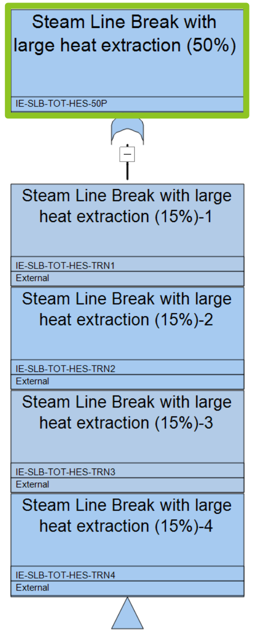
Fault Tree for TPD System(s)

- Single train: increased piping diameter and pressure rating (wall thickness)
- Multi-train: 2 for 30% extraction, 4 for 50% extraction
- Valve rupture (all valves) and failure to close (isolation valves only) considered
- Reboiler considered as a heat exchanger

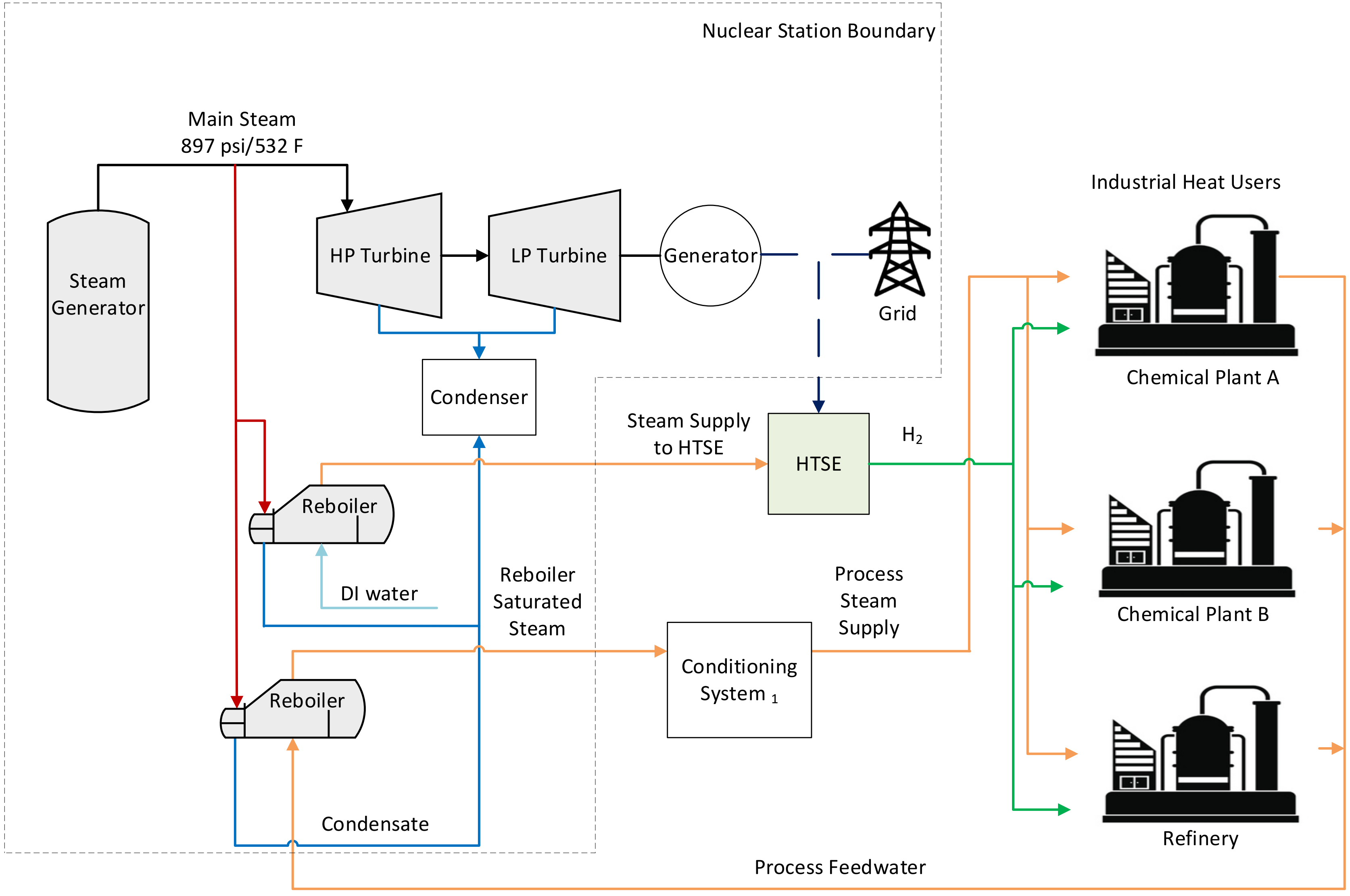




Or

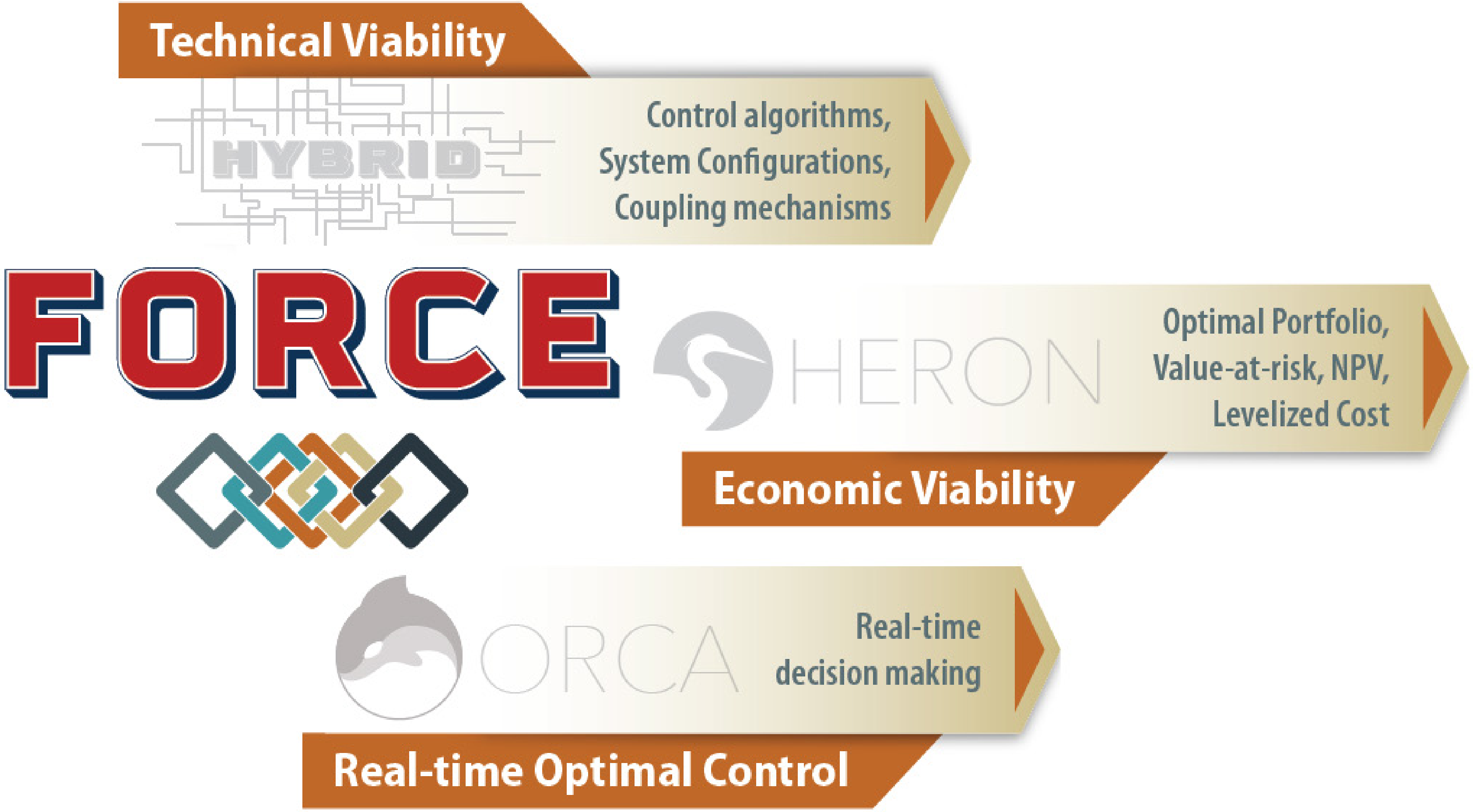


2025 Analysis of Nuclear Power Plant Direct Coupling with Large Industries



[1] Case 1: HP steam is delivered via multiple parallel pipes requiring an electrical heater
Case 2: HP steam is delivered via a single pipeline which requires mechanical vapor compressors located at each industrial site
Case 3: MP steam is delivered which requires an electrical heater

Framework for Optimization of Resources, Controls, and Economics (FORCE)

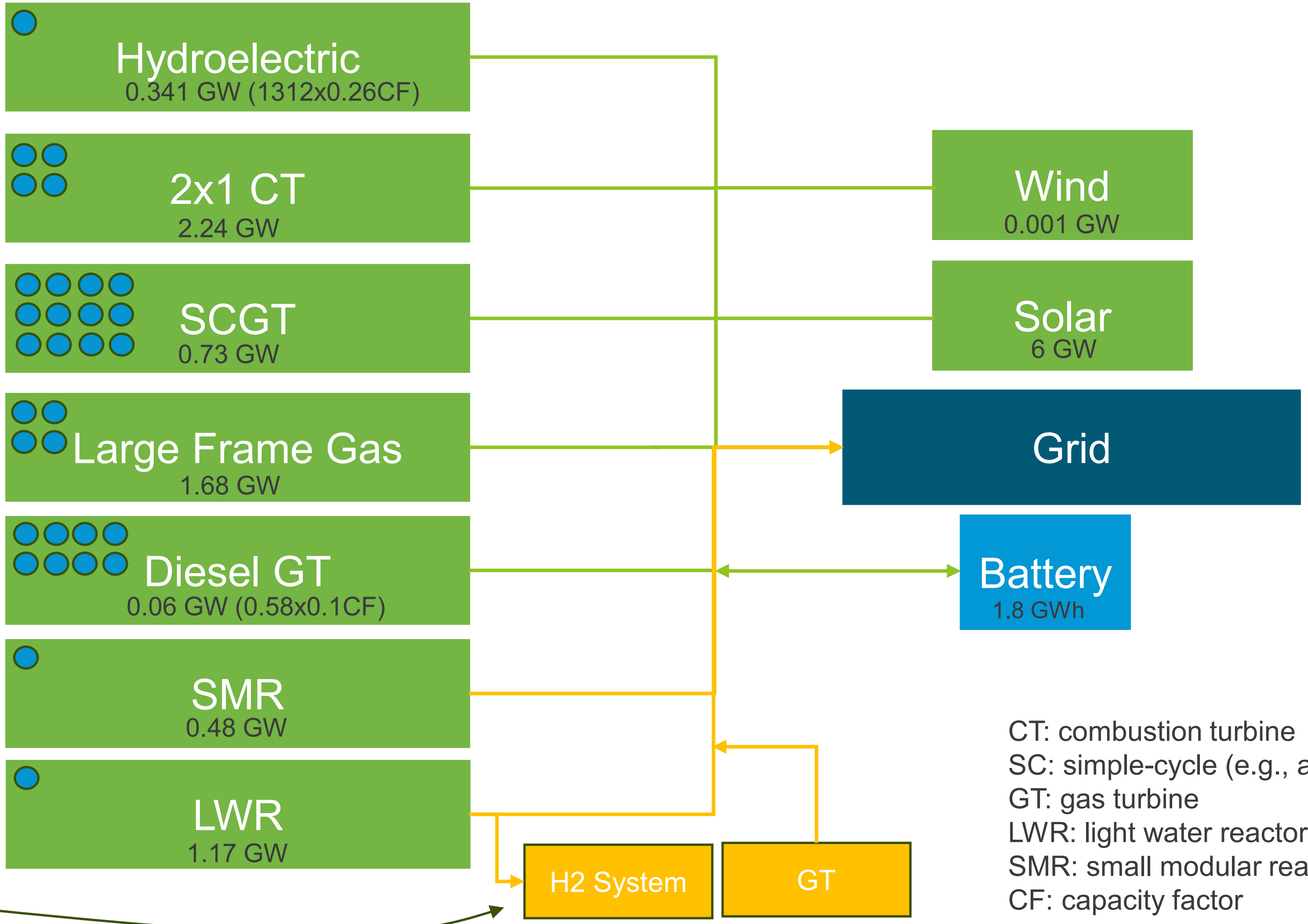


In 2025, two utility companies are collaborating with FPOG to further develop and use the FORCE capability to evaluate plant nuclear dispatch and utility-scale energy storage

Demonstration Scenario – Simulation Utility Portfolio

Case 2
Integrated Energy System (IES)

End results:
- *<u>What size</u> of IES?*
- *What is the <u>cost savings</u>?*
- *How much is <u>reliability</u> increased?*



- 20 years of operation
- CAPEX for IES
  - HTSE 0.1, 0.5, 2 GW
  - Storage 0.1, 0.5, 1 GWh
  - Turbine 0.05, 0.1, 0.5 GW
  - Refine mesh based on results

CT: combustion turbine
SC: simple-cycle (e.g., aero)
GT: gas turbine
LWR: light water reactor
SMR: small modular reactor
CF: capacity factor

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

lwrs.inl.gov