IES
Integrated Energy Systems

LWRS
LIGHT WATER REACTOR SUSTAINABILITY

IES Demonstration Cases

FORCE Workshop

March 18, 2022

INL/MIS-22-66362 Rev:00

Presented by: Dr. Konor Frick

Prepared by: Dr. Konor Frick and Use Case Team Members

Motivation

Demonstrate FORCE toolset use and evolution through industry and cross-lab collaboration

Previous Use Cases (public releases)

- APS – Desalination
- Exelon (now Constellation) – Hydrogen production in the Midwest
- EPRI – Regulated vs. De-regulated – Hydrogen production
- EPRI – Thermal Energy Storage in NYISO

Current Use Cases

- Thermal Energy Storage
- Synthetic Fuels
- Carbon Conversion

Ongoing CRADAs

- APS – Hydrogen production
- Constellation (formerly Exelon) – Hydrogen production

Completed Case Studies Using FORCE

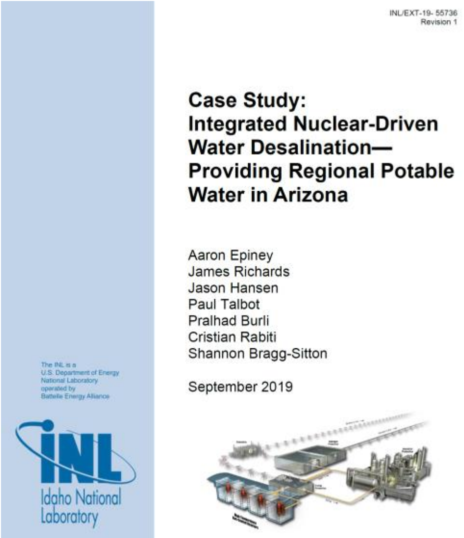
APS Case Study 2019 – Desalination

Arizona Public Service (APS) Challenge

Net Grid Demand < Generation

- Economic dispatch
- Negatively priced sales
- Desalination

- "Classic" considerations:
  - Wear and tear on plant components (difficult to determine)
  - Negligible variable costs (e.g., fuel cost) (true?)
  - Electric grid price will be negative (how to assess this?)
- Another option: **Desalination**
  - **Change in water procurement costs**
  - **Other cheaper water sources available (brackish water)**


INL/EXT-19- 55736
Revision 1

Case Study: Integrated Nuclear-Driven Water Desalination—Providing Regional Potable Water in Arizona

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Paul Talbot
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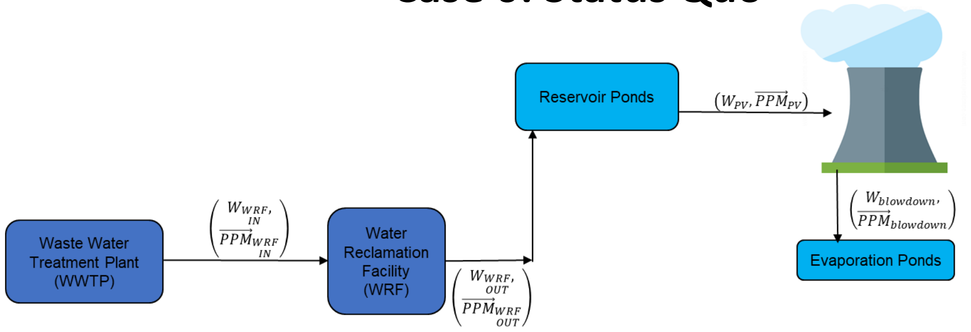
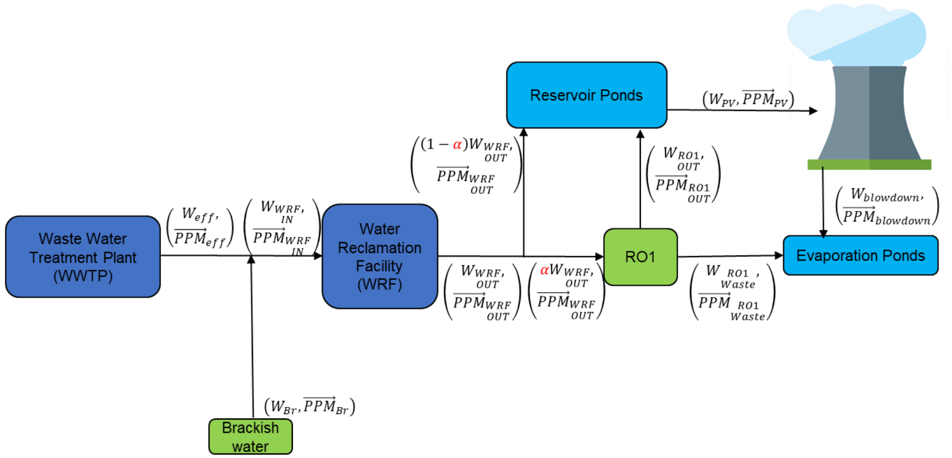
Potential Scenarios

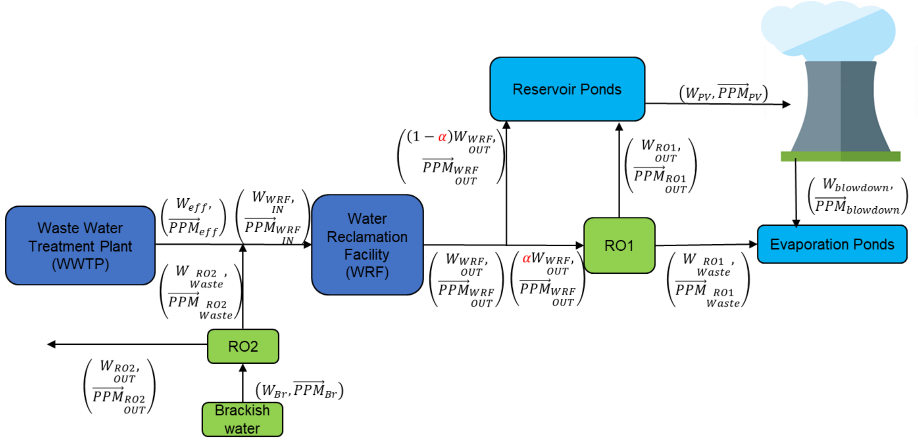
Case 0: Status Quo



Case 1: Desalination for Plant Cooling

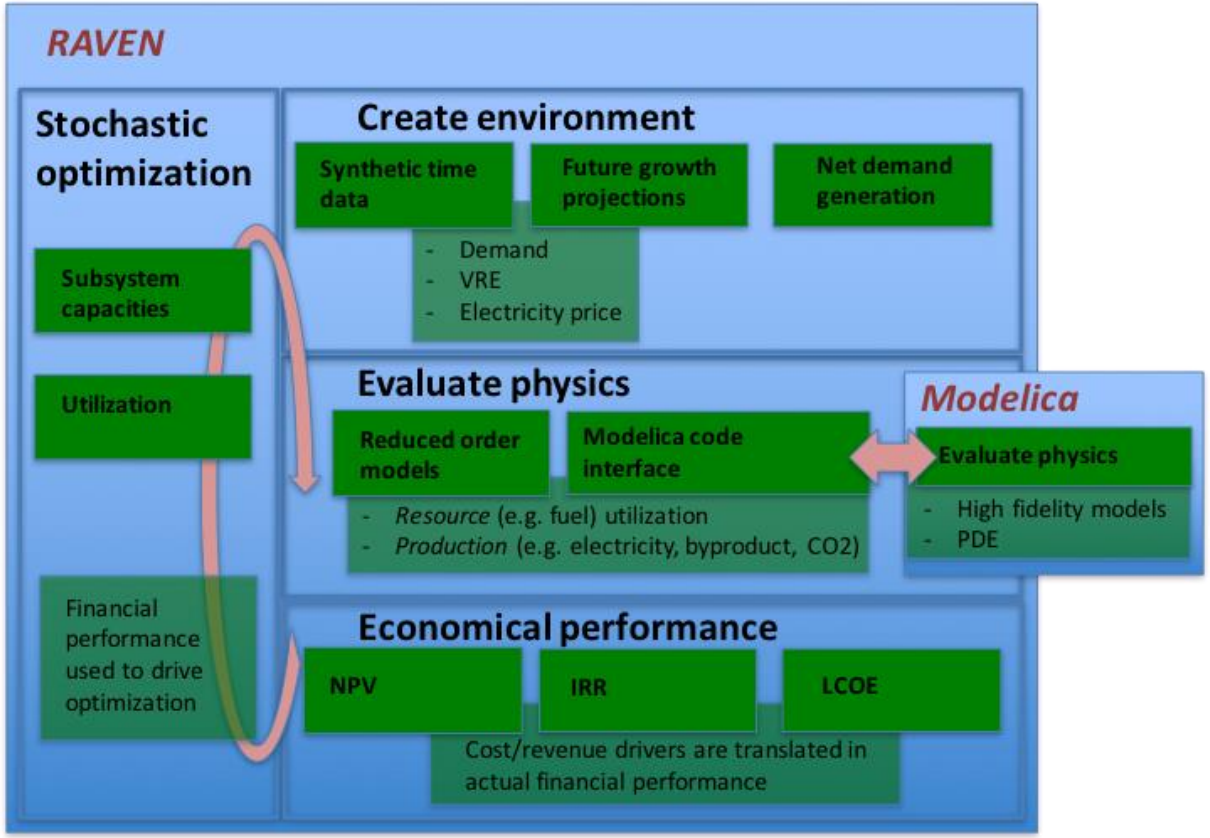


Case 2: Desalination for Plant Cooling Plus Potable Water



Computational Framework

- **RAVEN:**
  - **Drives the problem**
  - Manages the data exchange between the different codes and models involved in the framework
  - Generates synthetic data (**environment**)
  - Optimization, sensitivity, and statistical analysis needed
- **Modelica**
  - Simulates the dynamics (**physical model**) of the N-R HES
- **Economics**
  - RAVEN plugin ("CashFlow")
  - Computes cash flows from cash flow drivers
  - Economics indicators, net present value (NPV), and the internal rate of return (IRR) (**financial performance**)



- **Software implementation**
  - Flexible, allowing assembly of components (e.g., nuclear reactor, gas turbine, battery, industrial process, renewables)
  - N-R HES models version controlled in GitLab

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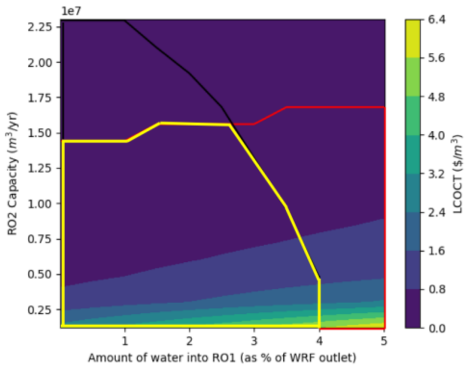
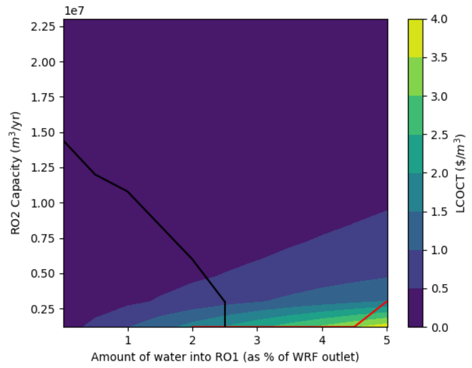
INL Collaboration Shows the Economic Feasibility of Implementing Desalination Onsite at Palo Verde Plant

- Results demonstrated to industry partners that onsite desalination (RO1) was unnecessary

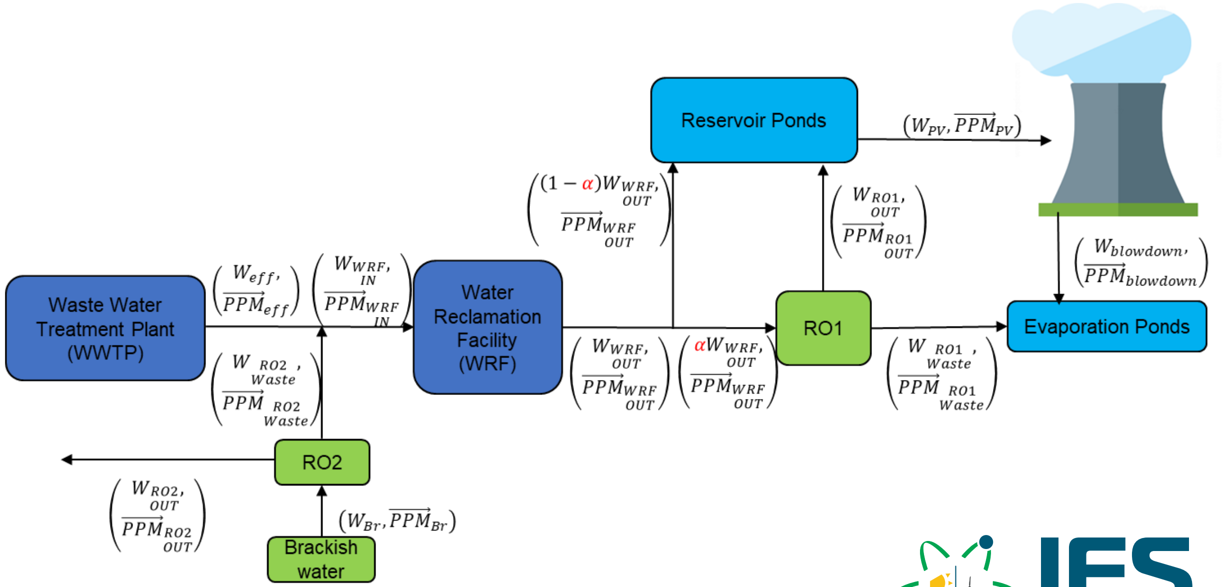
- Demonstrated that, to maximize profits, RO2 could be built larger, given regional water demands.
  - The primary constraint on low-cost water is creating larger effluent ponds to store excess brackish water



Brackish water 0.0 m^3/yr (0 AF/yr).



Brackish water 1.9e7 m^3/yr (15500 AF/yr).



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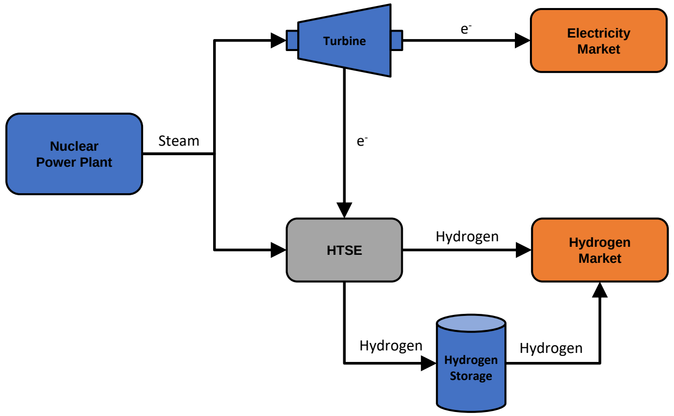
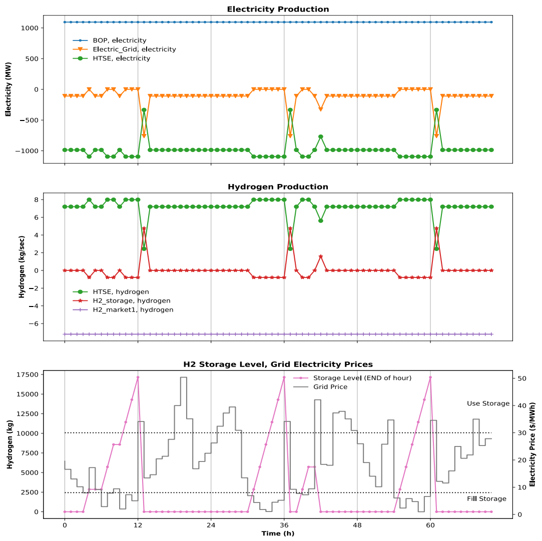
Exelon Case Study 2019 – Hydrogen Production Coupled with an Existing LWR

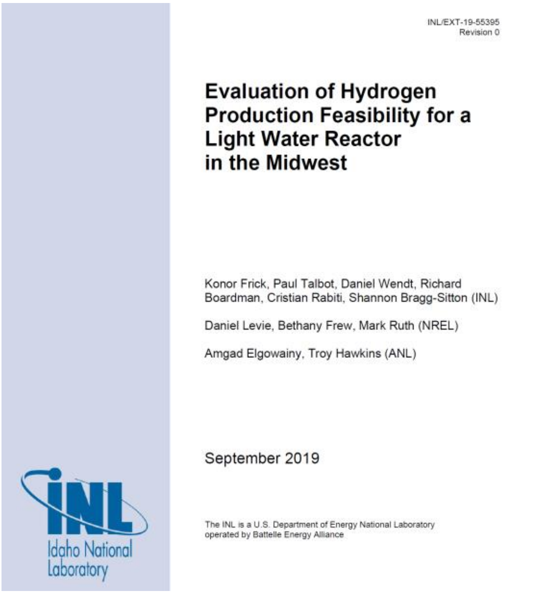
Hydrogen Co-generation

- **Goal:** Evaluate the co-generation of hydrogen at an existing plant in order to enhance the economics of LWR operations
- **Approach:** Techno-economic analysis of the high-temperature steam electrolysis (HTSE) process under selected operating modes and market conditions
  - Evaluate NPV of LWR operation scenarios
    - Business as usual (electricity generation only)
    - Dynamic hydrogen production (incorporate hydrogen storage to enable variable electricity and hydrogen dispatch)
  - Analysis tools
    - HTSE process steady state & dynamic performance: Aspen HYSYS & Dymola Modelica
    - Capital costs estimates: Aspen Process Economic Analyzer, HTSE module manufacturer cost projections, HTSE literature
    - Resource dispatch projections: Risk Analysis Virtual Environment (RAVEN), Heuristic Energy Resource Optimization Network (HERON)
- **Assumptions**
  - HTSE plants do not thermally cycle (to minimize stack degradation due to thermal gradients)
    - Decreases NPP electricity generation capacity
    - Reduces NPP capacity payments
  - Dedicated pipelines used for hydrogen transport
    - Use of existing natural gas pipelines would result in capital savings of ~$19,000,000 per kg/sec of installed HTSE capacity
  - Ancillary services market not considered
  - No subsidies for avoided carbon emissions





Example HERON dispatch. Top: electricity dispatch. Middle: hydrogen dispatch. Bottom: hydrogen storage level and electricity price


INL/EXT-19-55395
Revision 0

Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest

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Daniel Levie, Bethany Frew, Mark Ruth (NREL)

Amgad Elgowainy, Troy Hawkins (ANL)

September 2019

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

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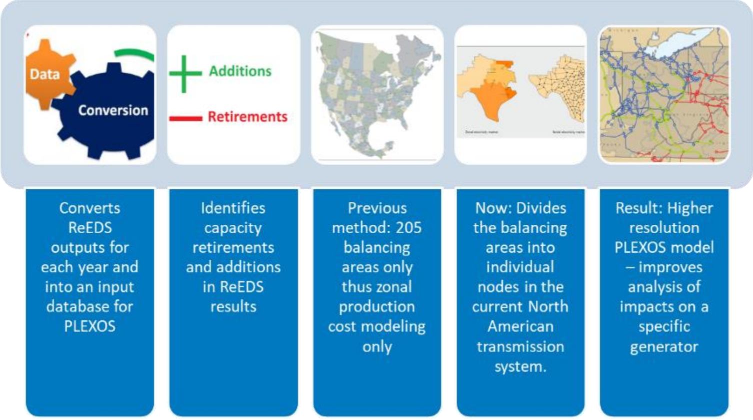
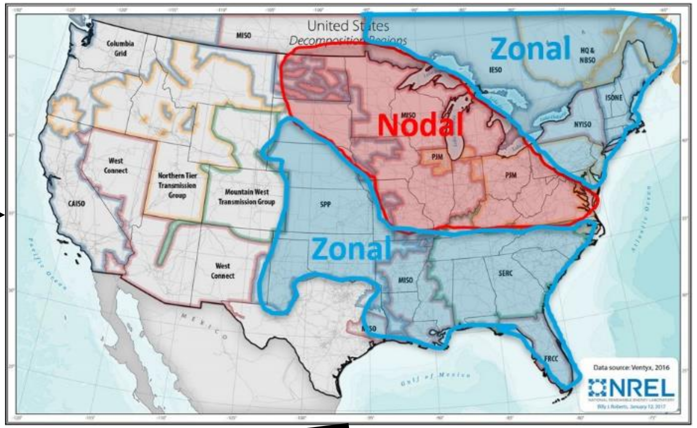
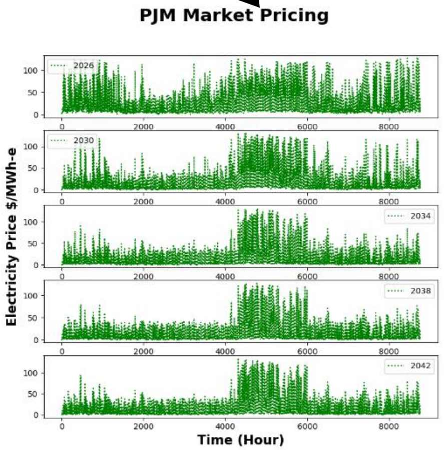
Modeling Tools and Progression of Boundary Conditions

ReEDS

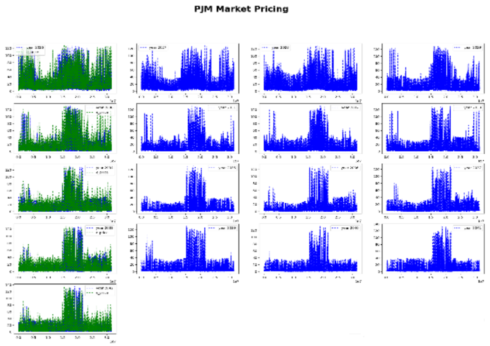


PLEXOS





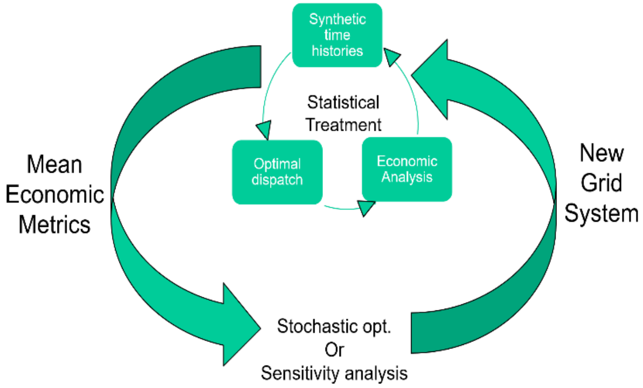
ARMA Training



Modeling Tools (Cont.)

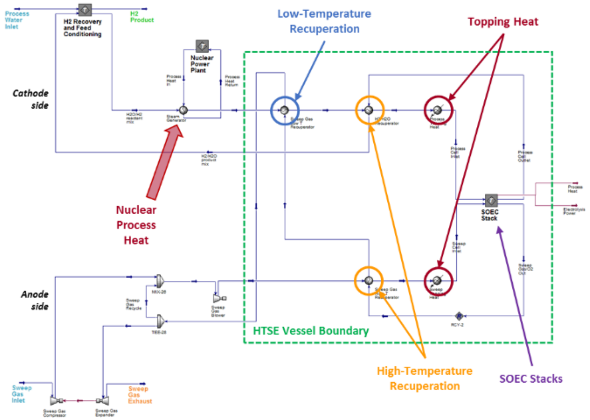
Stochastic History Generation / Dispatch Optimization

RAVEN/HERON



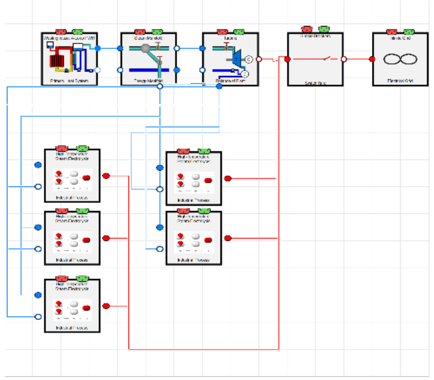
Steady-State Process Models / Economic Values

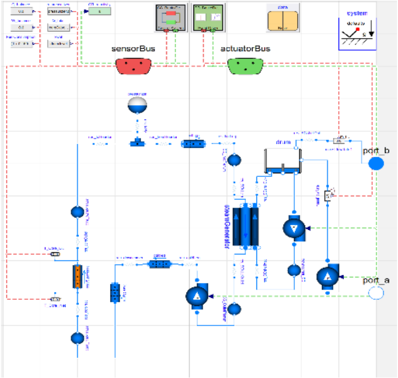
ASPEN/HYSYS

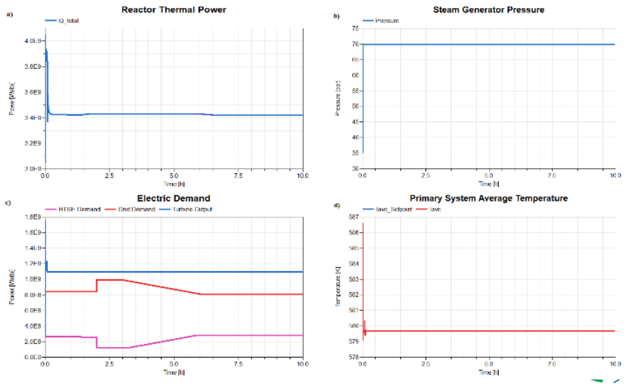


High-Fidelity Models / Control Schemes

Modelica (Dymola)







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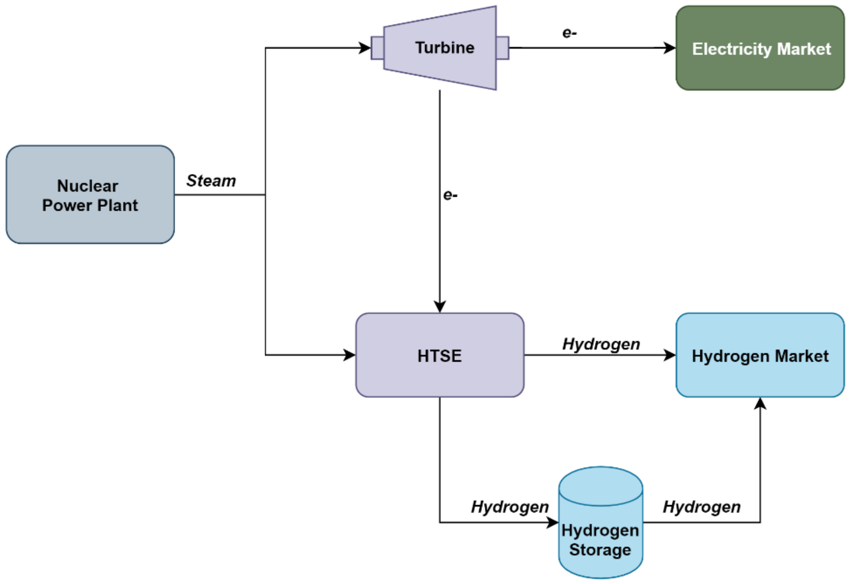
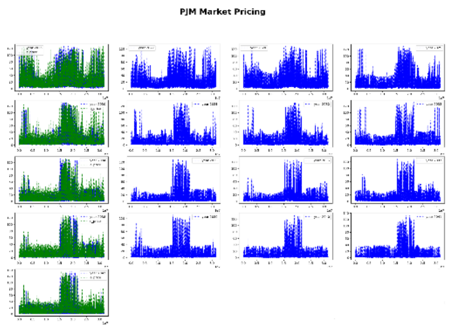
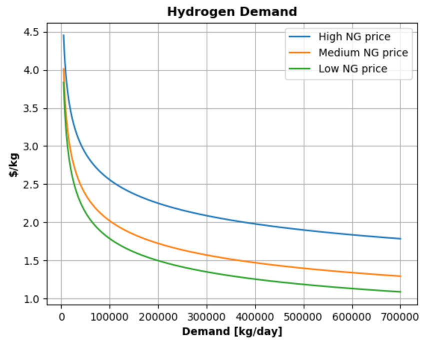
Techno-economic Selection Process







- Hydrogen market = fixed demand
- Hydrogen storage operates on buy/sell logic.
  - If $/MWh-e < setpoint value, then store hydrogen. If $/MWh-e > setpoint value, then sell hydrogen.
- NPP remains at constant power
- HTSE always needs ~10% of its nominal power requirements.
- Dispatch optimization is an hourly walk using HERON.
  - Compares electricity price to the storage buy/sell price and storage level.
    - If the buy price is higher than the storage setpoint value, the system dispatches hydrogen from the storage tank first, then fulfills the rest of the hourly demand through the HTSE. The rest is sold as electricity.

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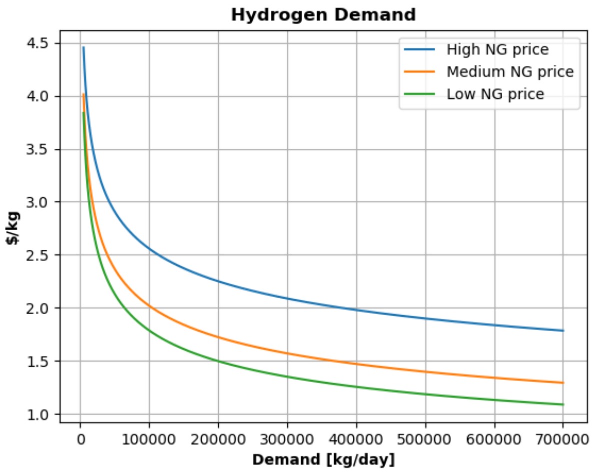
Final Results

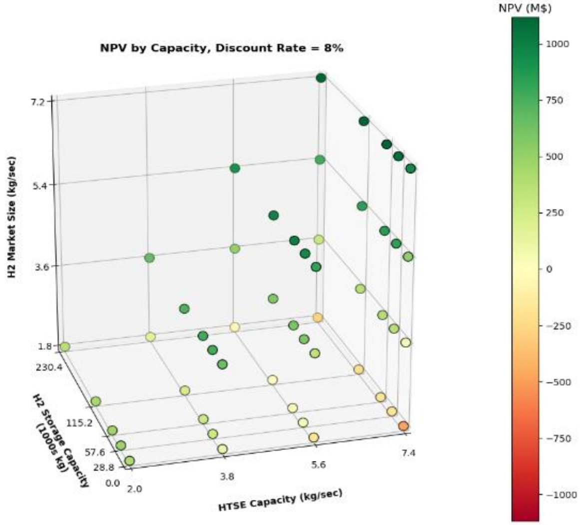
- During times of low electrical pricing, producing hydrogen is more profitable. During times of high pricing, selling to the grid is more profitable. Hydrogen storage gives the plant the flexibility to choose between the two options. (The hydrogen off-take satisfies the demand generated by steel manufacturing, ammonia and fertilizer production, and fuel cells for transportation.)

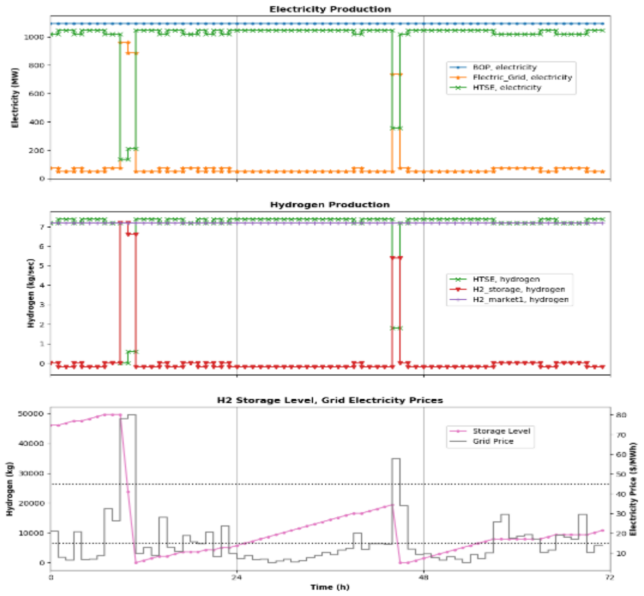
- Results suggested that a revenue increase of $**1.2 billion ($2019)** over a 17-year span was possible.

- Led to an award from the DOE EERE Fuel Cell Technologies Office (FCTO), with joint NE funding for follow-on work and demonstration at an Exelon plant.

Full Report: Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest (INL/EXT-19-55395)







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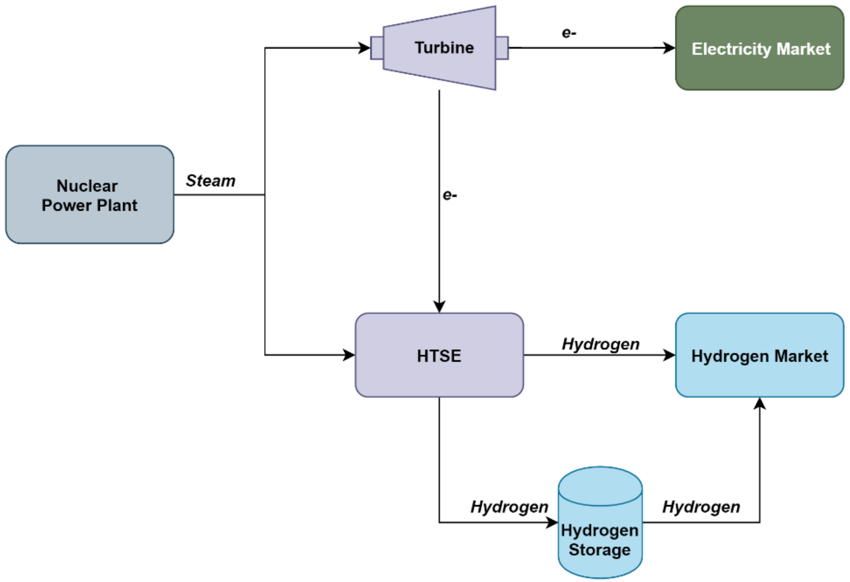
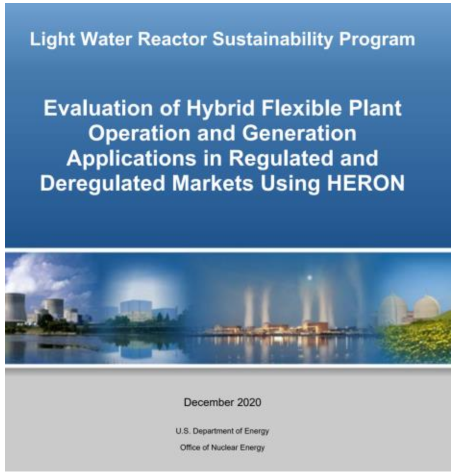
EPRI 2020 – Using HERON to Evaluate Hybrid Plant Operations in Regulated and Deregulated Markets

Mission

- Demonstrate the capability of the HERON toolset to operate in both regulated and deregulated markets.





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Deregulated

- NPV maximization problem formulation
  - Objective = $max\left(NPV\left(f(Capacities, Dispatch)\right)\right)$
- The question becomes:
  - Can a nuclear reactor capable of producing hydrogen for a customer and the electricity for the power grid be more profitable than operating in a grid-centric mode?
- In these markets, yes, hydrogen production can add value to the nuclear generating capacity

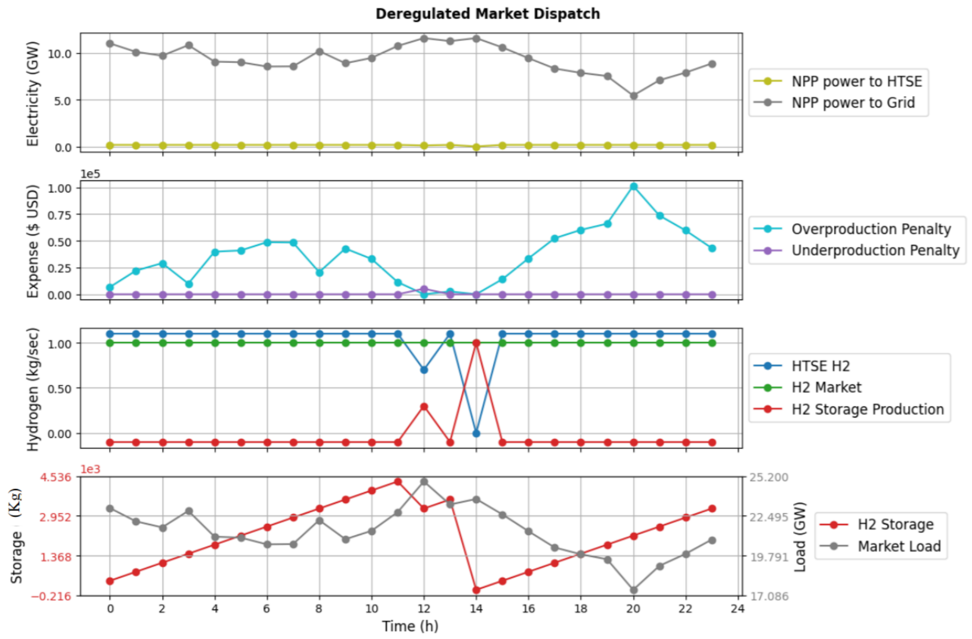
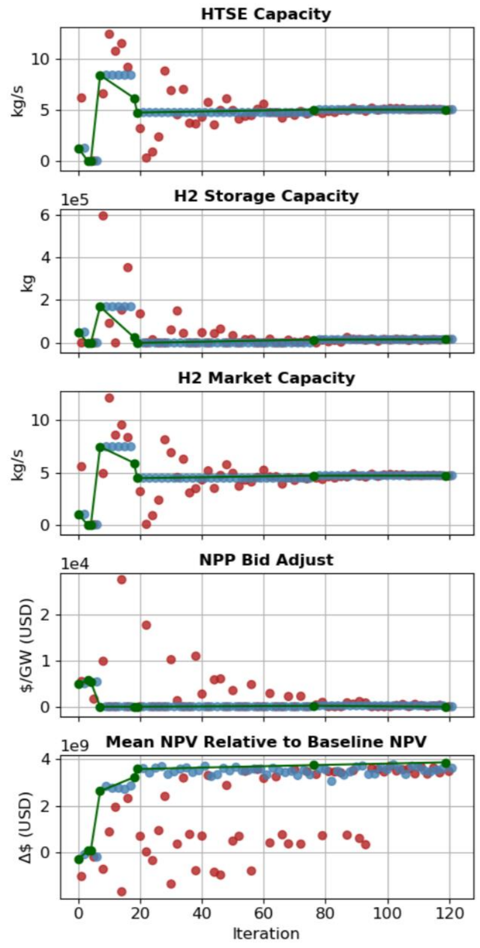


Figure 42. Deregulated, example dispatch optimization.

Table 14. Deregulated, final accepted iteration step results.

Case	HTSE Capacity	H2 Storage Capacity	H2 Market Capacity	NPP Bid Adjust	Mean NPV	ΔNPV
Carbon Tax Default	3.04E+00	3.69E+04	-2.88E+00	0.00E+00	-1.59E+09	2.97E+09
Carbon Tax LNHR	1.68E-01	2.14E+05	-9.04E-03	7.68E+03	3.28E+10	8.86E+07
Nominal Default	5.04E+00	1.69E+04	-4.70E+00	0.00E+00	7.24E+09	3.85E+09
Nominal LNHR	9.41E-02	4.74E+05	0.00E+00	9.67E+04	8.62E+09	3.01E+08
RPS Default	0.00E+00	0.00E+00	0.00E+00	4.39E+03	0.00E+00	0.00E+00
RPS LNHR	1.51E-01	2.62E+04	-1.15E-01	2.70E+04	3.19E+10	2.65E+08



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Regulated

- Cost minimization problem formulation
  - Objective = $min\left(LCOE\left(f(Capacities, Dispatch)\right)\right)$
- The question becomes:
  - Can sales of hydrogen to a secondary market overcome the capital cost of constructing/maintaining the HTSE and hydrogen storage unit, as well as the extra electricity required to produce the hydrogen?
- In this case, hydrogen sales cannot, in the long run, overcome the regulating markets incremental cost of electricity.

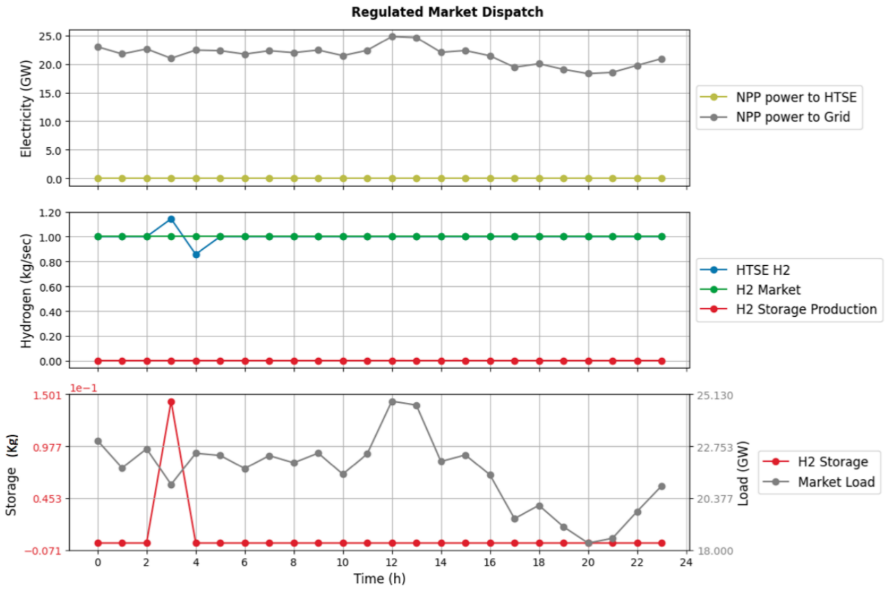
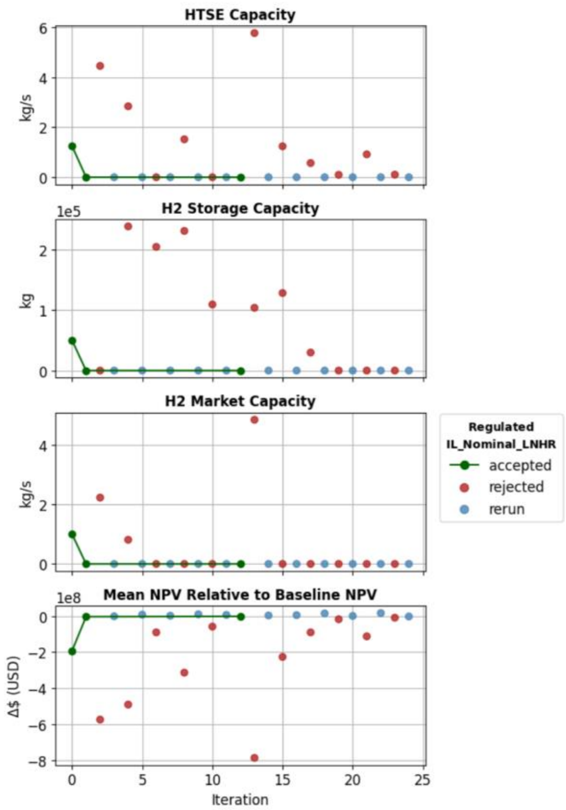


Figure 35. Regulated, example dispatch optimization.

Table 13. Regulated, final accepted iteration step results.

Case	HTSE (kg/s)	H2 Storage (kg)	H2 Market Capacity	Opt. Mean NPV	Δ NPV
Carbon Tax Default	1.00E-10	0.00E+00	-1.00E-10	-2.67E+09	-2.00E-01
Carbon Tax LNHR	1.00E-10	0.00E+00	-1.00E-10	-1.74E+10	1.35E+06
Nominal Default	3.41e-02	0.00E+00	-3.41E-02	-1.74E+10	1.54E+07
Nominal LNHR	1.00E-10	0.00E+00	-1.00E-10	-1.73E+10	-1.60E+06
RPS Default	1.00E-10	0.00E+00	-1.00E-10	-9.24E+09	-2.97E+06
RPS LNHR	1.00E-10	0.00E+00	-1.00E-10	-1.50E+10	3.94E+07



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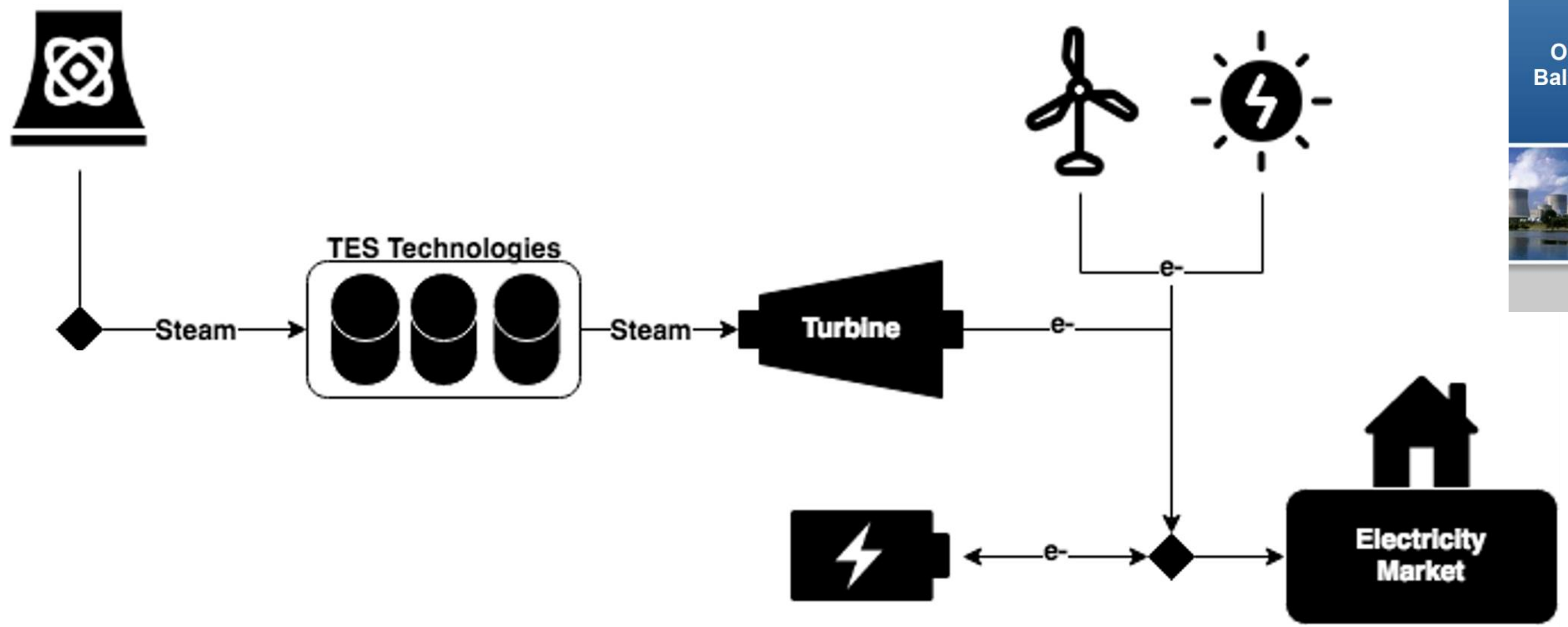
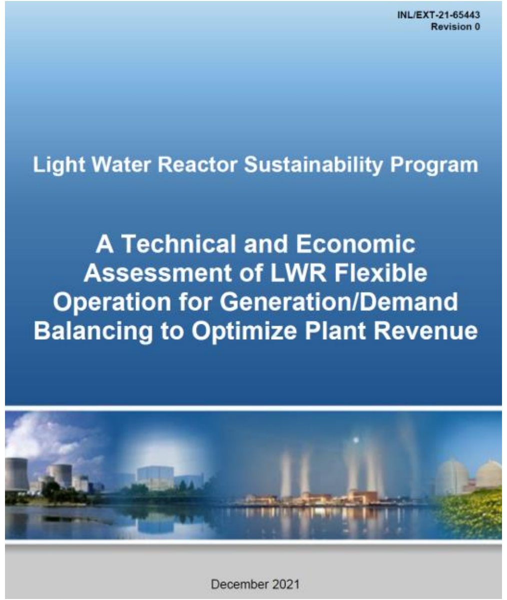
EPRI 2021 – Feasibility of Nuclear-Coupled Thermal Energy Storage for the Current Fleet

System Description

- Project lifetime of 20 years
- Synthetic histories generated using load demand and wind/solar utilization





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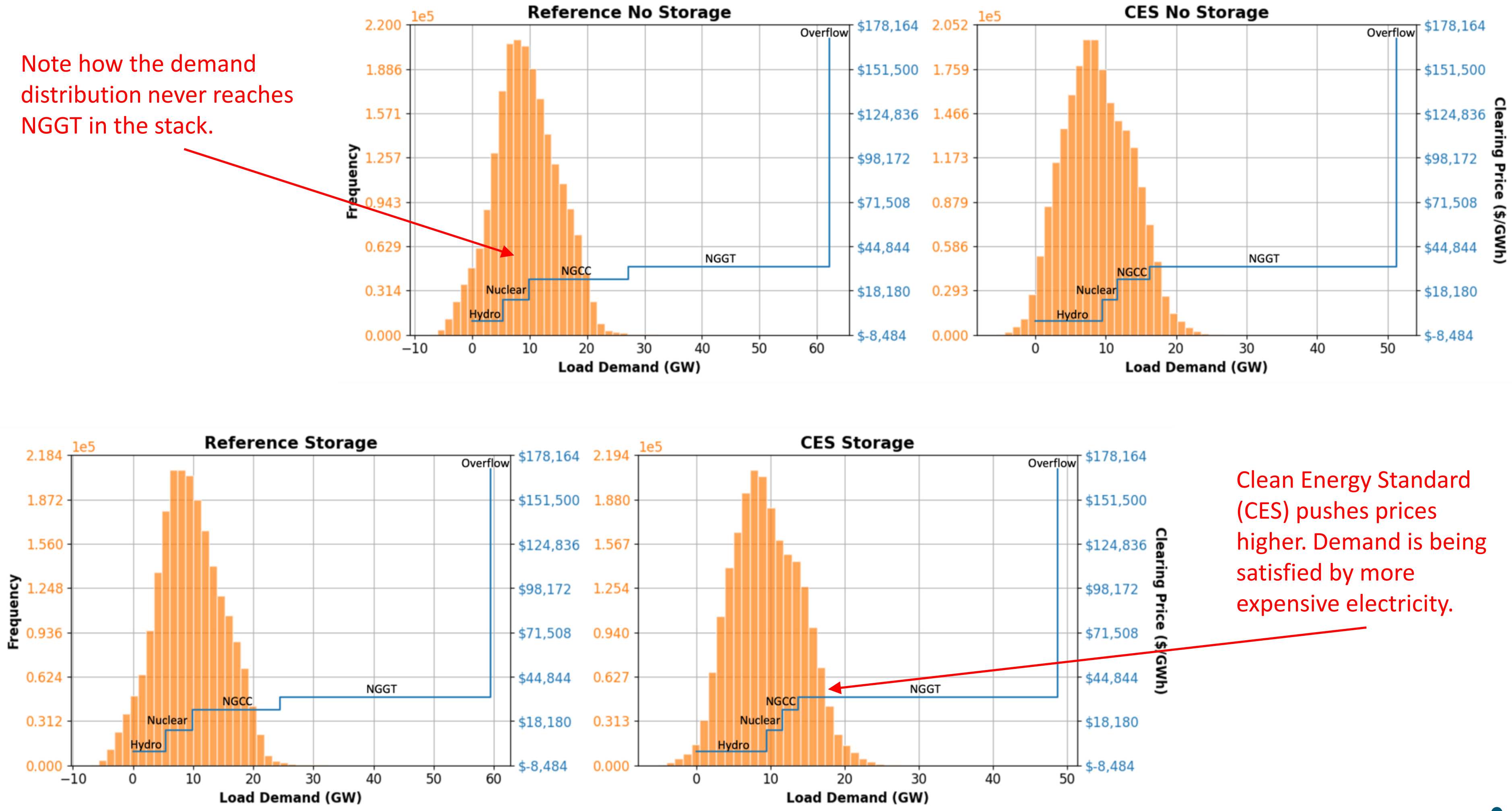
Demand Distribution & Cost Curve

Note how the demand distribution never reaches NGGT in the stack.



Clean Energy Standard (CES) pushes prices higher. Demand is being satisfied by more expensive electricity.

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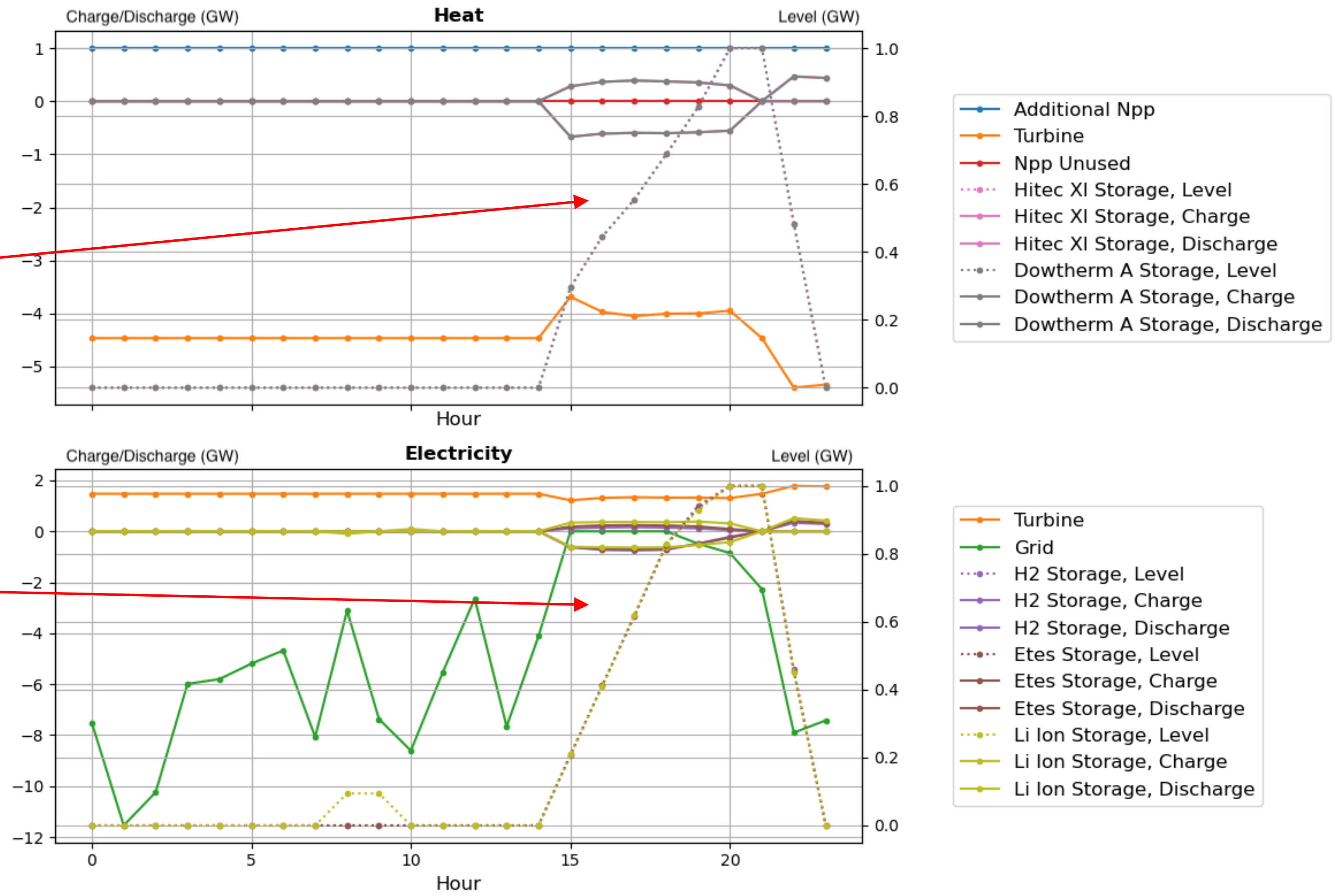
Dispatch Optimization

As the grid fluctuates, electricity and heat are stored during periods of low demand so they can be sold off during periods of high demand.



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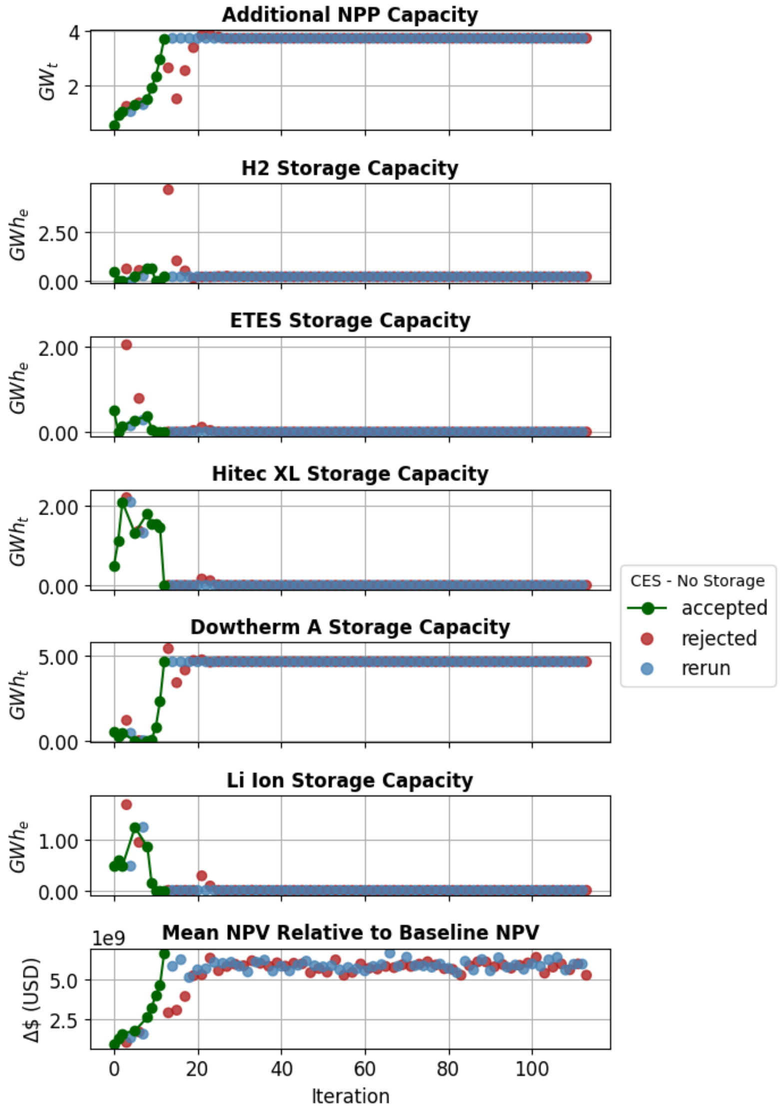
Capacity Optimization

- In the CES scenario, the optimizer quickly builds out the TES capacity
- The profitably builds 5 GWh of Dowtherm A storage
- Installs ~4 GWt (1.3 GWe) of additional nuclear capacity
- The expected NPV is $6 billion higher than the baseline



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Conclusions

- The high construction costs of the TES are potentially cost-prohibitive.
- Minimizing costs and implementing the Clean Energy Standard may allow for profitable TES utilization.

Scenario	Hydrogen Storage GWh_e	ETES GWh_e	Hitec XL GWh_t	Dowtherm A GWh_t	Li-ion GWh_e	Mean NPV $MM	Baseline NPV $MM	Δ NPV $MM	Change %
Reference – No Storage	0.00	0.00	0.10	1.53	0.00	$2,273	$2,347	-$74	-3.16%
Reference – Storage	0.25	0.26	0.41	0.25	0.45	$1,511	$2,034	-$523	-25.73%
CES – No Storage	0.23	0.00	0.00	4.64	0.00	$49,368	$42,662	$6,706	15.72%
CES – Storage	0.54	0.50	0.45	0.43	0.46	$43,835	$43,054	$780	1.81%

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Fiscal Year 2022 Case Studies Using FORCE

Nuclear-Thermal Energy Storage

Problem Statement – Nuclear/TES Use Case

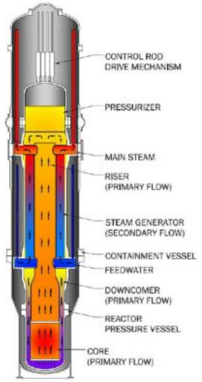
Goal: Demonstrate the Economic and Safety Opportunity of Coupling Advanced Nuclear Reactors with Thermal Energy Storage

Primary Questions:

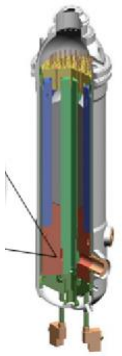
1. **Coupling**
   - What are the current Thermal Storage Technologies?
   - What are the current Advanced Reactors?
   - What systems work best together?
2. **Economics**: Which Markets have the most opportunity?
   - Electricity?
   - Ancillary Products?
   - Constrained Grids?
   - Reduction in Balance of Plant Costs
3. **Control**
   - How do we safely couple and control the units?
   - Dispatch Optimization

Note: Nuclear Industry Engagement Ongoing

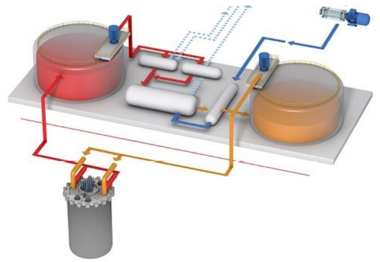
- Westinghouse, TerraPower, Kairos, USNC, and others



Advanced SMR

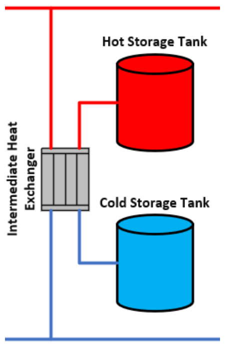


Advanced HTGR



Advanced Sodium Fast Reactor

+

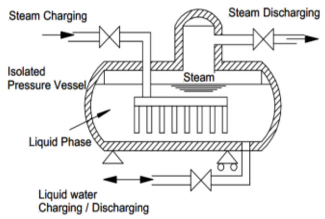


Two Tank Sensible Heat

or

Concrete

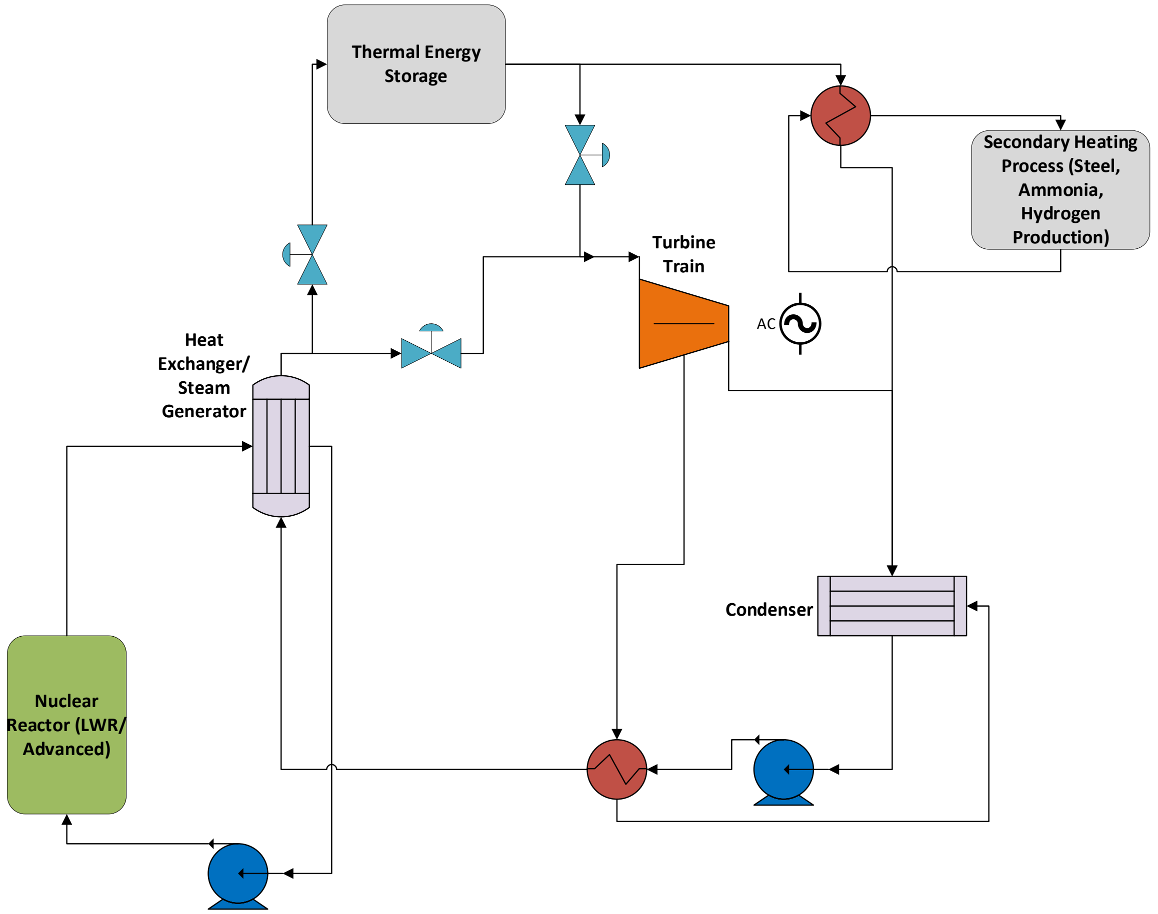
or



Steam accumulator

TES Case Study

1. Selection of the most widely applicable advanced reactor + TES + market configurations
2. Parallel efforts
   - **Economic**:
     - Select a few markets in which to run the analyses of profitability potential.
       - Acquire historical pricing data for these markets.
     - Determine economic factors of the reactor + TES (CAPEX, OPEX, lifetime, MACRS table).
   - **Coupling**:
     - Determine physical integration and control points for optimal **economic** output. (Optimal does not necessarily mean the most efficient.)
3. Run analyses using FORCE
   - HERON
     - Run 30-year technoeconomic dispatch scenarios with a value-at-risk option to determine the optimal sizing of the systems and to ensure a profitability of "x amount" at least "y%" of the time. This value at risk is a new option we are adding to further substantiate claims.
       - Trends are based on the previous 5 years extrapolated forward for 30 years at either (1) a flat rate or (2) based on the linear growth rate of the previous yearly data
       - Timescale dependent on data availability and physical unit capability (hourly, 15 minutes, 5 minutes)
       - Sensitivity study on baseline costs (no carbon credit, flat line, standard CapEx)
         - Sensitivity on costs, carbon credit (based on Canada, $100–200/ton, etc.)
   - HYBRID
     - Demonstrate the coupling mechanisms, control, and transient feedback operations of the coupled systems.
     - Creates the transfer functions that are input into HERON to impose ramp rates and other limitations on the dispatcher.



Nuclear-Carbon Conversion Case Study

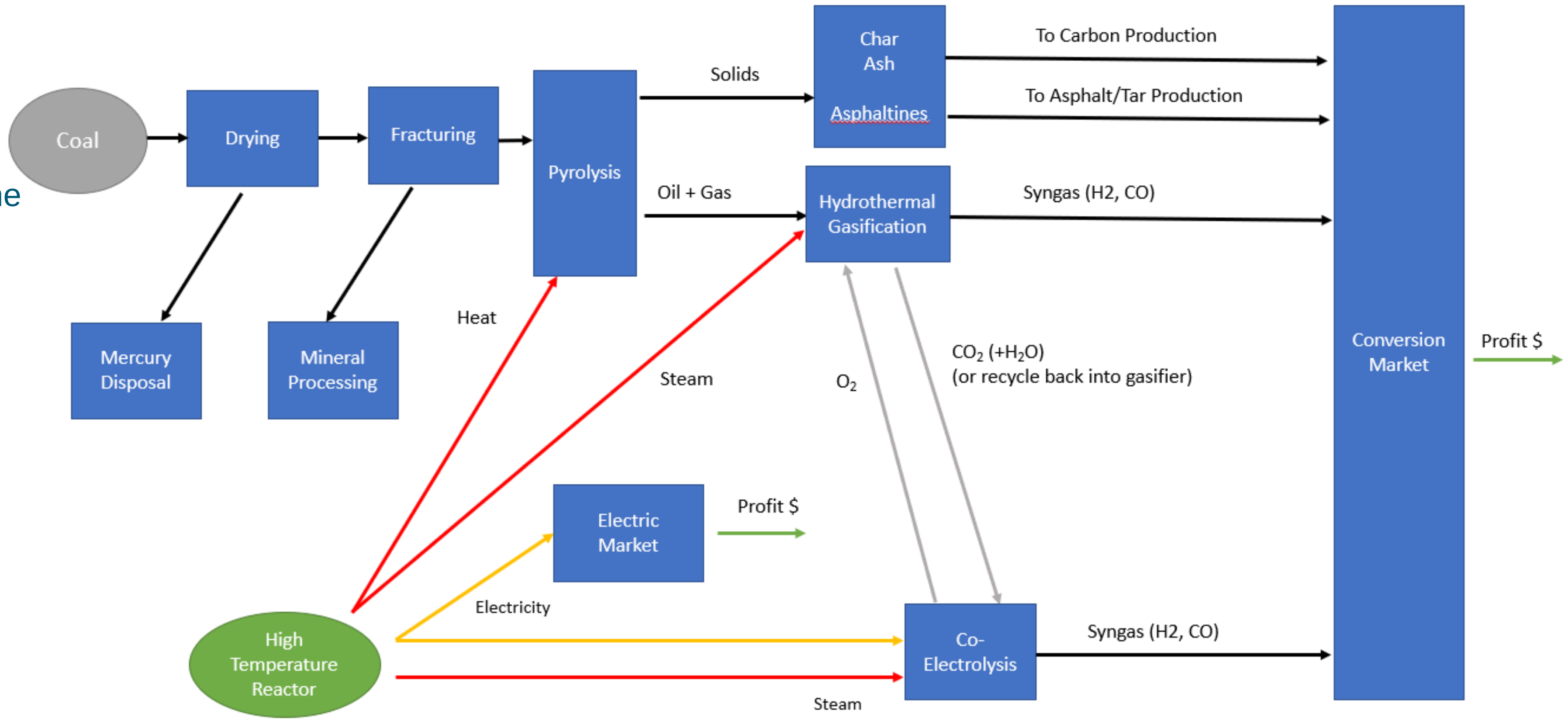
Project Summary

Motivation: To provide a pathway to preserve/transition coal-related jobs and create new jobs associated with the clean energy transition for communities in the Appalachian Region of the United States

- Use an advanced reactor to generate steam, heat, and electricity for a coal conversion plant
- Convert regionally available coal feedstock into:
  - Tar and asphaltene substitutes to produce roof materials and asphalt road mixtures
  - Char to be sold to the conversion market for further processing
  - Syngas, which will be refined to generate products for various markets
  - Recycled CO_2 for producing syngas via co-electrolysis.
- Optimize the chemical process for coal conversion, based on market needs
  - Chemical process optimization done in ASPEN
  - Market optimization done in the FORCE framework
- Use NPV and avoided carbon cost to evaluate cases
  - Optimize electric and hybrid conversion markets
  - Use multiple cases to determine the value of coal markets relative to electricity and hydrogen co-generation, and the value of coal markets both with and without hydrogen production capabilities

Process Design

- (1) Dry coal and drive off as much mercury as possible
  - Immobilize mercury with sulfur and other metals
- (2) Mechanical process to fracture the coal and separate mineral matter
  - Mineral processing
- (3) Pyrolysis
  - Char converted to carbon
  - Low-API tar for roofing materials
- (4) Oil/gas processing
  - Hydrothermal gasification
  - Supercritical water oxidation
  - Plasma gasification
- (5) Syngas refining
  - Methanol
  - Alcohols
  - Polymers



Production of Nuclear-Based Synthetic Fuels

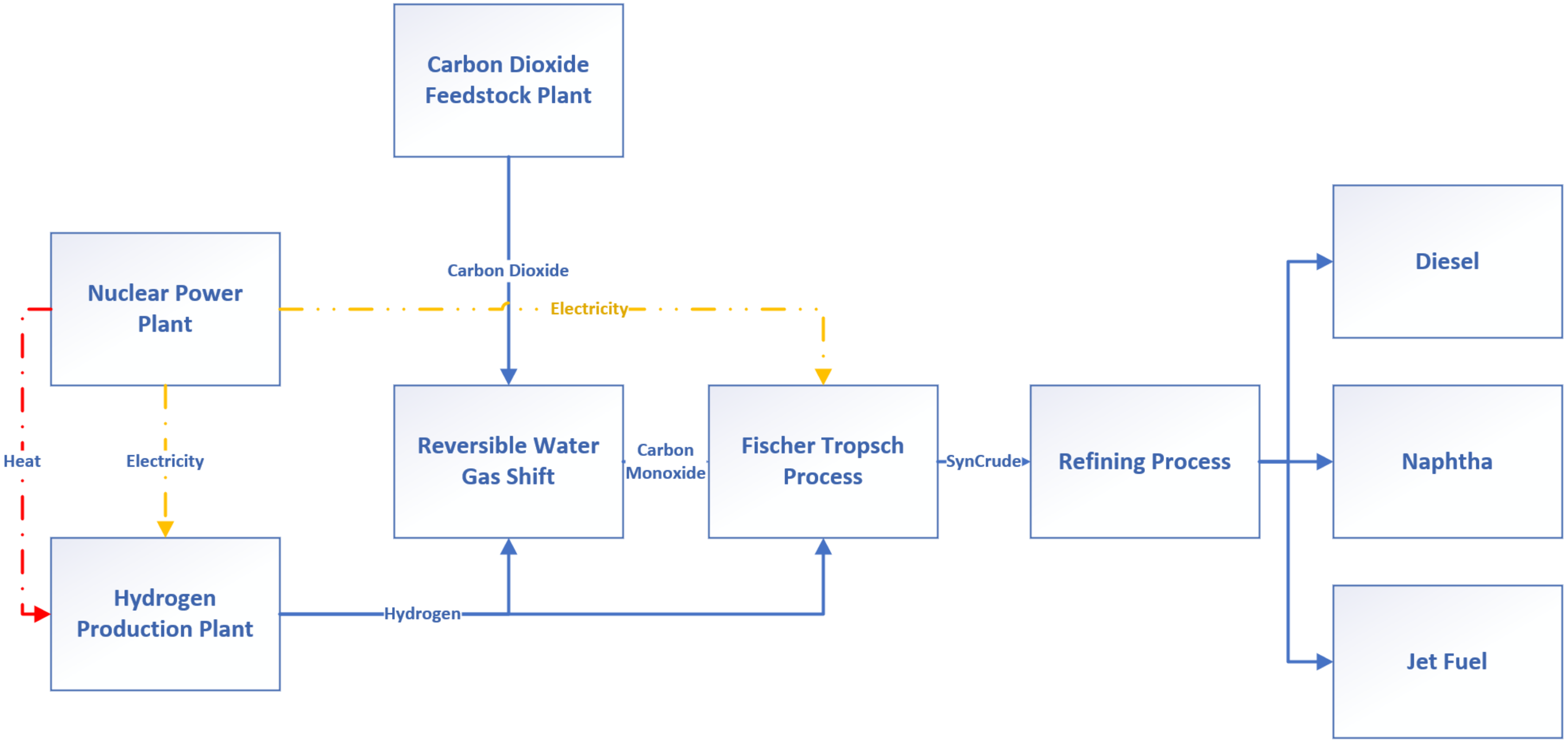
LWRS LIGHT WATER REACTOR SUSTAINABILITY

IES Integrated Energy Systems

Case Study: Advanced Nuclear + SynFuels Analysis

- **Main Question**
  - What is the economic potential of using advanced nuclear reactors for creating synthetic fuels?
- **Other Focus**
  - Demonstrate multimarket participation benefits for advanced nuclear reactors when considering risk metrics
- **Tools**
  - FORCE, which includes HERON, RAVEN, and HYBRID; Aspen Plus/HYSYS; INL Biomass Feedstock Logistics Model
- **Outcomes**
  - Optimized advanced-reactor/synthetic-fuel process, demonstration of proper coupling mechanisms for use with select advanced reactors, transient synthetic fuel models in Modelica

Example of Nuclear Reactor + Synthetic Fuel Production



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Synthetic Fuels Case Study

1. Selection of the most widely applicable advanced reactor + synfuels process + market configurations
2. Parallel efforts
   - **Economic**:
     - Select a few markets in which to run the analyses of profitability potential.
       - Acquire historical pricing data for these markets.
     - Determine economic factors of the reactor + TES (CAPEX, OPEX, lifetime, MACRS table).
   - **Coupling**:
     - Determine physical integration and control points for optimal **economic** output. (Optimal does not necessarily mean the most efficient.)
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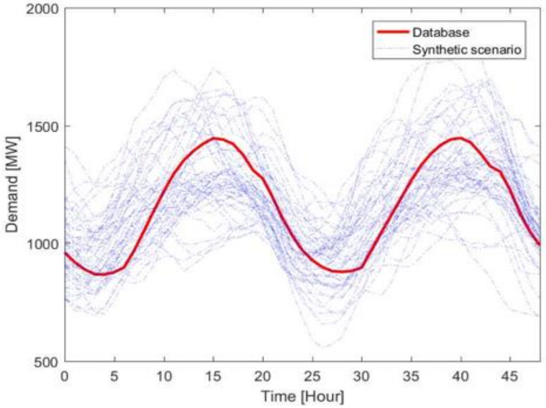

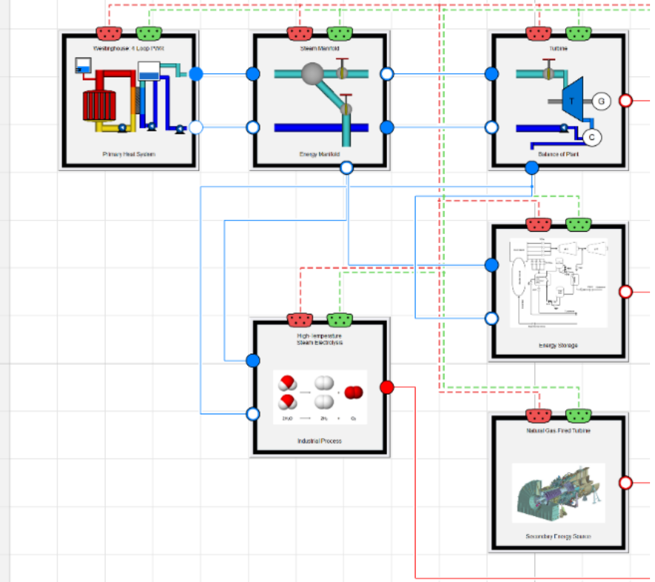

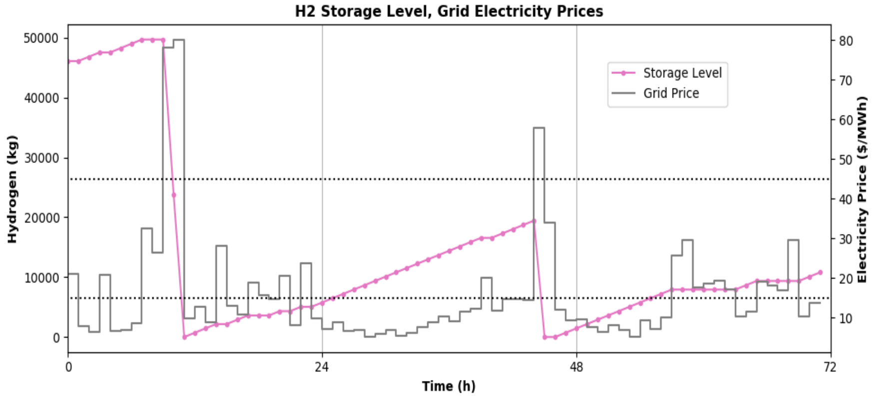

Source: Frick, et al. Applied Energy 306 (2022)

Ongoing CRADA Use Cases

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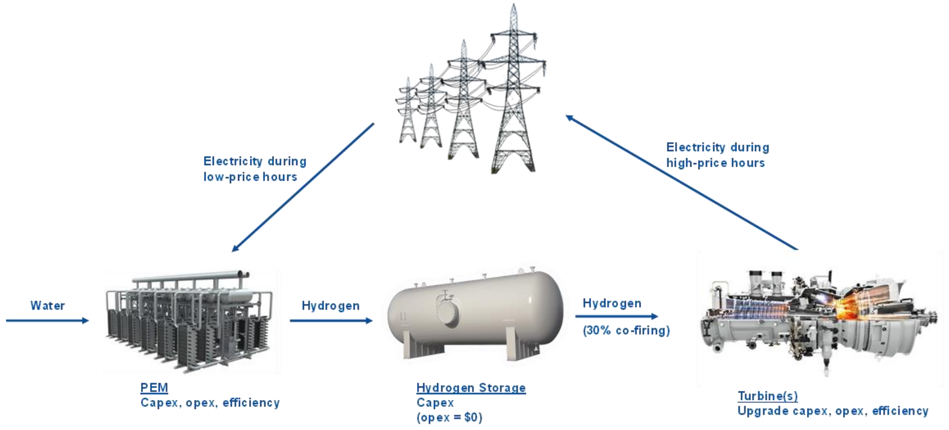
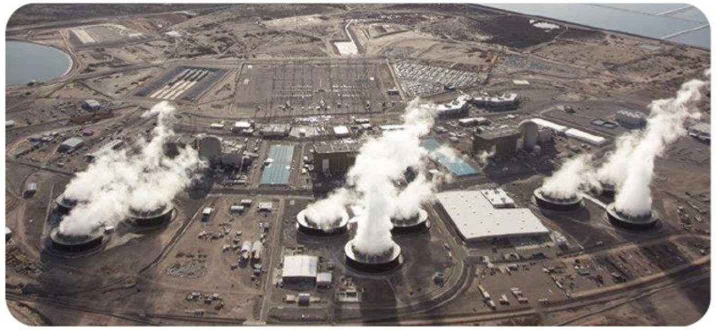
Arizona Public Service – Hydrogen Production

Arizona Public Service

- APS is planning investments in hydrogen production, storage, and utilization for potential grid and non-grid applications
- Hydrogen production alternatives include low-temperature electrolysis with grid power through PEM units, and higher temperature electrolysis at the Palo Verde NPP
- Anticipated uses of FORCE in future phases:
    - Stochastic analysis of hourly electricity prices to evaluate the value of hydrogen energy storage for the grid (RAVEN)
    - Optimal investment sizing and operational decisions regarding hydrogen assets (HERON)
    - Uncertainty in hydrogen capital and operating costs (TEAL)



APS gets $20 million to make hydrogen earmarked for a local peaking plant



APS's Palo Verde plant. (Photo: INL)

Arizona Public Service is the latest nuclear utility with confirmed plans to install hydrogen production capacity, an investment decision that is based on analysis conducted under the Department of Energy's H2@Scale program and backed by a $20 million DOE award.

APS will be able to draw on six metric tons of stored hydrogen produced using low-temperature electrolysis at its three-unit, 4-GWe Palo Verde plant to generate about 200 MWh of electricity

receiving $12 million from the DOE's Hydrogen and Fuel Cell Technologies Office and $8

Source: ANS, *Nuclear News*, Dec. 2021, p. 73

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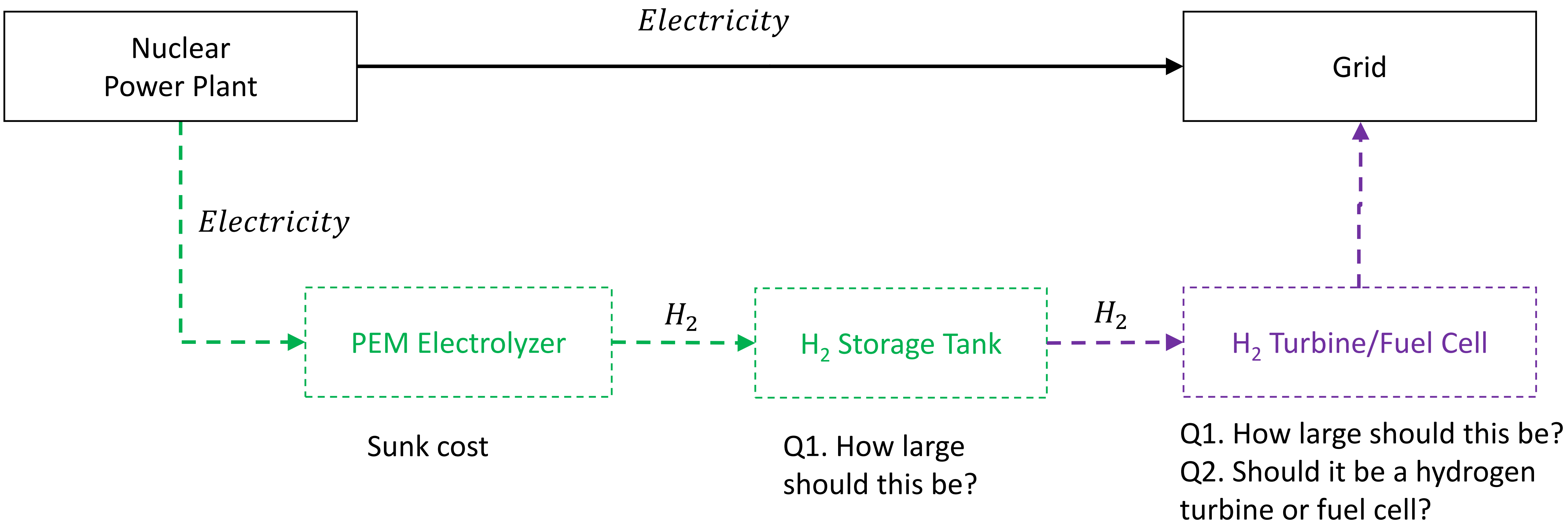
Constellation (Formerly Exelon) – Hydrogen Production for Power Peaking

Constellation Use Case

PEM has been bought via a cost share with DOE.
Excess PEM capacity: Can the NPP be made more profitable by using this hydrogen for power peaking?



Thank you for your attention!