LWRS Spring Review Meeting

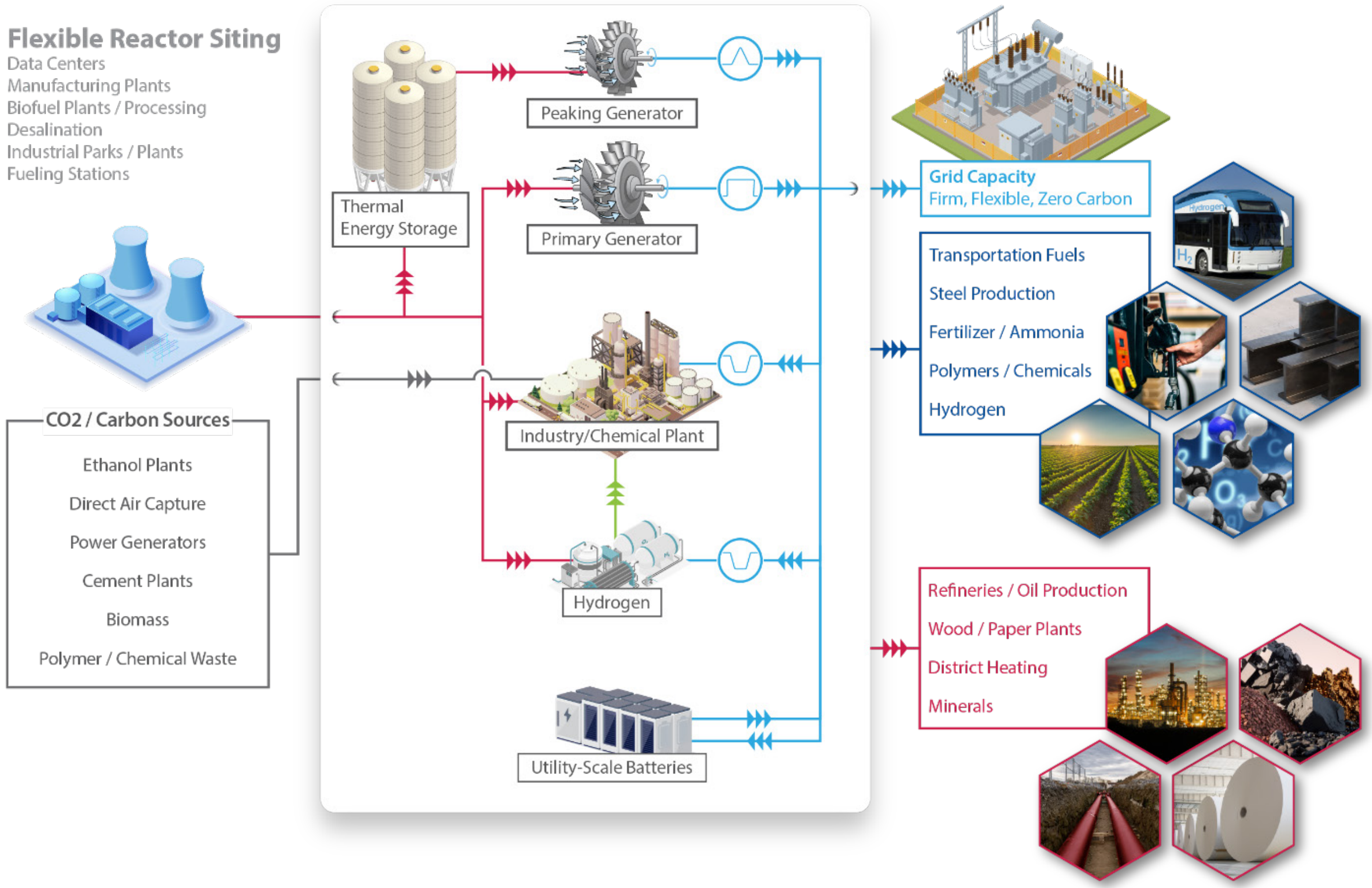
April 27-28, 2025

Flexible Plant Operations and Generation (FPOG)

Richard Boardman - Pathway Lead

Tyler Westover, Jack Cadogan, Paul Talbot – Technical Leads

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



Research Focus Areas:

- Technical and economic assessments
- Thermal energy offtake and delivery to the second user
- Controls & Human Factors
- Safety hazards and regulatory review research

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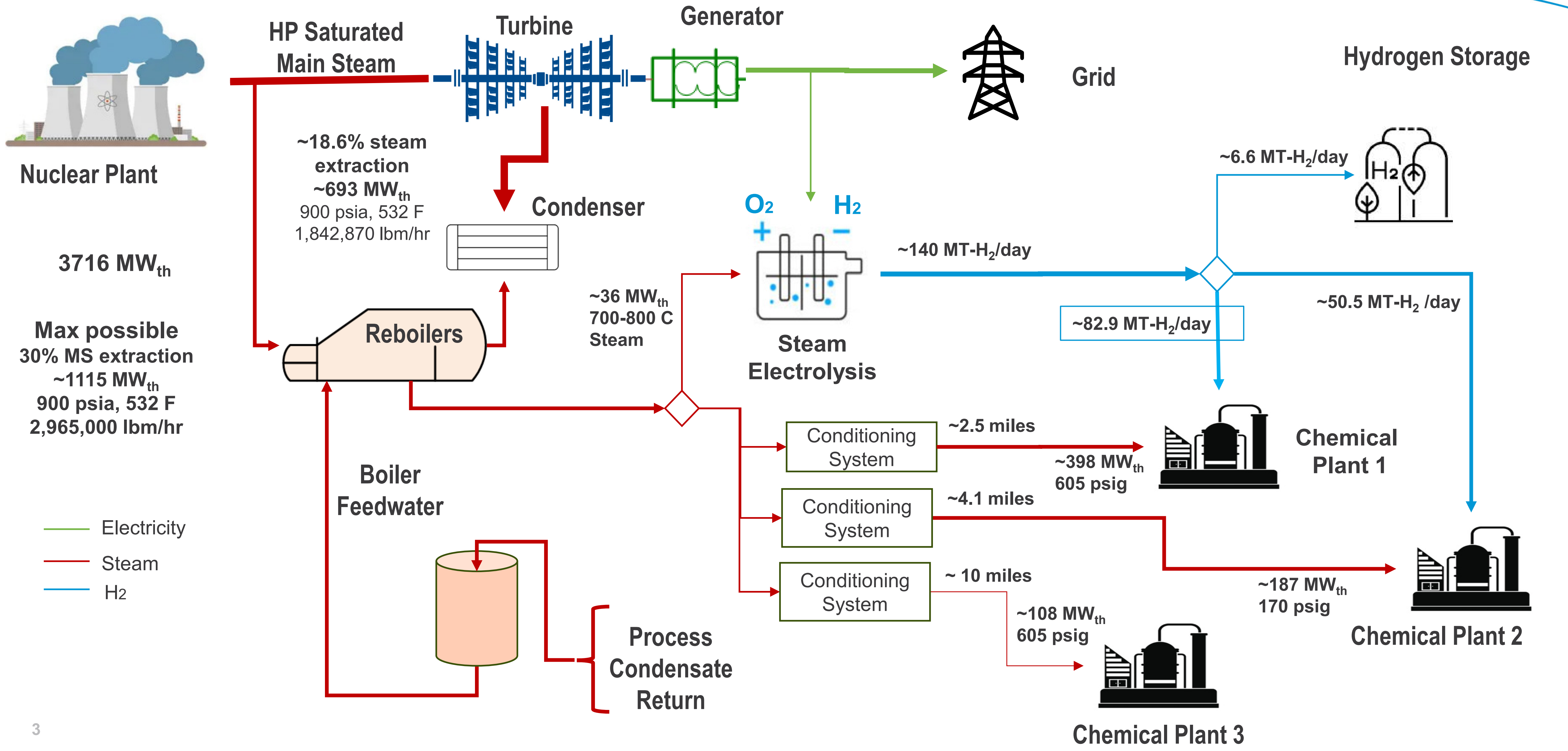
Reference Example



FPOG Topics Presented Today

1) Summary of Hydrogen Production Guidance, Risk Assessments, Fire Protection, and License
2) High-Capacity Thermal Extraction for Industrial Heating
3) Development of End User Tools for Evaluation and Optimization of Resource Expansion and Use

NPP Alternate Energy Stream Research Progression

STAGE 1
2021
Early Hybrid Operations Research & Testing

STAGE 2
2022
Mature Conceptual Design & Licensing Approaches

STAGE 3
2023
Detailed Risk Analyses and Design Cases

STAGE 4
2024
Preliminary Regulatory Alignment on Fire Separation

STAGE 5
2025
Final Fire Separation Eval & 45V Plant-Specific Economics

Progressive Technoeconomic & Market Analysis Research

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FPOG 2024/2025 Hydrogen Technical and Economic Assessments

Provision of nuclear heat and electricity for hydrogen & heat delivery to existing industry, maximizing the use of existing infrastructure

H_2 Market Assessment

- H_2 and Heat market opportunities around Light Water Reactors in the Gulf Coast Region.

Business Case Assessment

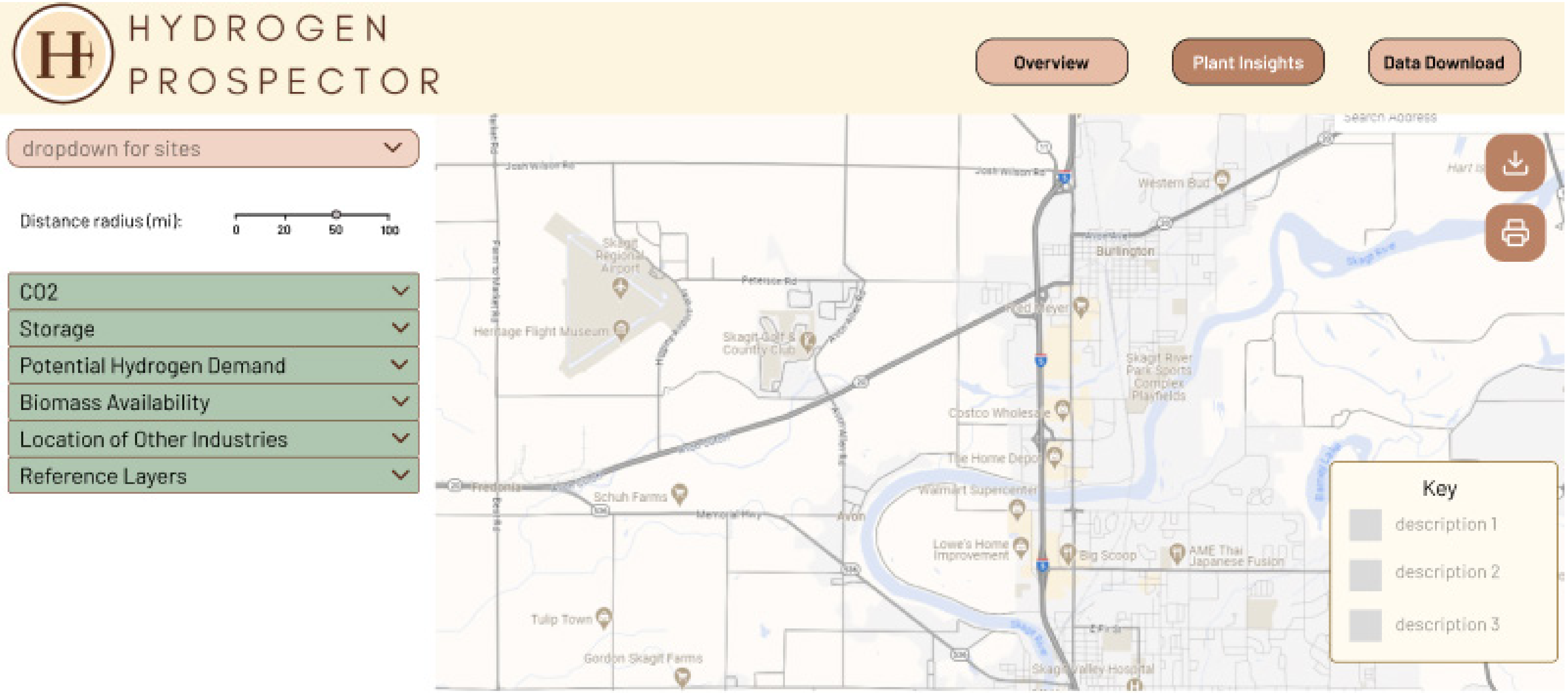
- Opportunities to produce and **distribute hydrogen and heat** from Gulf Coast NPPs to local industry.
- Techno-economic assessment of options with/without PTC credit.

Yearly Plans

- **FY24:** Steady State TEA for Hydrogen Production
- **FY25:** Steady State and Dynamic TEA for Heat delivery vs. H_2 and Electricity Generation.

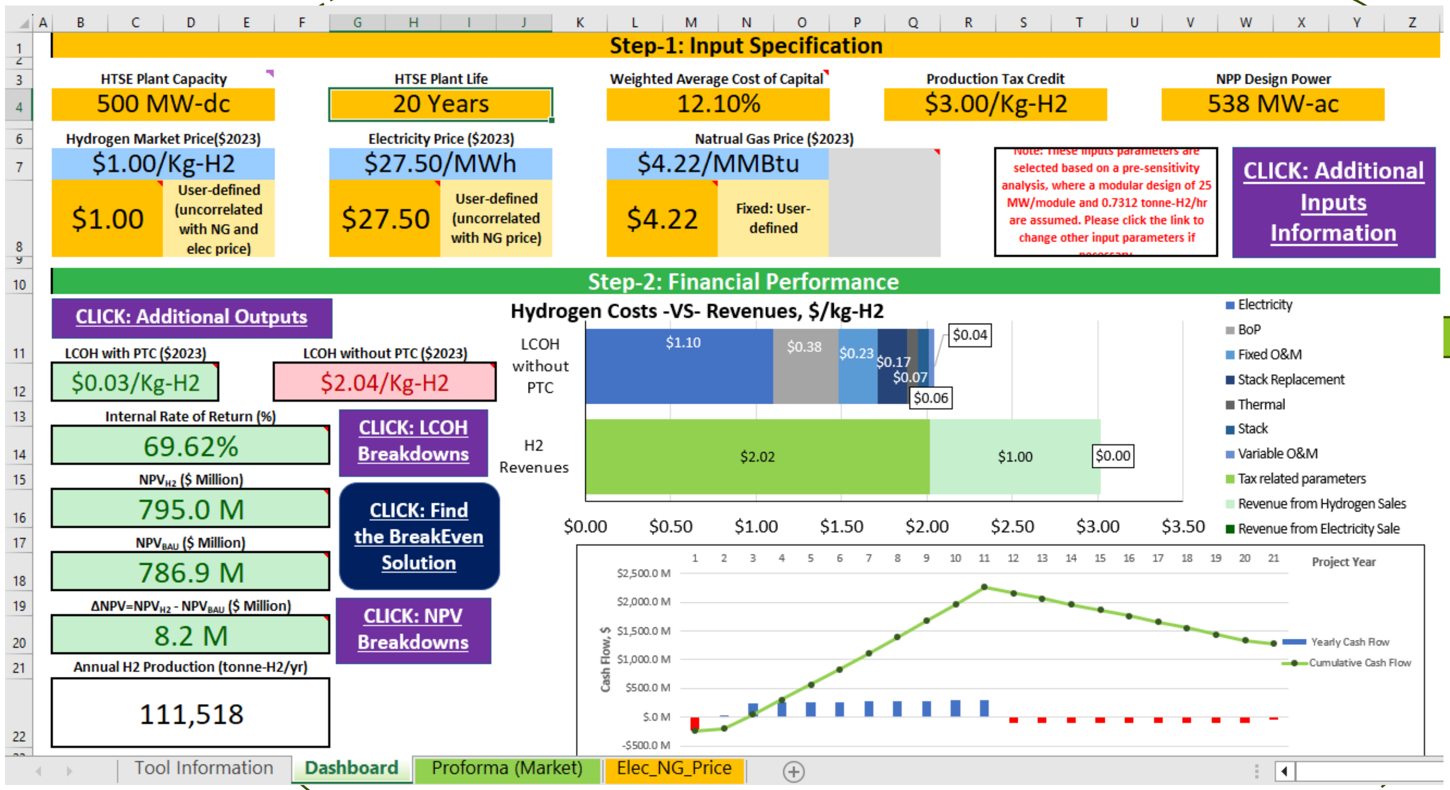
Hererra de Reyes, M. et al, (2024) Hydrogen Generation and Industrial Heat Opportunities for Nuclear Plants in the Gulf Coast. INL/RPT-24-80189. https://doi.org/10.2172/2439929

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

Ongoing Equipment and Operational Interface Testing

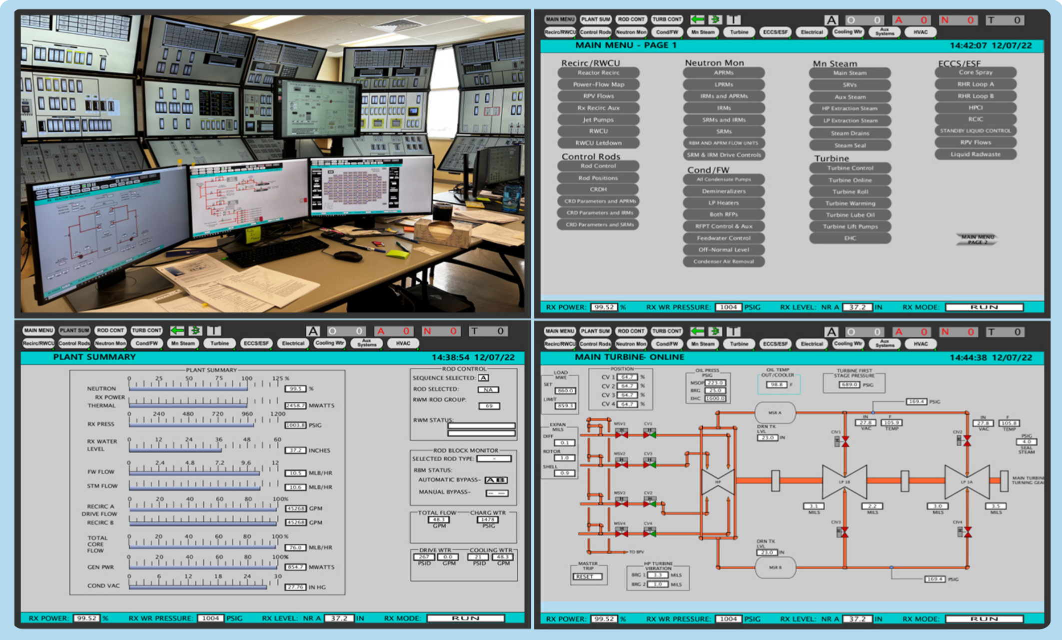
- Human, and component test with limited scope, pilot-scale coupled thermal and electric power dispatch simulators
  - 150+ kW High Temperature Steam Electrolysis system
  - INL Real-Time Grid Emulator
  - Human Systems Simulation Lab
  - Validate simulator predictions and hardware performance

Real-Time Grid Simulator

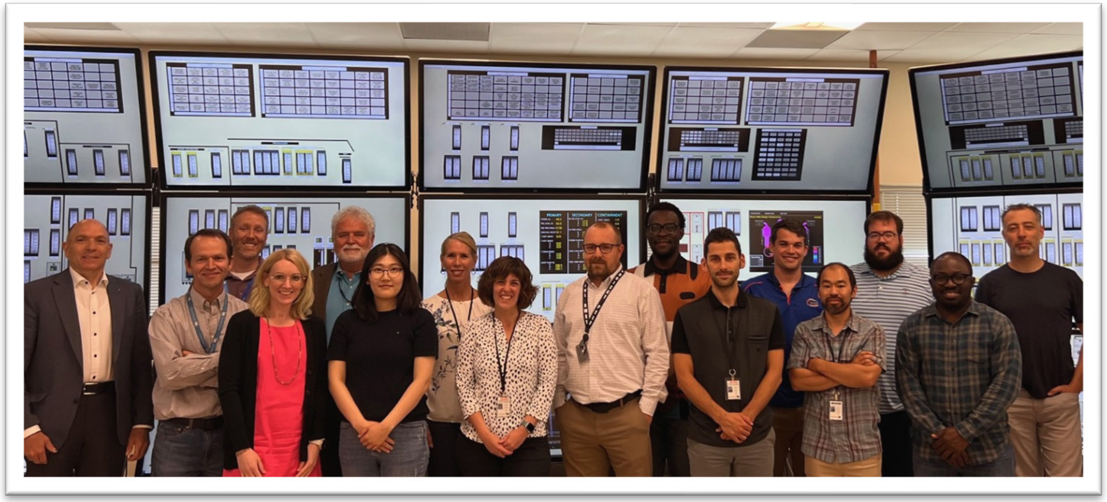
High Temperature Electrolysis (Bloom 150 kWe Module)

Human Systems Simulation Laboratory

Development and Testing of FPOG Operating Concepts



Modified boiling water reactor simulator used in the INL Human Systems Simulation Laboratory



FPOG plant operations concepts testing supported by Westinghouse, GSE, and the University of Idaho

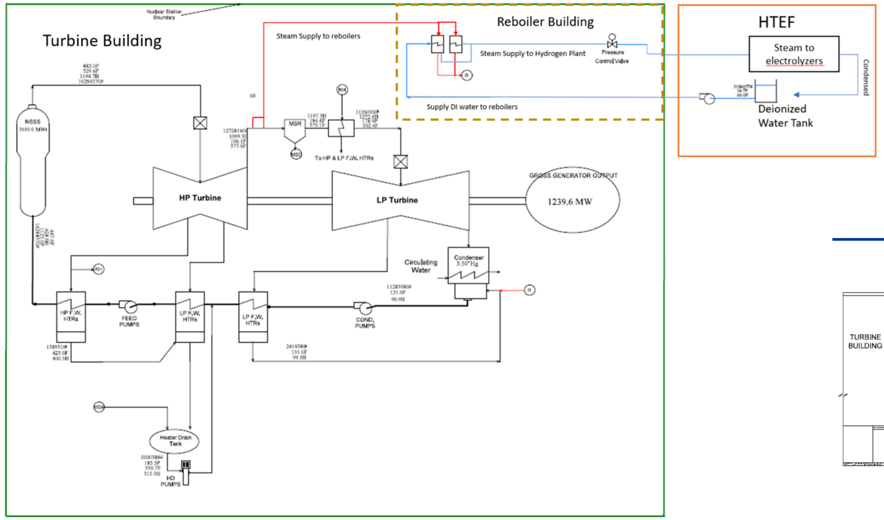
Full-Scope plant simulators were used to successfully test human factors and verify power and steam and be efficiently and safely dispatched to a user connected to the nuclear power plant transmission station.

An Architectural/Engineering company was subcontracted to provide conceptual designs steam and electricity supply to large-scale H_2 plants

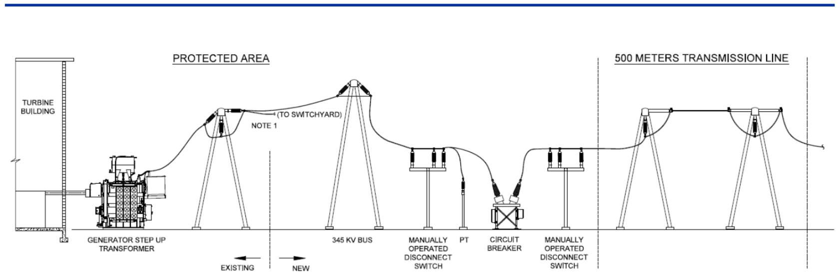
Idaho National Laboratory (INL)
Battelle Energy Alliance (BEA)

Pre-Conceptual Design for Large-Scale Nuclear Integrated Hydrogen Production Facility

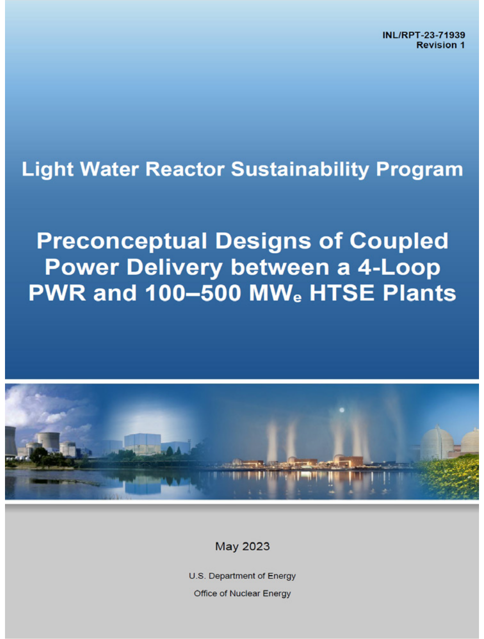
A/E pre-conceptual design is being used to estimate costs of hydrogen production and to address safety and licensing consideration



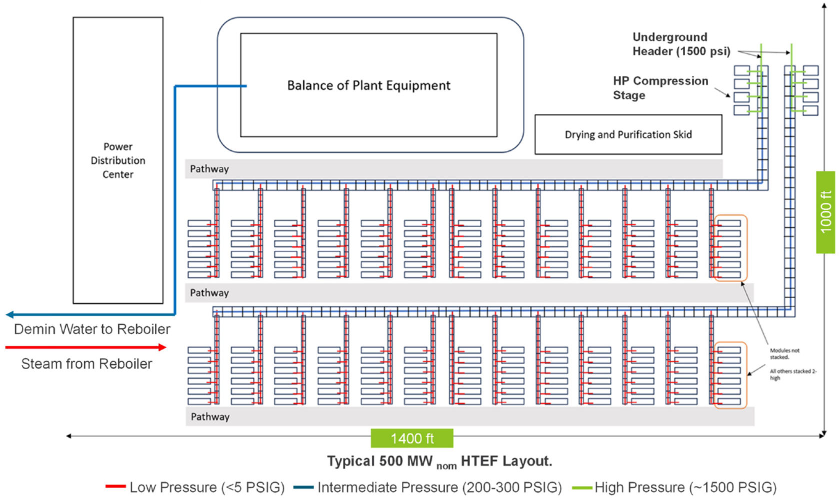
Steam off-take using a reboiler for high temperature electrolysis heating (PWR and BWR plants)



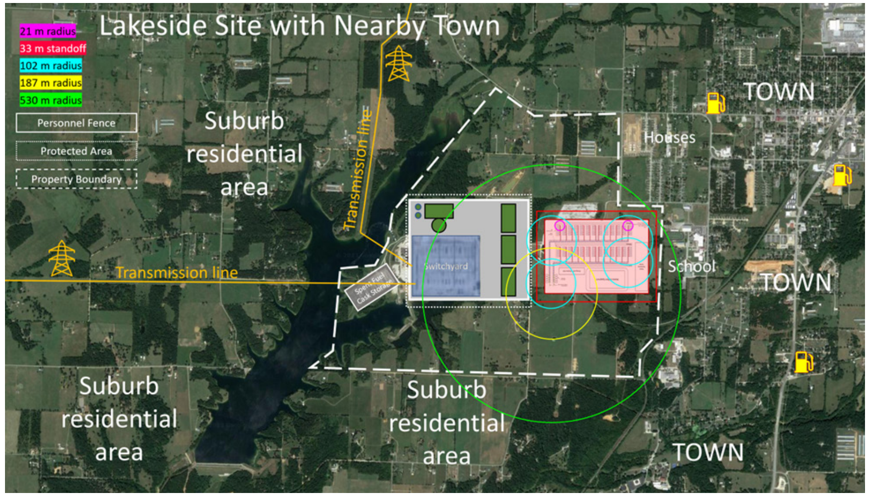
Electrical power take-off from nuclear plant switch yard



https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_65909.pdf



100, and 500 MWe modular high temperature steam electrolysis plant layout and piping



Probabilistic Risk Assessment (PRA) to determine hydrogen plant stand-off distance

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Probabilistic Risk Assessment Approach

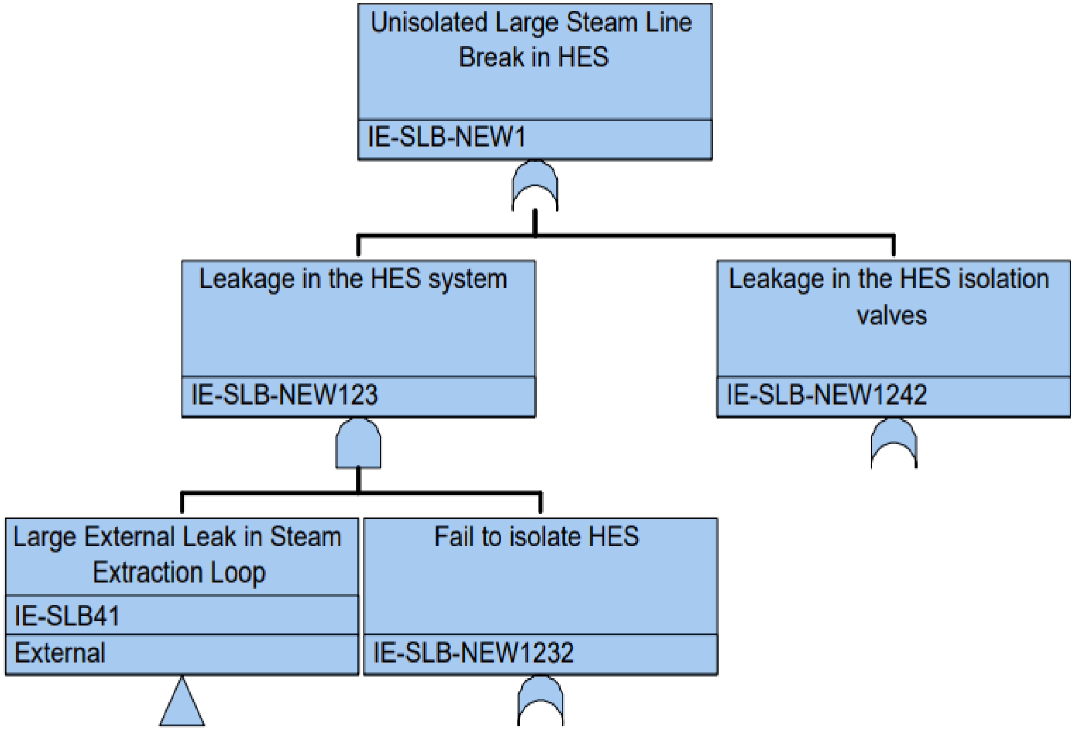
Early simplified PRA approaches

Initiating events, fault trees, FMEA addressed

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

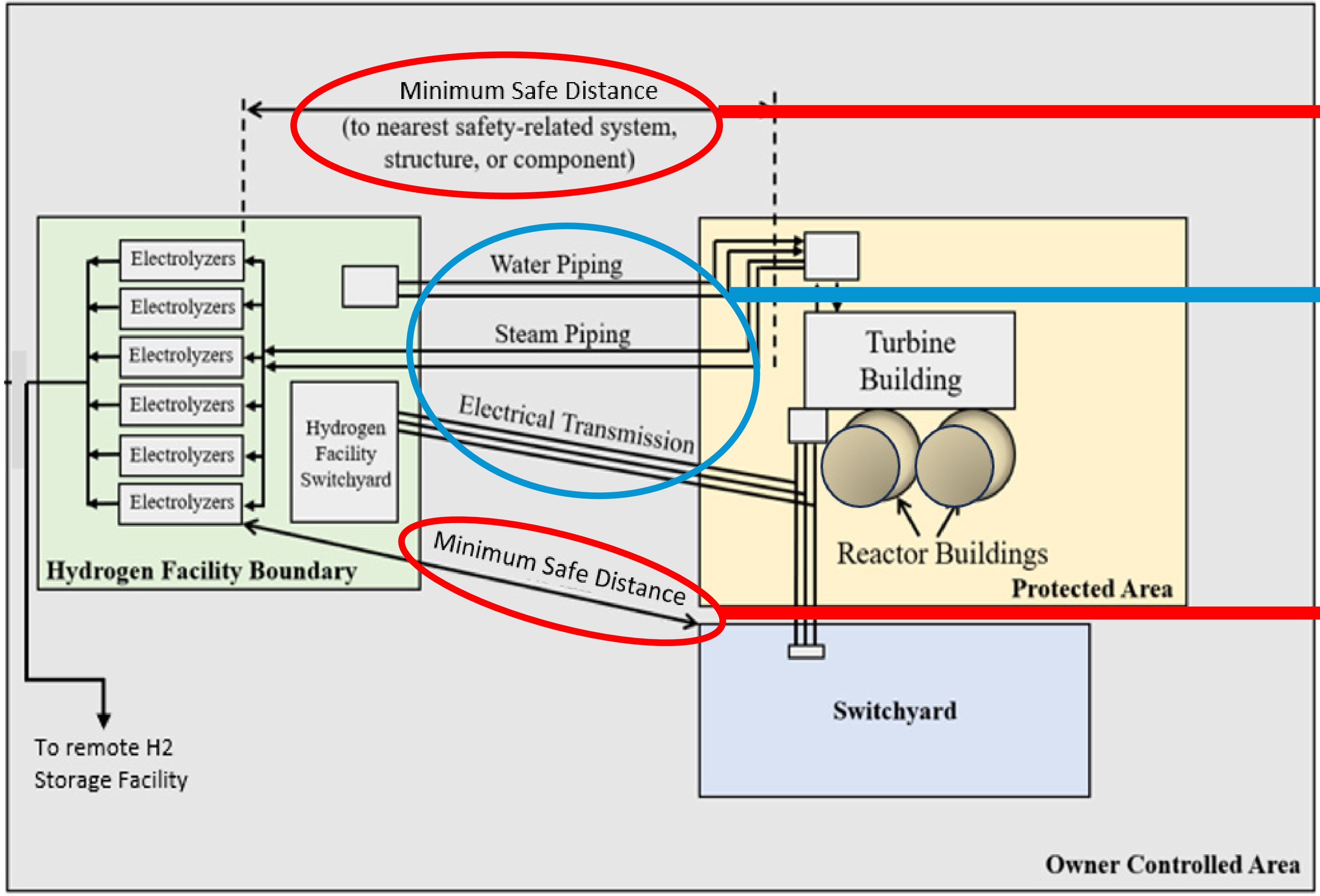
Qualitative hazards assessment for potential community and utility business risks

Offset distances to hydrogen plant from NPP SSCs evaluated



PRA Case: HTEF Interconnect Risk Impact on NPP Large Steam Line Break Frequency

Comparative HTEF - Licensee Evaluation Approaches

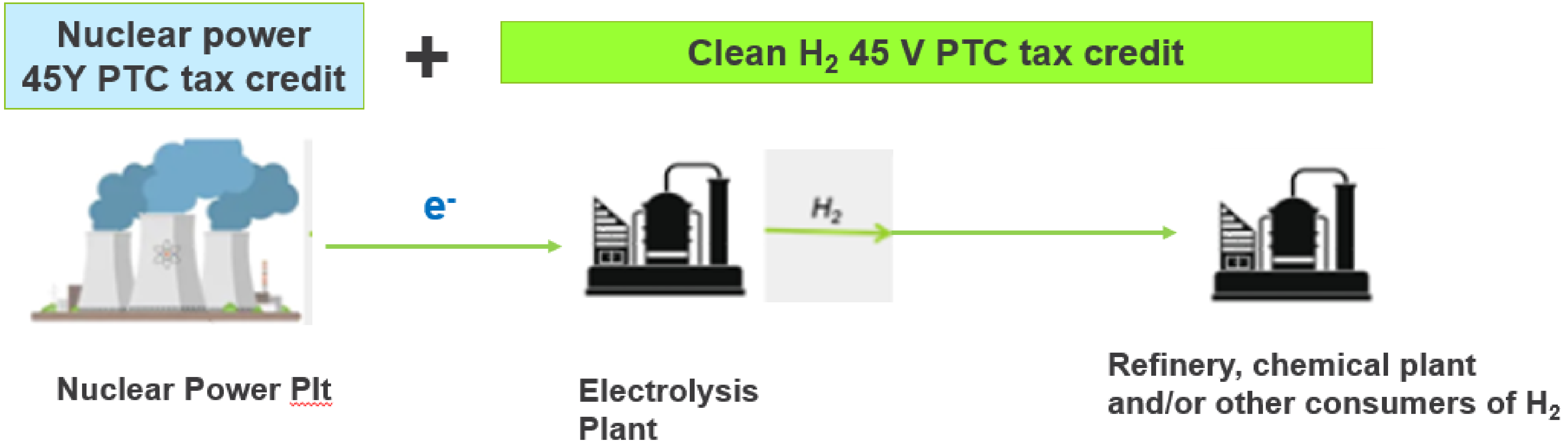


Mechanical and Electrical Interfaces Evaluated under 50.59

Hydrogen Fire and Detonation Separation Evaluated under FPEE

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

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



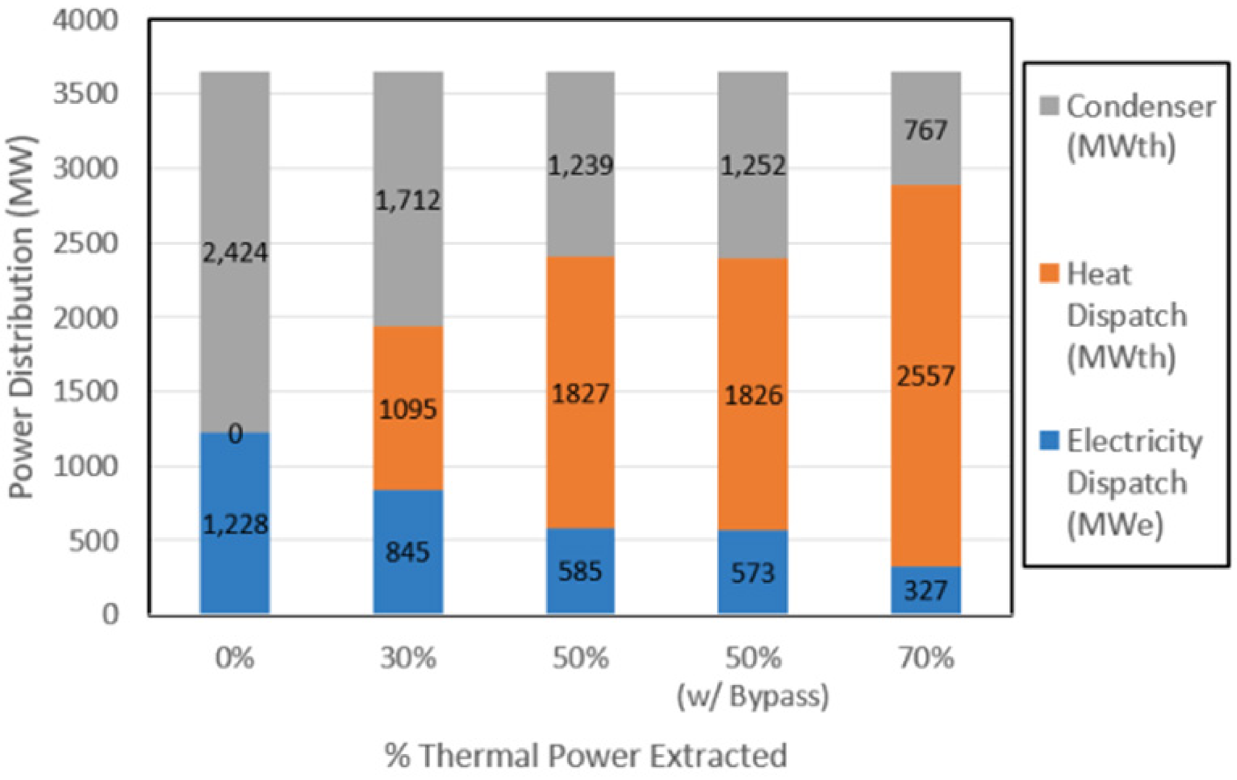
Determine credible NPP candidates for hydrogen production based on:

- 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

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

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



Summary of thermal power destination for 0%, 30%, 50%, and 70% TPD. As TPD increases, condenser duty drops.

Thermal Power Dispatch Options

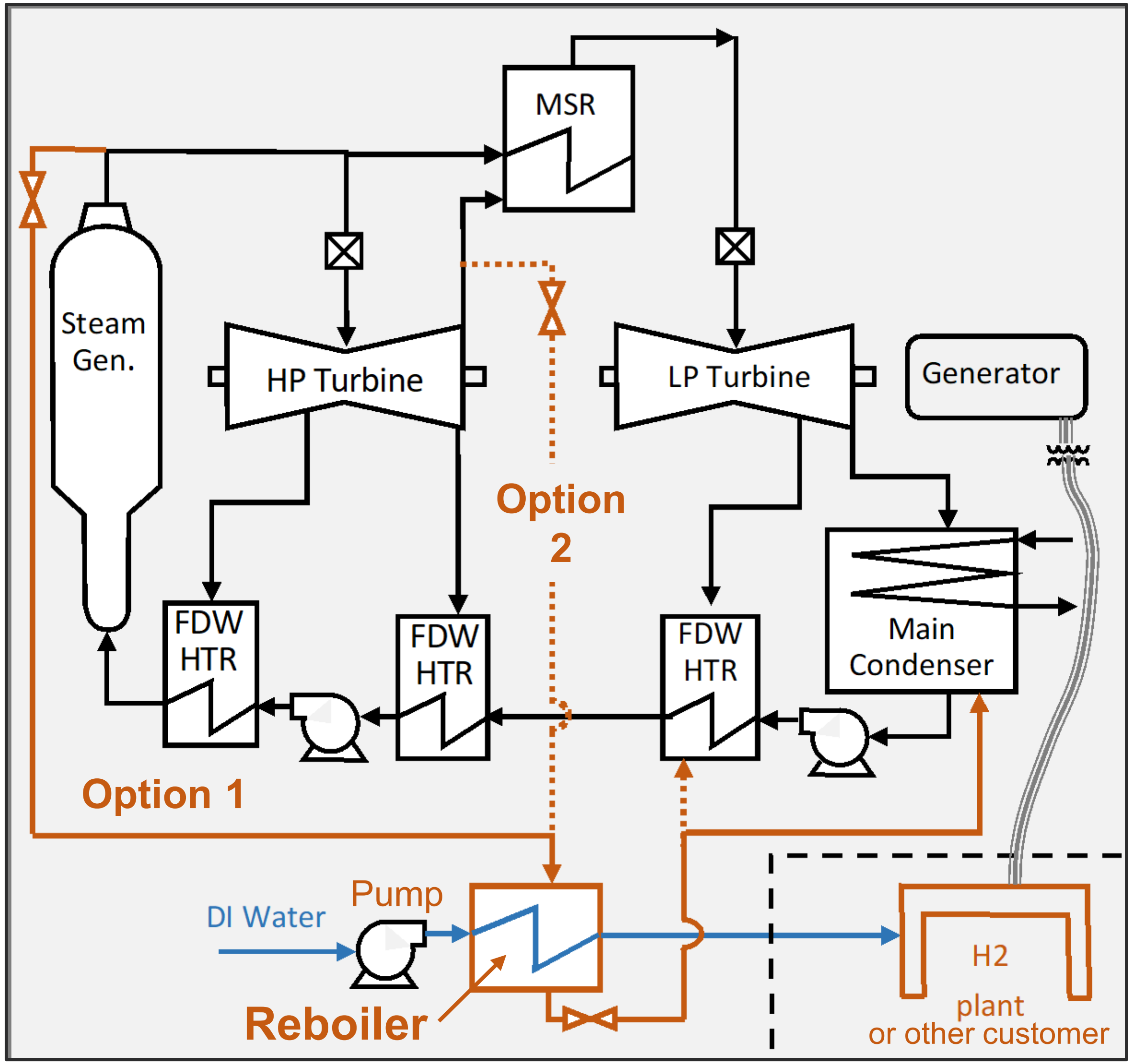
Design Option #A: Extract steam from main steam line

- For high levels of thermal power dispatch (TPD) for applications in which high temperature steam is required (>400 ºF)

Design Option #B: Extract steam downstream from high pressure (HP) turbine

- For lower levels of thermal power extraction or for applications in which low temperature steam is sufficient (<360 ºF)

- Both options send steam to a reboiler that condenses secondary steam and generates tertiary steam for dispatch
- Secondary condensate is returned to main condenser

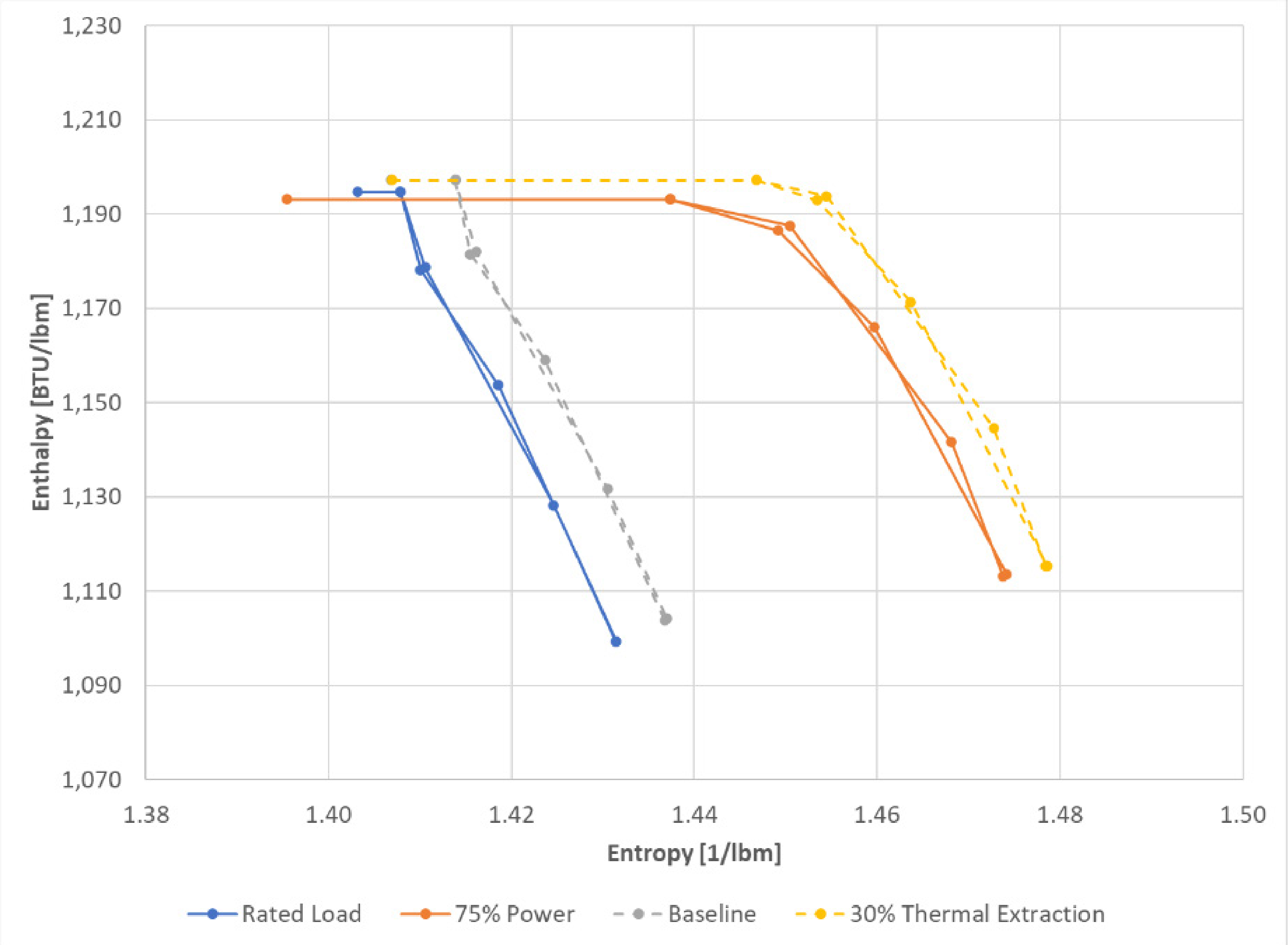


Simplified diagram of PWR/SOEC plant thermal power coupling options

Sargent & Lundy Analysis for 30% & 50% TPD

Nuclear Power Plant Major Equipment Reviewed

- ✓ High Pressure Turbines (HPTs)
- ✓ Low Pressure Turbines (LPTs)
- ✓ Pumps and Condensers
- ✓ Moisture Separator Reheaters (MSRs)
- ✓ Feedwater Heaters (FWHs)
- ✓ Extraction Steam
- ✓ Feedwater Heater Drains
- ✓ MSR Drains

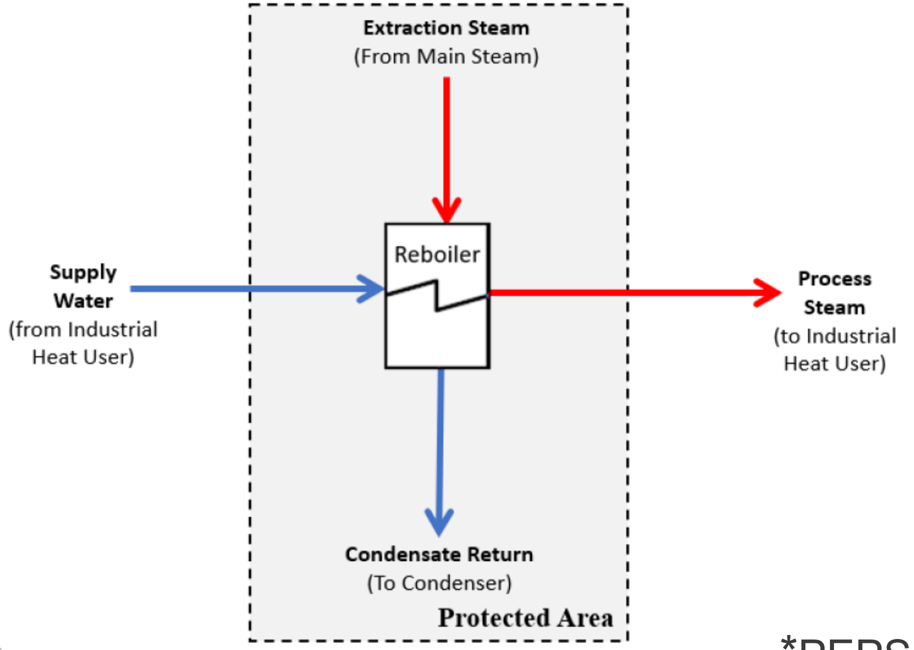


Outcomes

- *<u>For 30% TPD</u>, the analysis shows that the HPT and LPT performance is comparable to ramping reactor down to 75% of thermal output*
- *No major equipment replacements are required*
- *Specific plant components may need minor upgrades and maintenance*

S&L 50% TPD

- Electrical Output ↓ 52%
- Main Steam Flow ↓ 38%
- **Final feedwater temperature drops 52°F**
- **Pressures in Moisture Separator Reheater (MSR)/turbines drop 45%**



Methodology: PEPSE* heat balance models of a reference Westinghouse 4-loop PWR were used to determine the impact on equipment for different levels of TPD

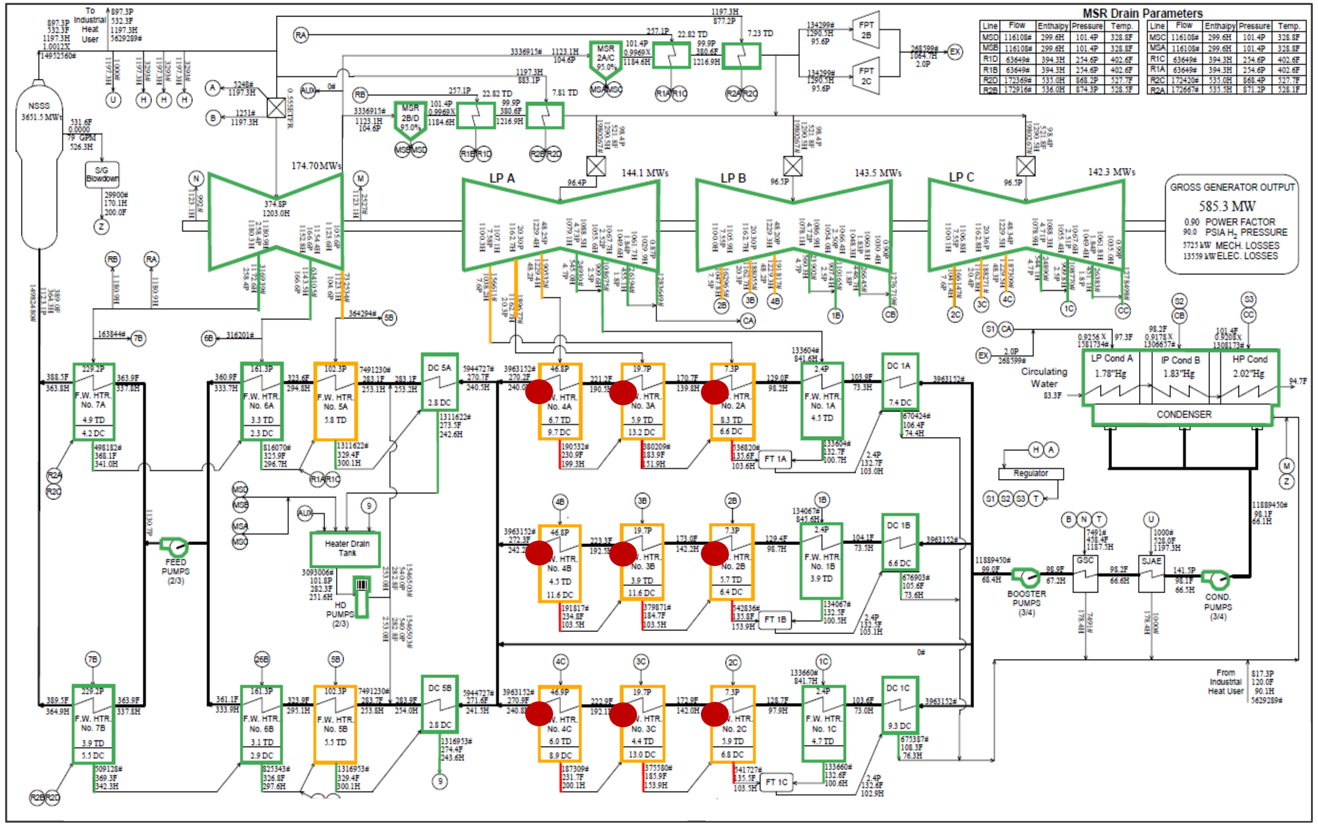
Description	Units	0%	50%	Δ (50%)
Generator Electric Power	MWe	1,228.0	585.3	-52.3%
Thermal Power Extracted	MWt	0	1,827	-
% of Flow - MS	%	0	37.6	-
MS Flow	lbm/hr	16,037,390	14,952,560	-7%
HP Turbine Inlet Flow	lbm/hr	15,218,400	8,615,524	-43%
HP Turbine First Stage Pressure	psia	651.5	374.8	-42%
MSR Inlet Pressure	psia	190.3	104.6	-45%
LP Turbine Inlet Flow	lbm/hr	3,673,069	1,980,267	-46%
LP Turbine Inlet Pressure	psia	175.5	96.43	-45%
Condenser Duty	BTU/hr	8.21E+09	4.18E+09	-49%
Condensate Pump Flow	lbm/hr	11,334,490	11,889,450	4.9%
Heater Drain Pump Flow	lbm/hr	4,732,792	3,093,006	-35%
Feedwater Pump Flow	lbm/hr	16,067,280	14,982,480	-6.8%
Final Feedwater Temperature	°F	440.9	389.0	**-51.9°F**
Cascading Drain Flow to Condenser	lbm/hr	817,619	670,424	-18%
Cogen HX Inlet Mass Flow	lbm/hr	-	5,629,289	-

*PEPSE: Performance Evaluation of Power Systems Efficiencies by Curtiss-Wright

S&L 50% TPD: General Evaluations

Low Impact
Medium Impact
High Impact

- Small Impacts for 50% thermal extraction
  - ❖ Turbines, MSRs, Pumps, Heater Drain Tanks
- O&M cost concerns for 50% thermal extraction
  - ❖ Feedwater Heaters (FWHs)
    - Flow accelerated corrosion evaluation
  - ❖ Extraction Steam Lines
    - Increased liner thickness requirements
  - ❖ FWH Drain Control Valves (DCVs)
    - Large increases in required flow capacity
    - Would result in automatic opening of the FWH emergency drains



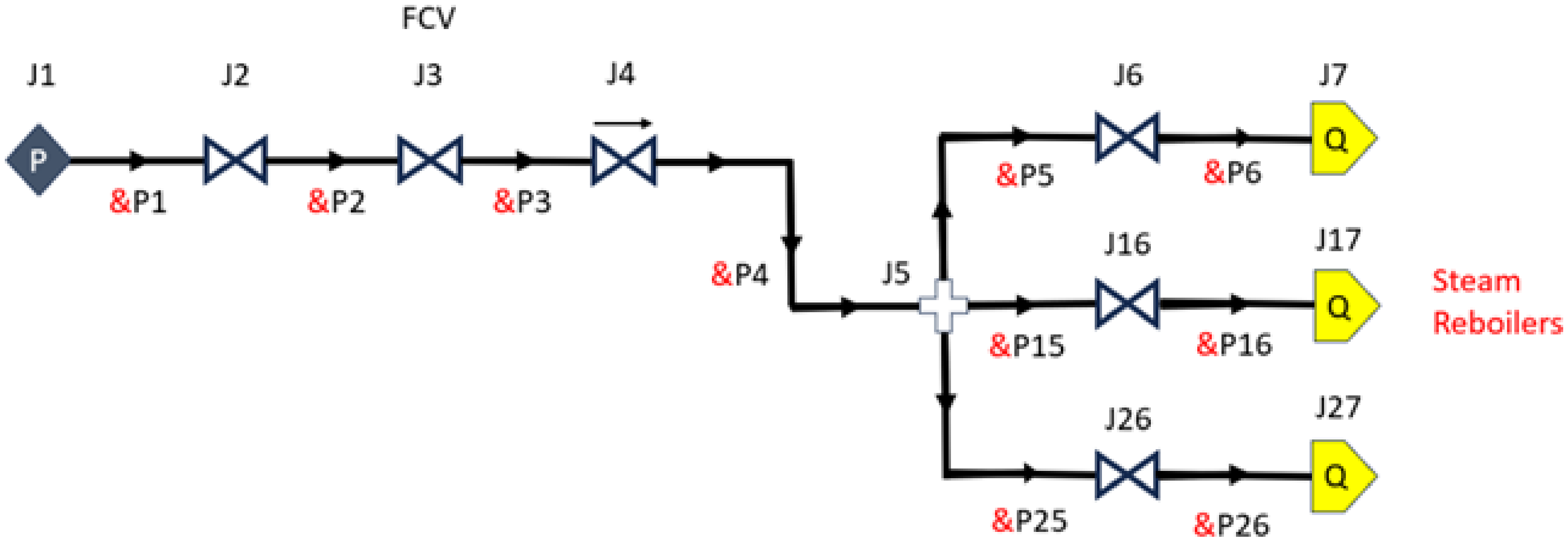
Color Coded Equipment Impacts for 50% Thermal Extraction

S&L 30% & 50% TPD

TPD System

Major Equipment Reviewed

- ✓ Reboilers
- ✓ Flow control valves
- ✓ Stop check globe valve
- ✓ Motor operated isolation valve
- ✓ Piping



Adapted S&L design of TPD line for 500 MW HTEF for 1000 MW HTEF (15% steam extraction). Also tapped off the main steam line.

Outcomes

- Increased Pipe Diameters and Pressure Ratings (Thicknesses)

  [or]

- 2 Trains of TPD Line for 30%
- 4 Trains of TPD Line for 50%

Failure Modes and Effects Analysis (FMEA)

Process Function	Hazard/Effect	Potential Causes / Mechanism of failure	Observations
Primary loop for transport of process steam	Loss of steam inventory in the balance of plant	Pipe rupture after main steam isolation valve (MSIV).	Causes loss of steam inventory in the balance of plant if an un-isolated rupture happens before the TPD reboilers. Also results in loss of thermal output to industrial customer.
	Damage to turbine building equipment, possibly safety power buses, depending on the plant	**Operational vibration, seismic, and erosion.**	Can be resolved by siting the TPD active components in their own building separate from turbine building. It also helps to lower temperature and noise in the turbine building for personnel's comfort and safety.

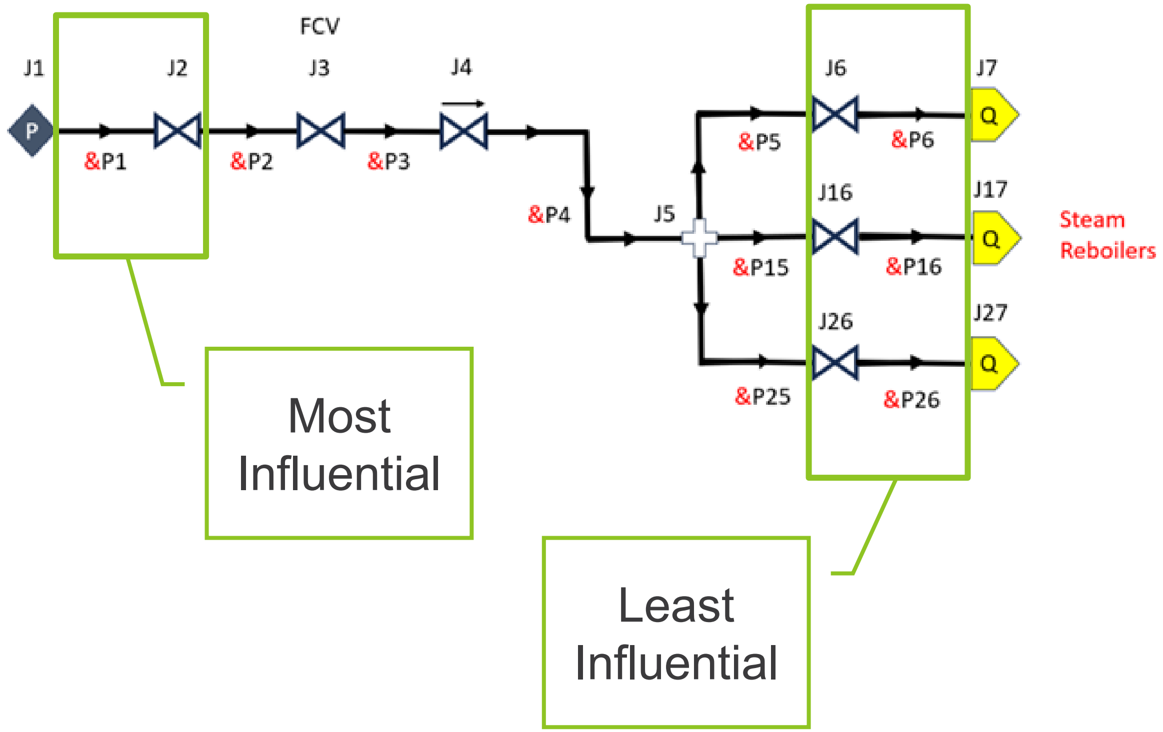
Probabilistic Risk Assessment (PRA)

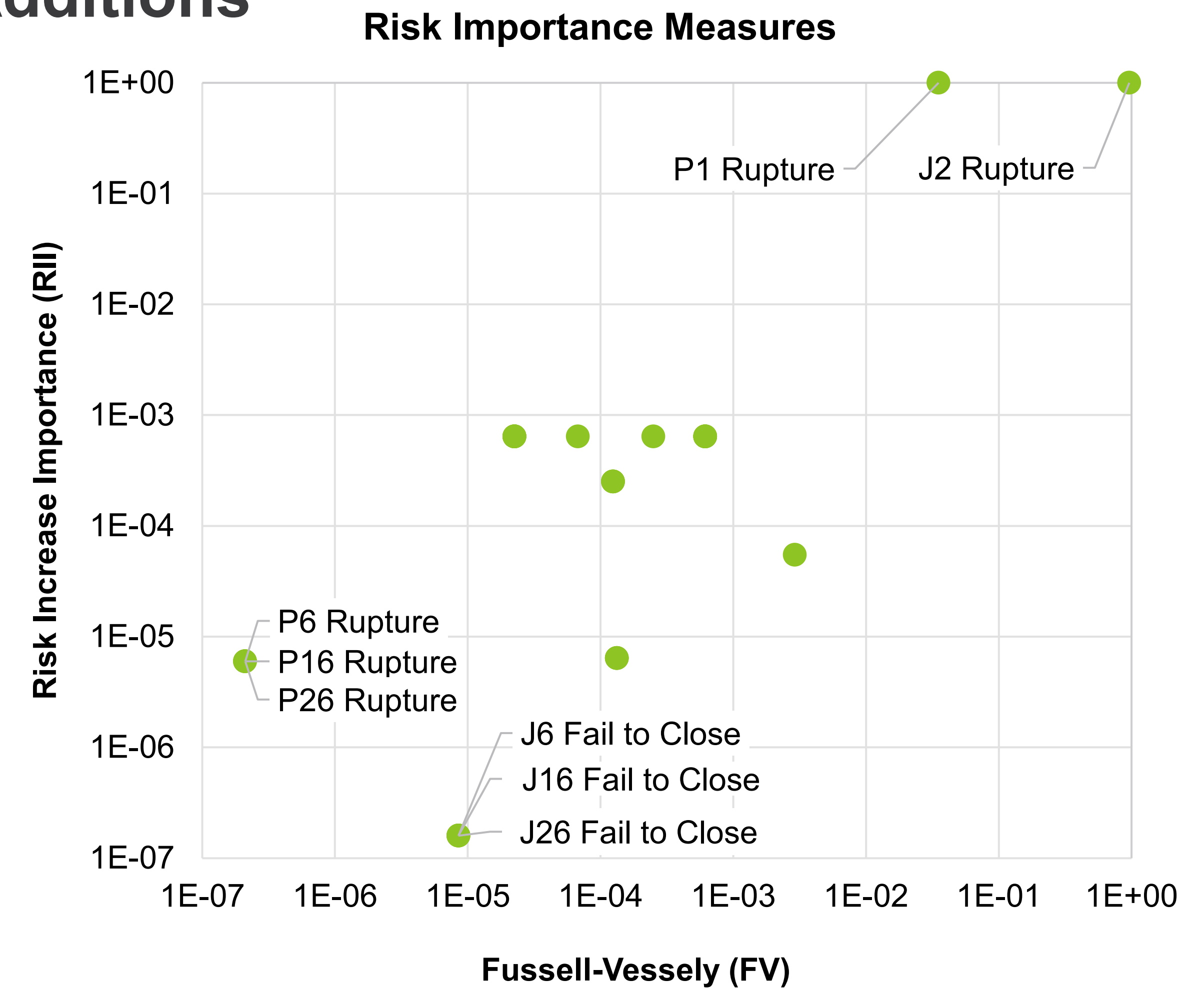
Calculation of Initiating Event Fault Tree Additions

- Solver conditions of Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE)
  - Minimal cutset upper bound (1.0E-12)
  - 10,000 Latin hypercube samples for uncertainty distribution
  - 3,000 Monte Carlo samples for importance measures
- Results
  - Increased frequency per year compared to the original MSLB IE frequency
  - Importance measures: Fussell-Vessely (FV) and Risk Increase Importance (RII)

Probabilistic Risk Assessment (PRA)

Results of Initiating Event Fault Tree Additions





Overall Conclusions and Next Steps

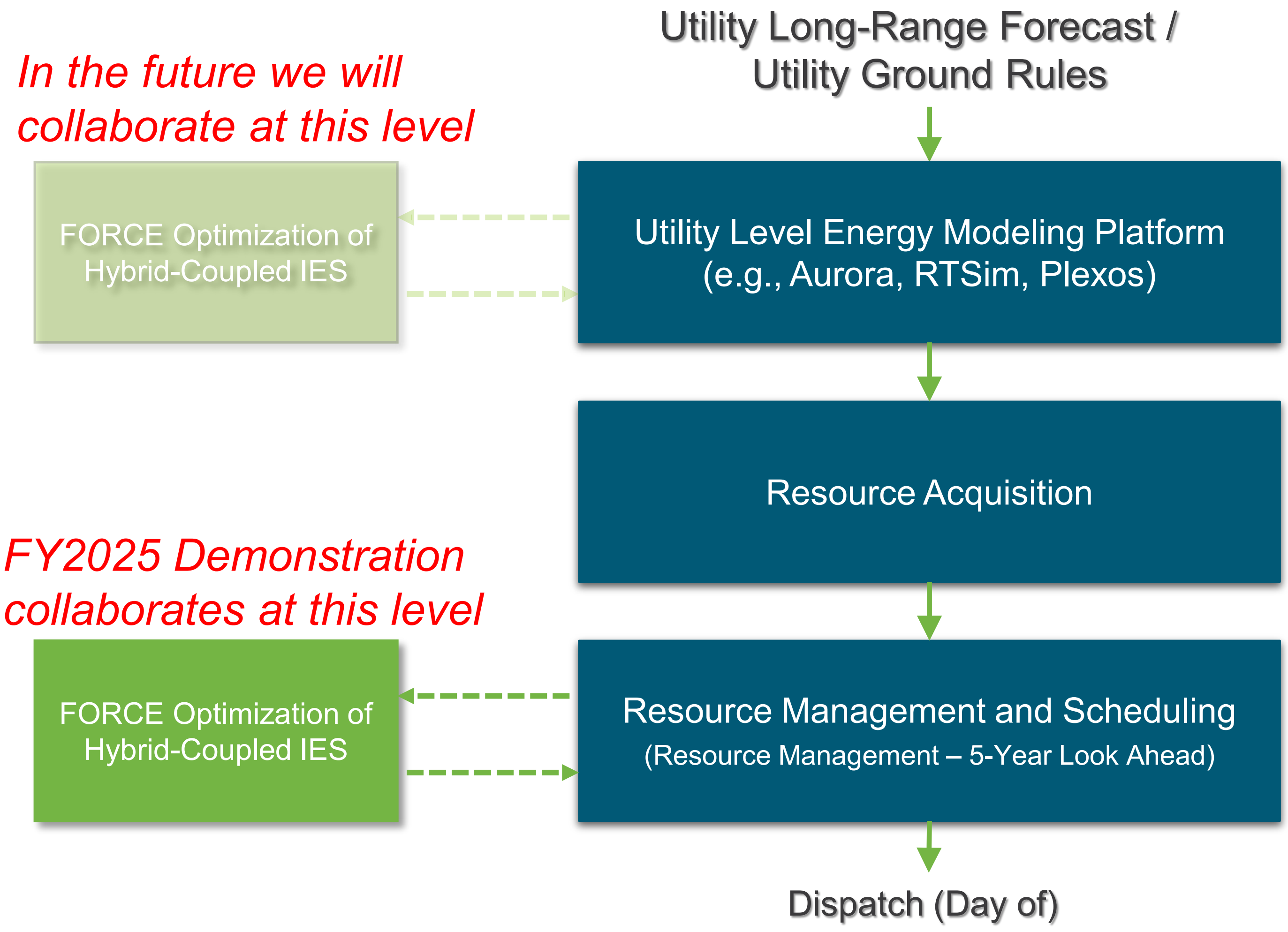
Overall Conclusions

- A MSLB at 50% thermal energy extraction increases PRA baseline less than 1%
- Additional considerations or adjustments could be made for J2 and P1

Next Steps

- Evaluation of licensing pathways
  - 10 CFR 50.59 (evaluate all eight criteria)
  - If desired, use full PRA results to inform RG 1.174 for changes for further Core Damage Frequency/Large Early Release Frequency risk informed support
- Consideration of condensate return line

Utility Resource Management Process

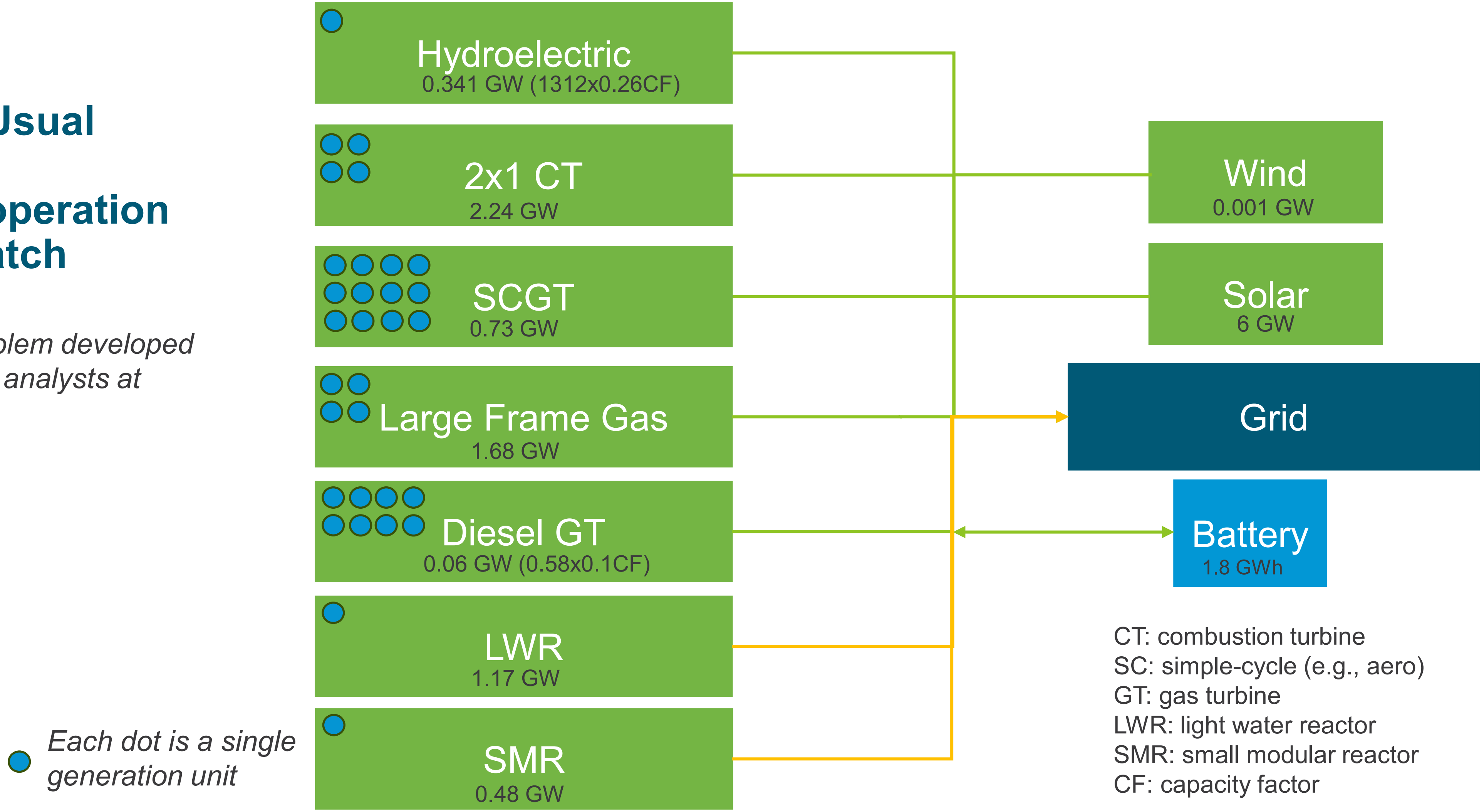


- New tools **provide utilities the capability** to assess the benefit of adding integrated energy systems to their portfolio.
- **Resource Planning**: what is the **right size** of IES to couple with existing heat and power to unleash energy resources? What should be the use for downstream products such as hydrogen, water, and heat?
- **Resource Management**: how does an IES help establish **energy resilience** and reliability? How can it free up valuable energy resources?

Demonstration Scenario – Simulation Utility Portfolio

Case 1:
Business as Usual
- No IES
- 20 years of operation
- Hourly dispatch

Demonstration problem developed with feedback from analysts at APS, Dominion

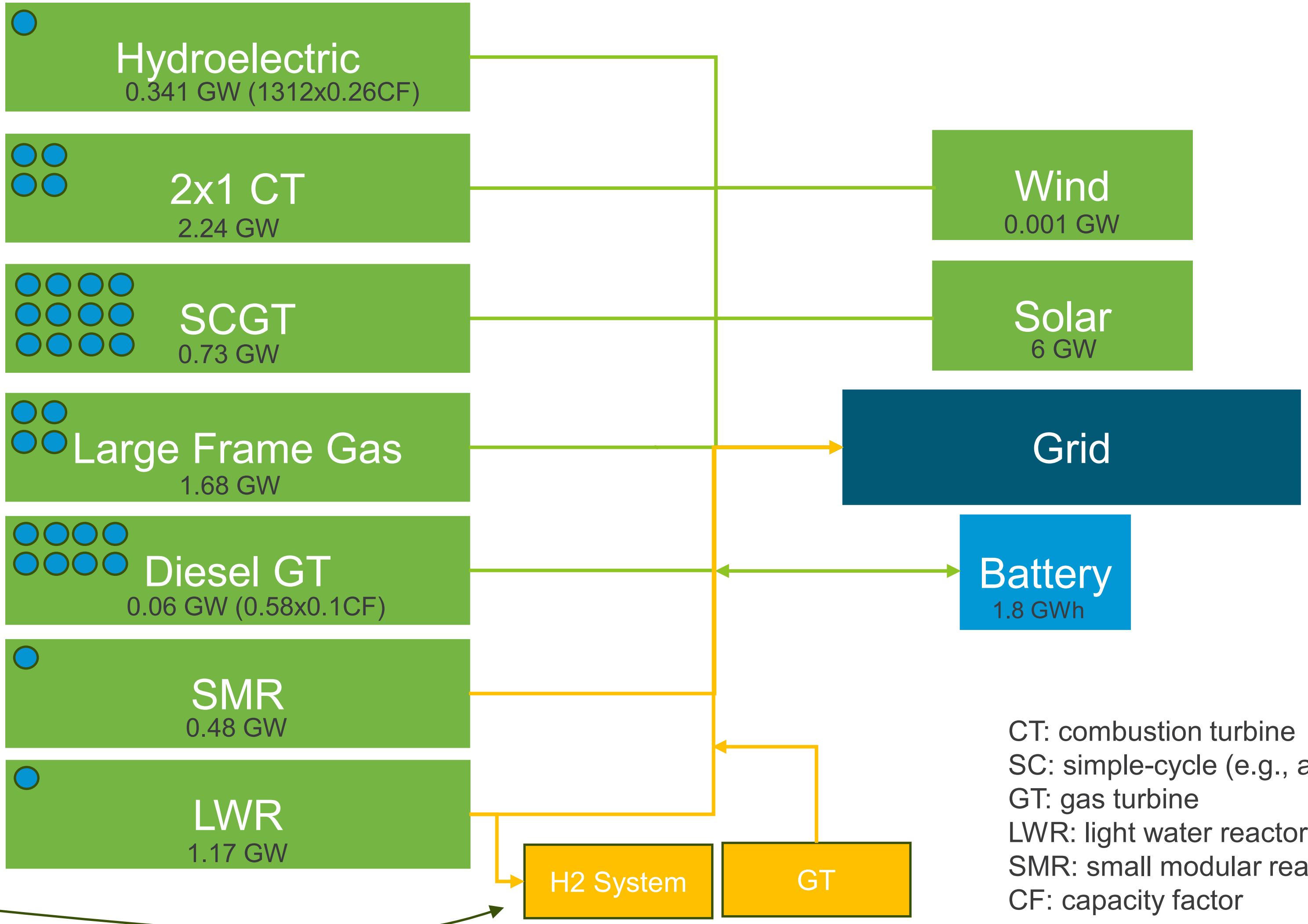


CT: combustion turbine
SC: simple-cycle (e.g., aero)
GT: gas turbine
LWR: light water reactor
SMR: small modular reactor
CF: capacity factor

Demonstration Scenario – Simulation Utility Portfolio

Case 2
Integrated Energy System (IES)

End results:
- *What size of IES?*
- *What is the cost savings?*
- *How much is reliability 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
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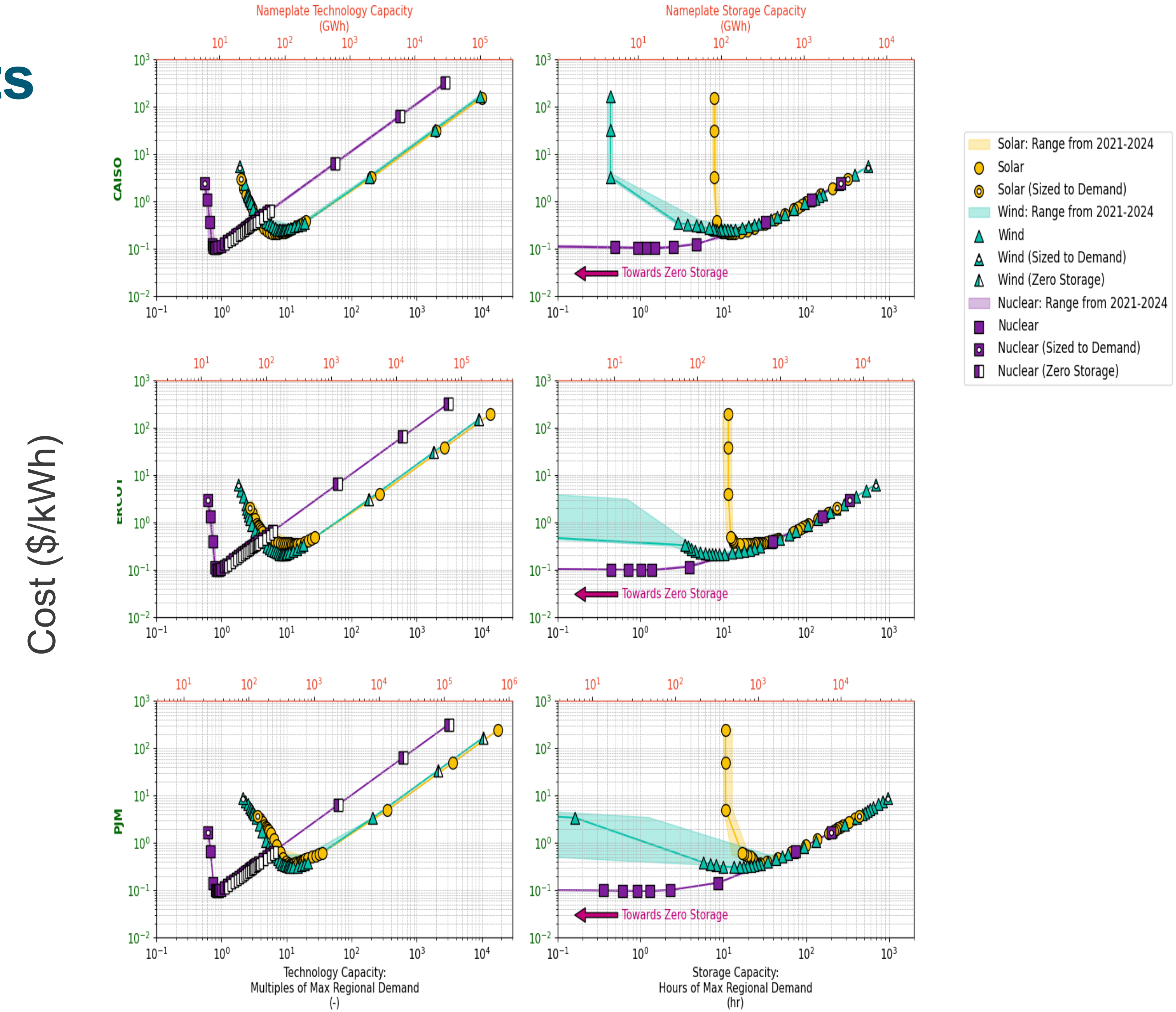
Example Results

- Identification of energy storage needs for grid balancing by CAISO, ERCOT, PJM
- Optimize generation of required storage capacity to minimize costs and maintain reliability by each generation technology
- Nuclear consistently less expensive due to reduced storage requirements for firm power



In Summary

1) FPOG is completing an evaluation of the possibility of producing hydrogen at nuclear plant sites in the United States. Technical, economical, safety evaluations, and regulatory guidance are summarized in an LWRS report.
2) High-capacity thermal energy extraction for industrial use is being evaluated based on Sargent & Lundy pre-conceptual design studies; research includes economic assessments for industrial centers, technical/operational impacts, and safety analysis.
3) Advanced computation tools are being developed to help utility strategy planners evaluate flexible hybrid systems, resource dispatch and energy storage options
4) Future work will explore capacity expansion and increased utilization of nuclear power plants

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Sustaining National Nuclear Assets

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