U.S. H2@Scale Vision and Hydrogen Earthshot Goal

Flexible Plant Operation & Generation

PSAM 16 Conference

June 28, 2022

Richard Boardman, Tyler Westover

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Hydrogen is a DOE Priority

- Hydrogen is central to the Department of Energy’s clean energy strategy
- Goal to reduce the cost of hydrogen to $2/kg in by 2025
- DOE Hydrogen Fuel Cell Technologies Office *Hydrogen Earthshot*
  - Announced by DOE Secretary Granholm in 2021
  - Goal to reduce the cost of hydrogen to $1/kg in one decade
- Infrastructure Investment and Jobs Act
  - Signed into law on November 15, 2021 by President Biden
  - Section 813. Regional Clean Hydrogen Hubs
  - Support the development of at least 4 regional hydrogen hubs; Demonstrate the production, processing, delivery,
    storage and end-use of clean hydrogen
  - Each hub eligible for up to $1.25 billion in federal support

Regional Clean Hydrogen Hubs

Feedstock Diversity

At least one hub demonstrating clean hydrogen production from each of the following sources (i.) **fossil fuels**, (ii.) **renewable energy**, (iii.) **nuclear energy**

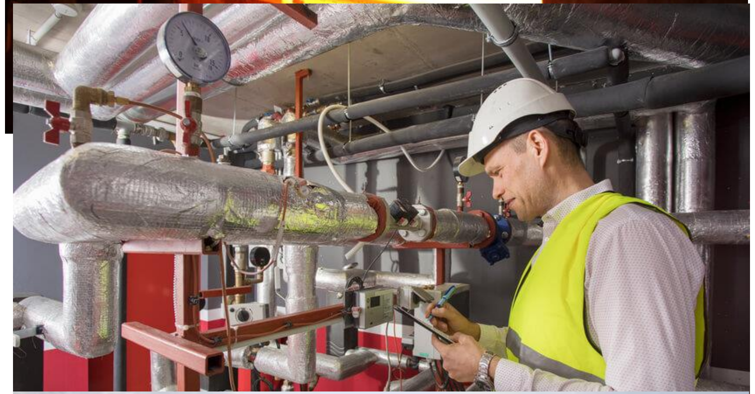
Employment

Priority given to regional clean hydrogen hubs that are likely to create opportunities for skilled training and long-term employment to the greatest number of residents in the region

DEI

Expected that DOE will require a plan for diversity, equity, and inclusion (jobs and improving the quality of life in under served communities)






Regional Clean Hydrogen Hubs

End-Use Diversity

- At least one regional clean hydrogen hub shall demonstrate the end-use of clean hydrogen in:
- Electric Power Generation
- Industrial
- Residential and Commercial Heating
- Transportation

Geographic Diversity

Each regional clean hydrogen hub:

- Shall be located in a different region of the U.S.
- Use energy resources that are abundant in that region

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Integrated Energy Systems with Nuclear
A New Paradigm

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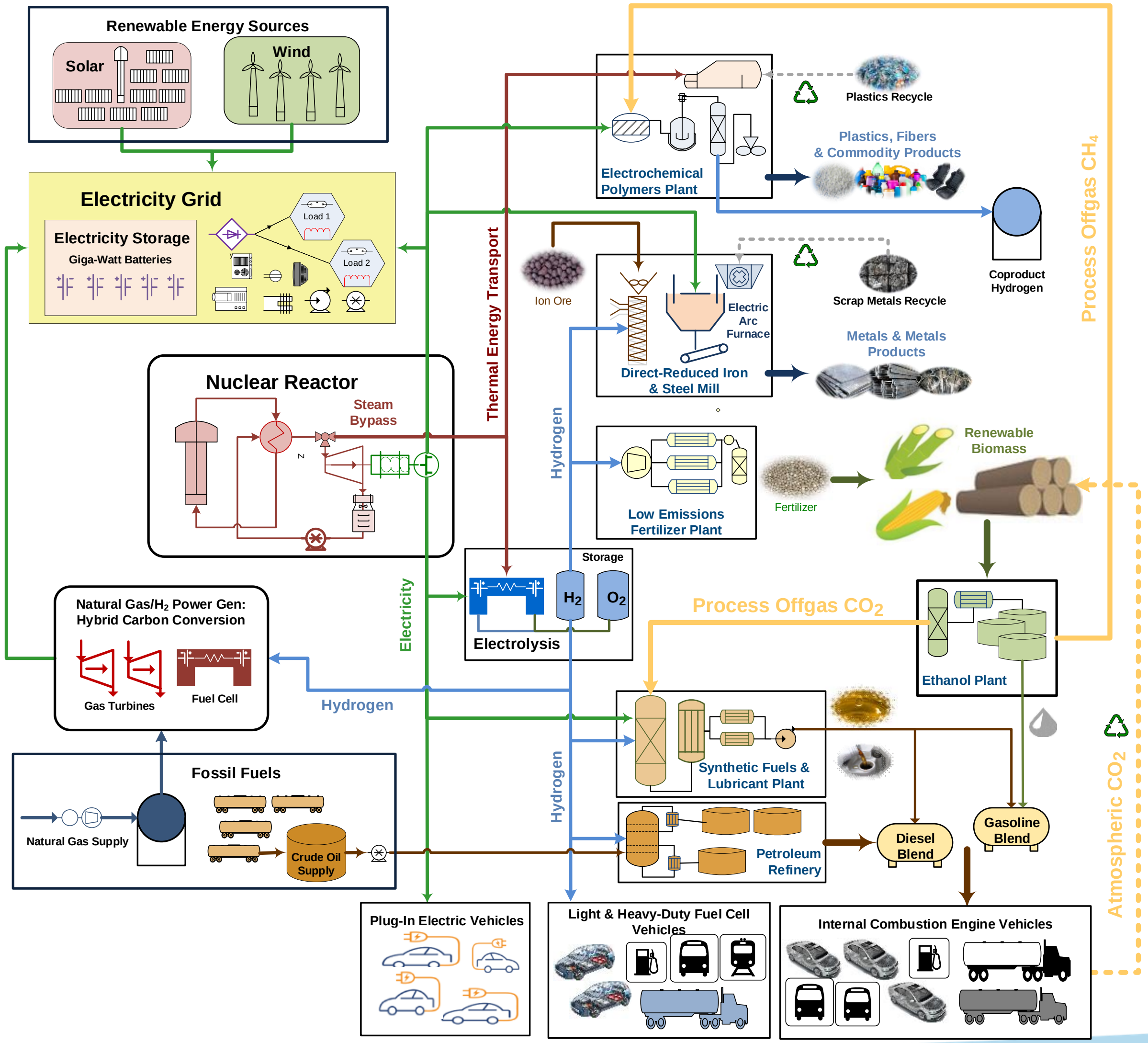
- **The role of hydrogen**
  1. Chemical reactant for hydrogen-bearing products (ammonia, fuels, lubricants)
  2. Reductant used for purification of metals and electronics & CO_2
  3. Clean combustible fuel

- **Target Large Industries**
  - Fuel Cells
  - Power generation
  - Fertilizers (ammonia, urea, phosphate)
    Transportation fuels (drop-in fuels)
  - Fired heaters / Steam boilers
  - Metals production (iron, steel, aluminum)



H2@Scale
U.S. Department of Energy

Argonne NATIONAL LABORATORY

ANL-20/35

Assessment of Potential Future Demands for Hydrogen in the United States

Energy Systems Division

by
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October 2020

NREL

The Technical and Economic Potential of the H2@Scale Concept within the United States

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1 National Renewable Energy Laboratory
2 Idaho National Laboratory
3 Lawrence Livermore National Laboratory
4 Argonne National Laboratory
5 Independent Contractor

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Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-6A20-77610
October 2020

Table ES-1. Serviceable Consumption Potential for Hydrogen Applications

Application	Serviceable Consumption Potential (MMT/yr)	2015 Market for On-Purpose H_2 (MMT/yr)[a]
Oil refining	7	6
Metals refining	12	0
Ammonia	4	3
Biofuels	9	0
Synthetic hydrocarbons	14	1
Natural gas supplementation	16	0
Seasonal energy storage for the electric grid	15	0
Industry and Storage Subtotal	**77**	**10**
Light-duty FCEVs	21	0
Medium- and heavy-duty FCEVs	8	0
Transportation Fuel Subtotal	**29**	**0**
Total	**106**	**10**

Oil refining is rounded from 7.5 MMT/yr to 7 MMT/yr in this table so that the total and subtotals match the sum of the rounded values.

[a] "On-purpose hydrogen" considers consumption of captive hydrogen (produced intentionally by the consuming industry) and merchant hydrogen (produced intentionally for sale), but not consumption of captive byproduct hydrogen production.

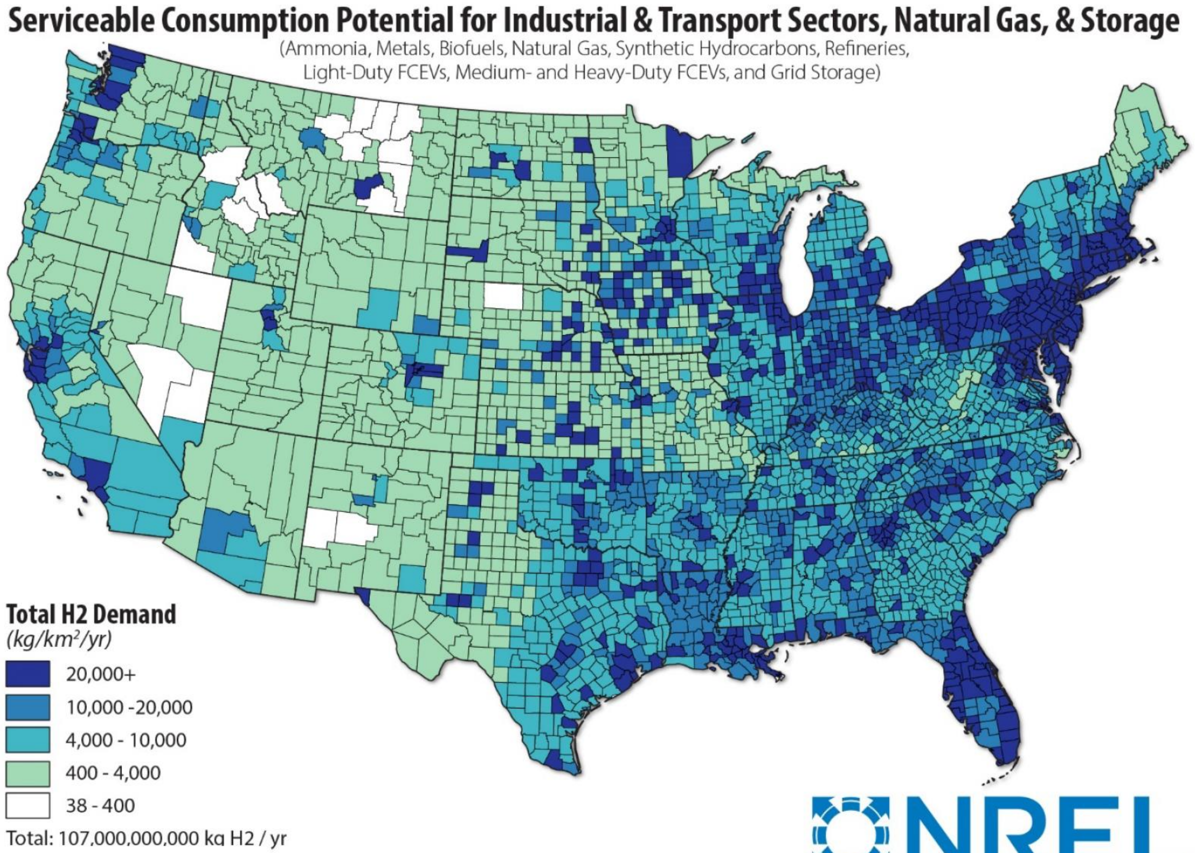


Figure 21. Locations of aggregated serviceable consumption potentials for all hydrogen applications

Table ES-2. Five Scenarios Used to Estimate Economic Potential

Scenario Name	Description
Reference	Current status of hydrogen technologies. Relatively low natural gas prices
R&D Advances + Infrastructure	Same as Reference scenario except with expected cross-sector hydrogen technology improvement and demand growth, fueling infrastructure availability, and robust hydrogen demand for metals
Low NG Resource/High NG Price	Same as R&D Advances + Infrastructure scenario except with higher natural gas prices
Aggressive Electrolysis R&D	Same as Low NG Resource/High NG Price scenario except LTE purchase cost reduced to $200/kW, and LTE receives some compensation for grid support
Lowest-Cost Electrolysis	Same as Aggressive Electrolysis R&D scenario except LTE purchase costs are reduced to $100/kW and wholesale electricity selling prices can be accessed for LTE

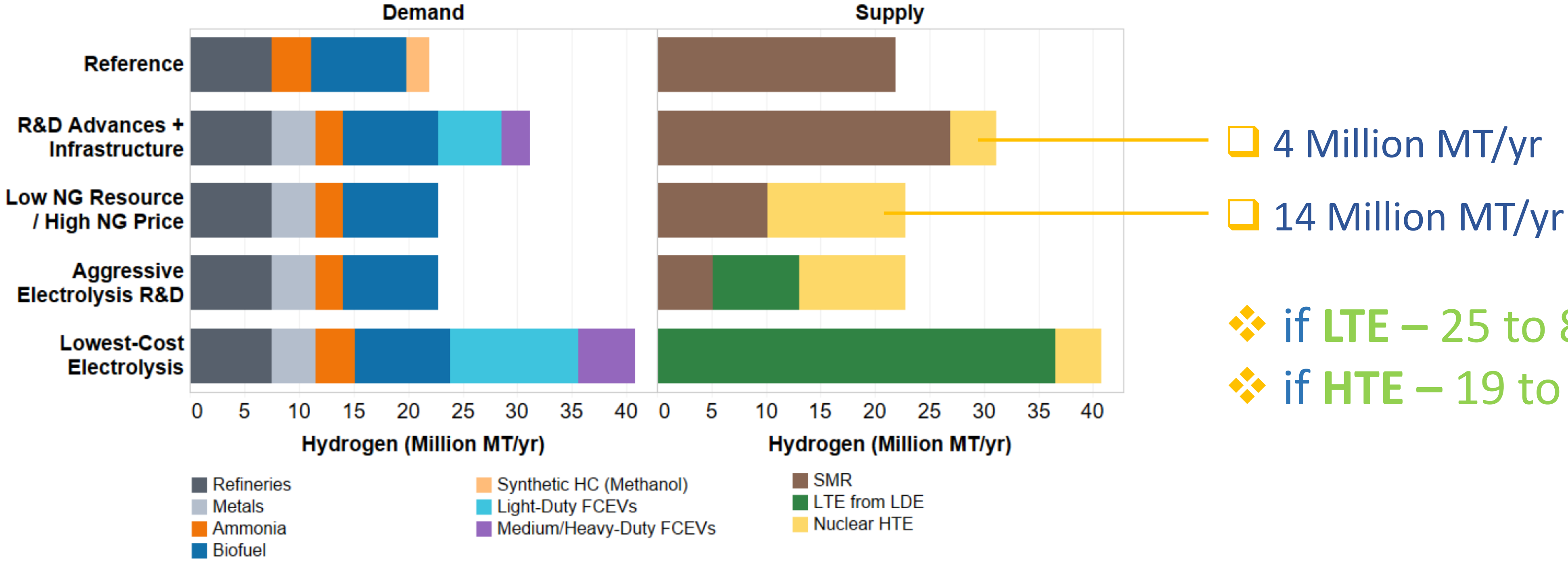
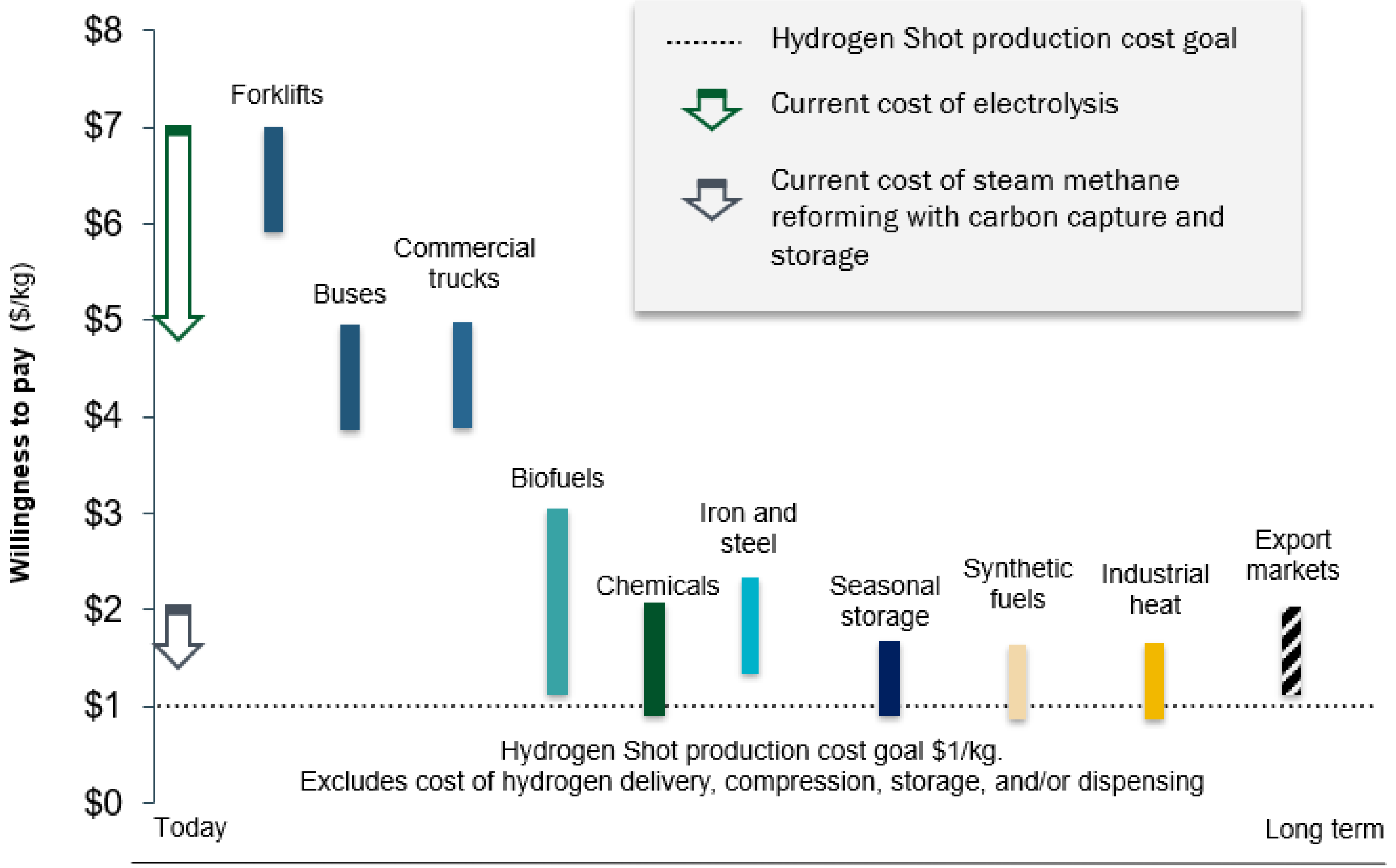


Figure ES-2. Hydrogen supply sources and demand applications for each H2@Scale scenario

- Assume 1 GWe LWR Nuclear Power Plant
- Hydrogen Production Capability:
- Low Temperature PEM Electrolysis:
  475 MT/day; 160,000 MT/yr
- High Temperature Steam Electrolysis:
  625 MT/day; ~210,000 MT/yr

- if **LTE –** 25 to 87 LWR Reactors
- if **HTE –** 19 to 66 LWR Reactors

Threshold Costs for Hydrogen to be Competitive Across Sectors



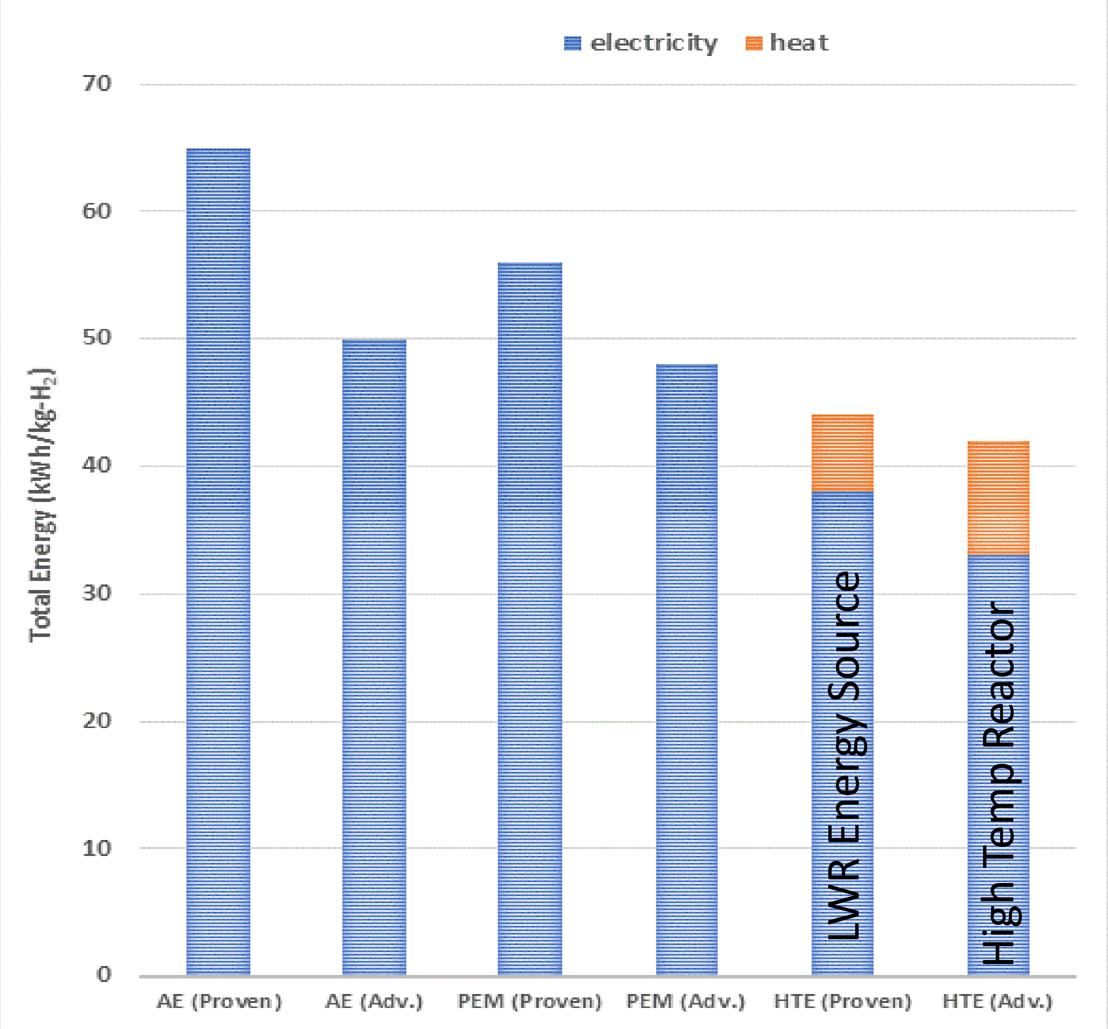
Cost for H_2 to be competitive will vary depending on the cost of incumbent fuels (such as diesel, and natural gas), the performance of end use technologies, and drivers for decarbonization.

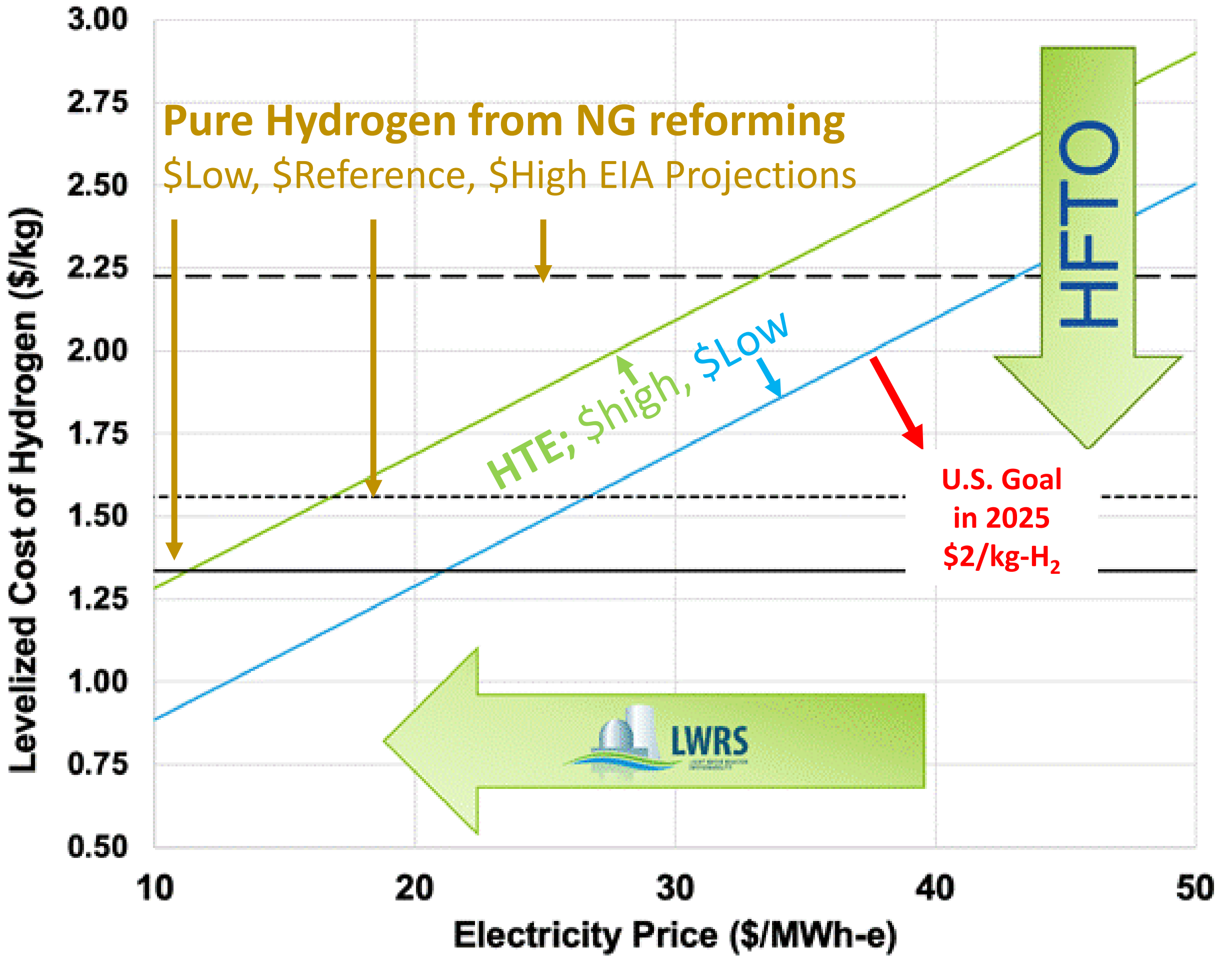
A range of threshold costs, including the cost of production, storage, delivery, and dispensing to the end user, were developed based on previous DOE and industry analyses and stakeholder feedback

Note: Cost represents delivered H_2 cost to end user, includes production, transport and dispensing cost. Hydrogen Shot goal of $1/kg in 1 decade is hydrogen production only.

Slide Credit: Sunita Satyapal- Program Director; Hydrogen and Fuel Cell Technology Office; June 2022 Annual Merit Review

Steam Electrolysis with Nuclear Heat & Power





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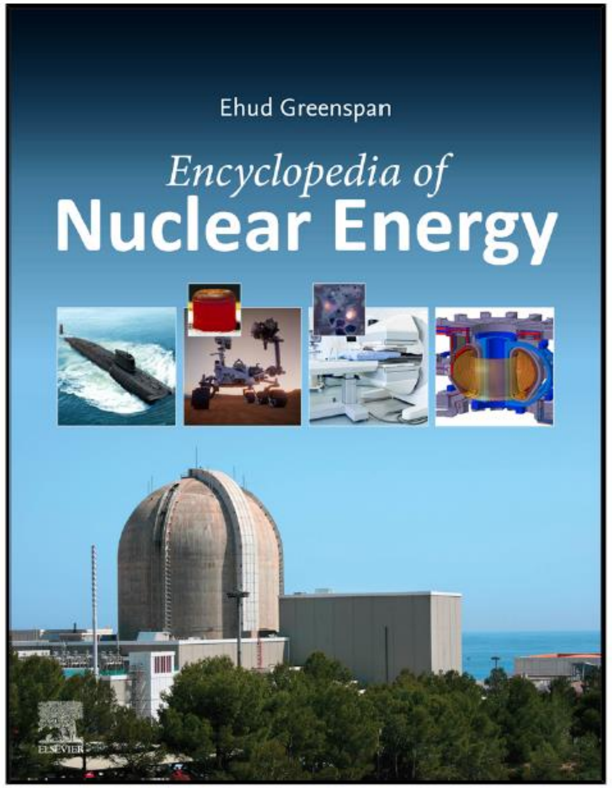
Heat Recovery is key for HTSE



From Boardman, R.D., 2021. High Temperature Steam Electrolysis. In: Greenspan, E. (Ed.), Encyclopedia of Nuclear Energy, vol. 3. Elsevier, pp. 82–93.
https://dx.doi.org/10.1016/B978-0-12-819725-7.00202-6.
ISBN: 9780128197257

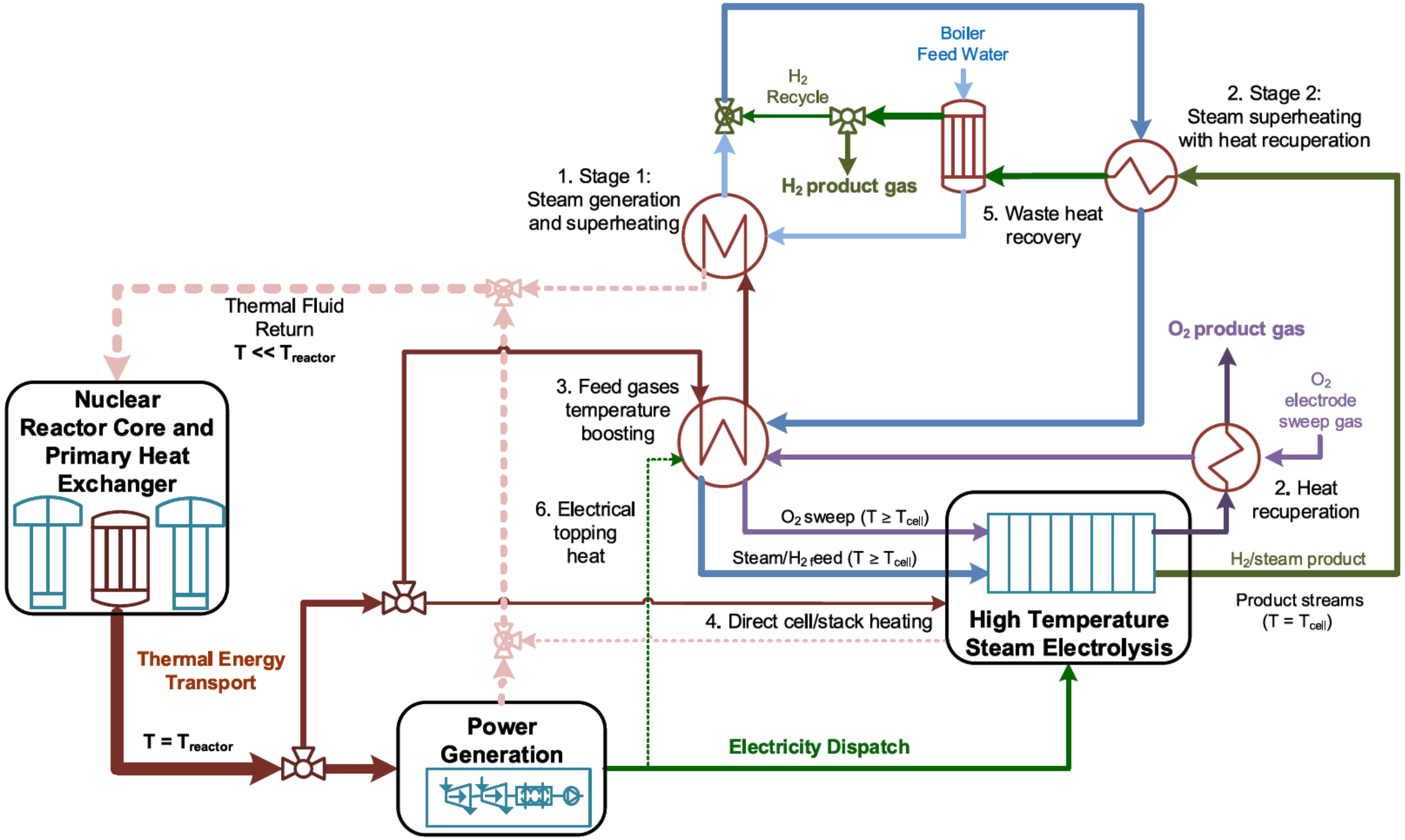


Fig. 7 Coupling of nuclear energy with high temperature steam electrolysis.

Begin with the end goal in mind… 10 or more U.S. Light Water Reactors producing hydrogen by 2030

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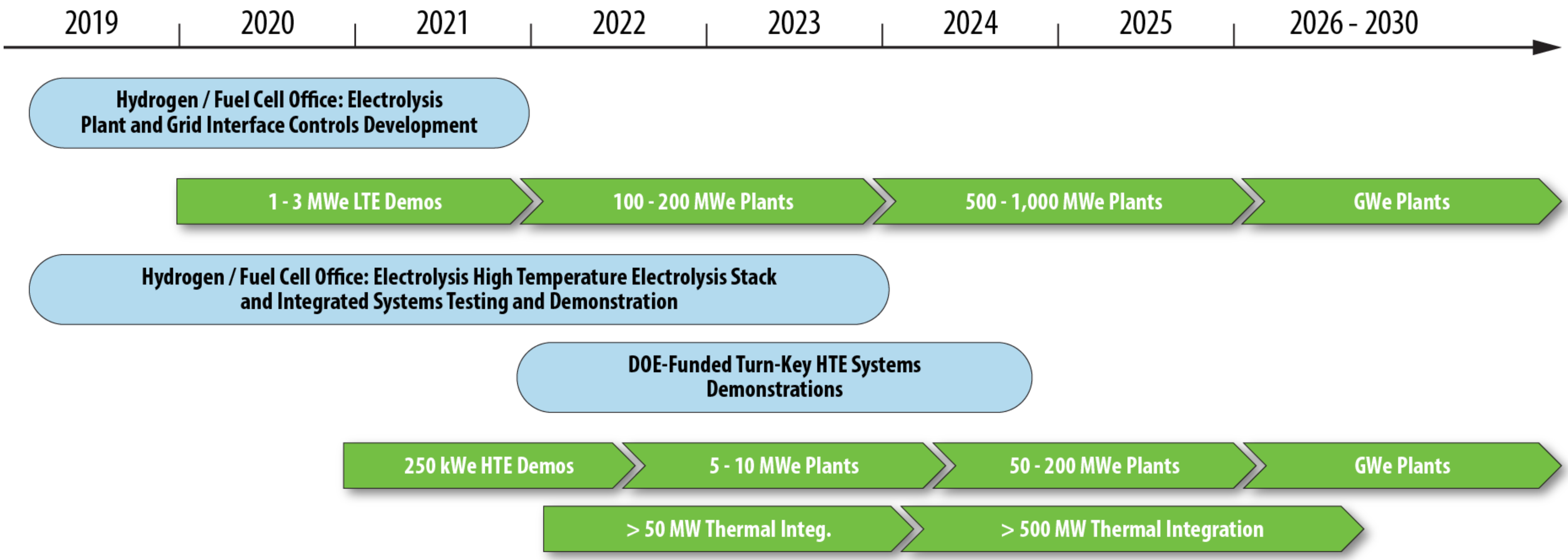


The initial LWRS FPOG Plan remains on track, with a schedule slip of two years for the first pilot-scale demonstration projects; Electrolysis commercial manufacturing is poised to scale up.

Nuclear-H_2 Demonstration Projects

Five projects have been selected for demonstration of hydrogen production at U.S. nuclear power plants (NPP)

- H_2 production using direct electrical power offtake
- Develop monitoring and controls procedures for scaleup to large commercial-scale H_2 plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce H_2 for captive use by NPPs and clean hydrogen markets

Projects

- Constellation: Nine-Mile Point NPP (~1 MWe LTE/PEM)
- Energy Harbor: Davis-Besse NPP (~1-2MWe LTE/PEM)
- Xcel Energy: Prairie Island or Monticello NPP (~150 kWe HTSE)
- APS/Pinnacle West Hydrogen: Palo Verde Generating Station (~15-20 MWe LTE/PEM)
- FuelCell Energy: Demonstration at INL (250 kW)

Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

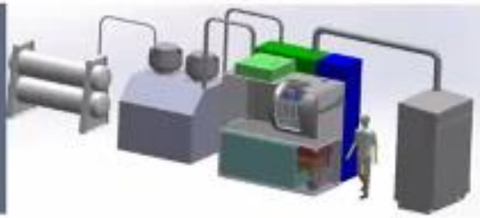
Thermal & Electrical Integration at an Xcel Energy NPP HTSE/SOEC

Prairie Island

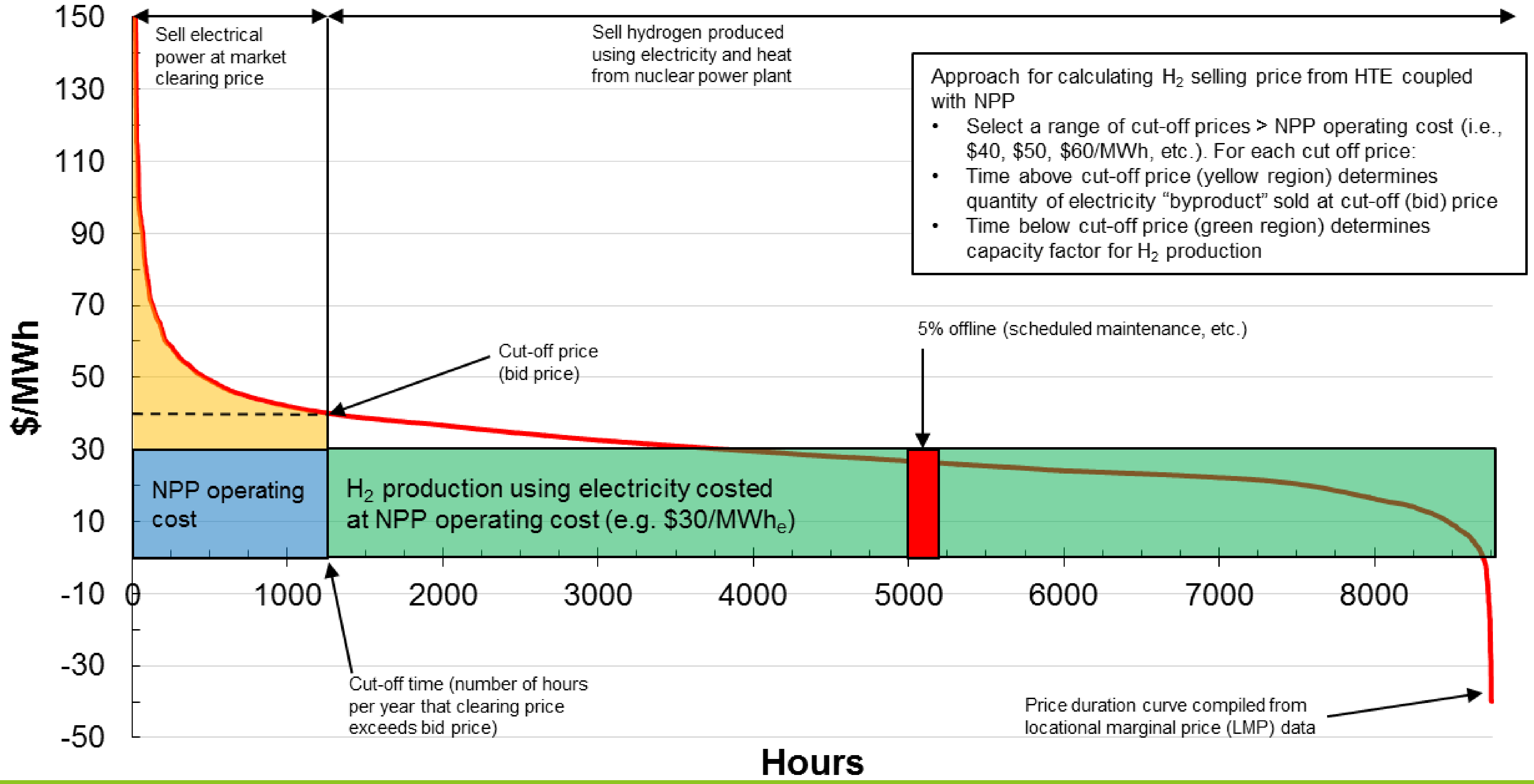
Monticello

Palo Verde Generating Station, H_2 Production for Combustion and Synthetic Fuels

Nuclear energy and solid oxide electrolysis, FuelCell Energy at INL; SOEC

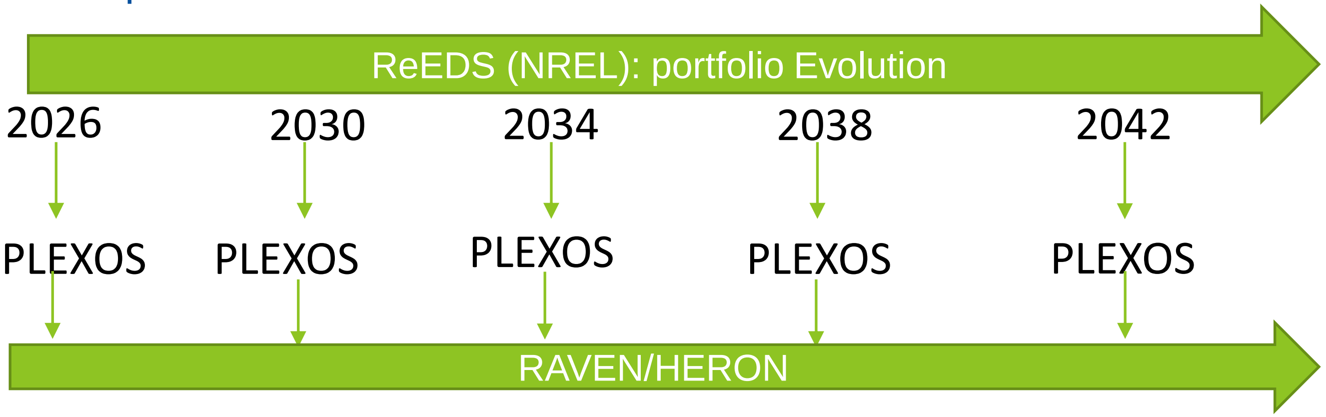


Technical Economic Assessments- Optimizing revenue through dynamic dispatching of electricity

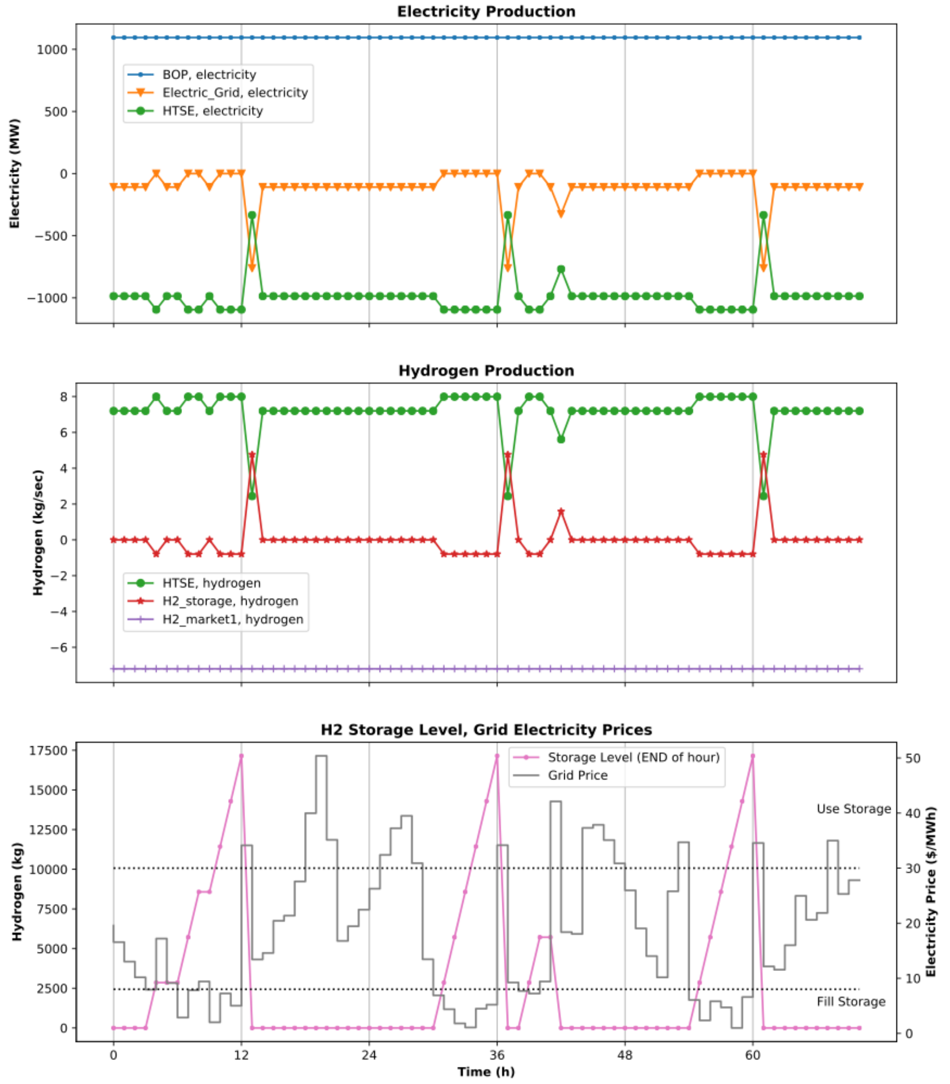


Plant- and Region-Specific Case Analyses by INL and NREL

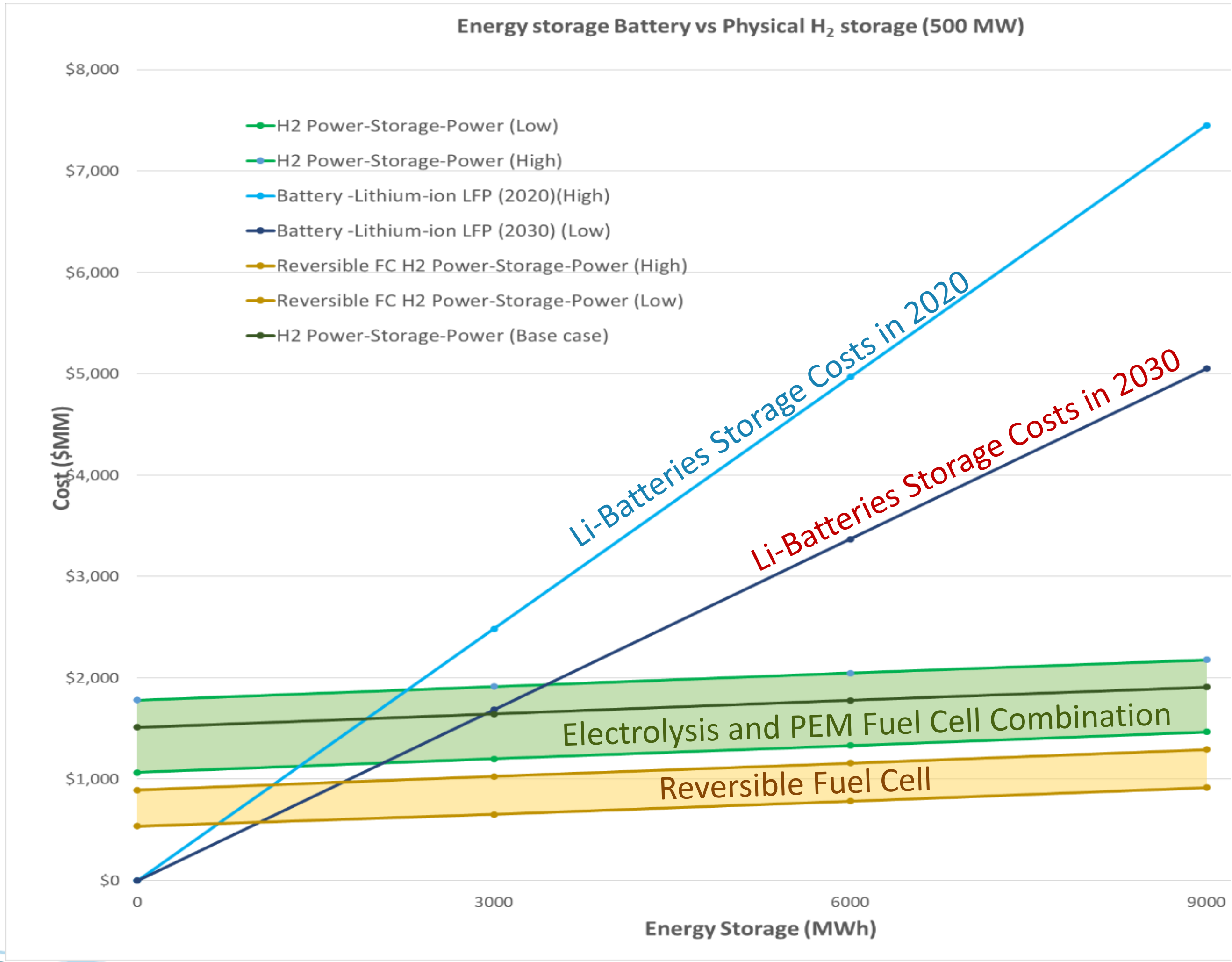
- **Developed method to generate synthetic data for future grid pricing**
  - NREL: ReEDs and PLEXOS used for capacity expansion and discrete time step grid pricing
  - INL: RAVEN/HERON used to generation continuous, hourly grid price data



- **Developed time-dependent physical models of nuclear plant and hydrogen production systems**
  - Dispatch power between grid and hydrogen production to optimize revenue
  - Optimized hydrogen plant and storage capacity based on discounted cash flow economics



LWR Plant Hydrogen Production and Electricity Dispatch Schedule



Hydrogen outcompetes Li-Ion batteries when storage capacity is:

- ***>1,500 MWh for a reversible fuel-cell***
- ***>3,000 for an electrolysis with PEM fuel cell***

Idaho National Laboratory