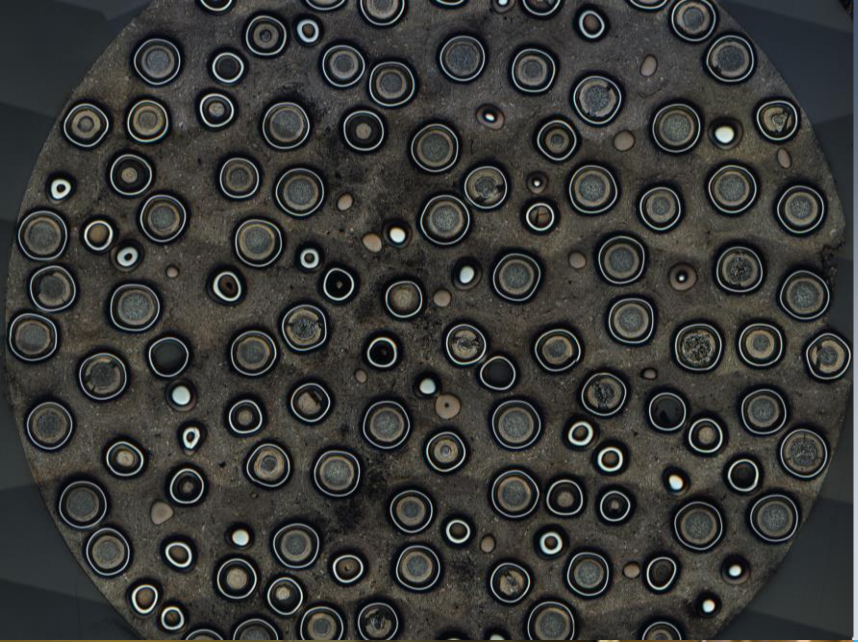
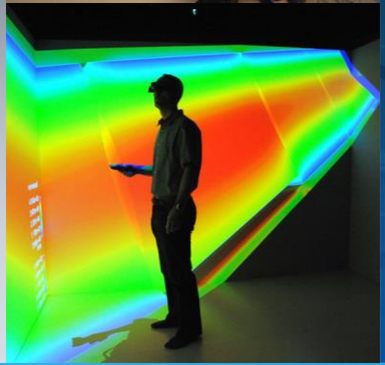
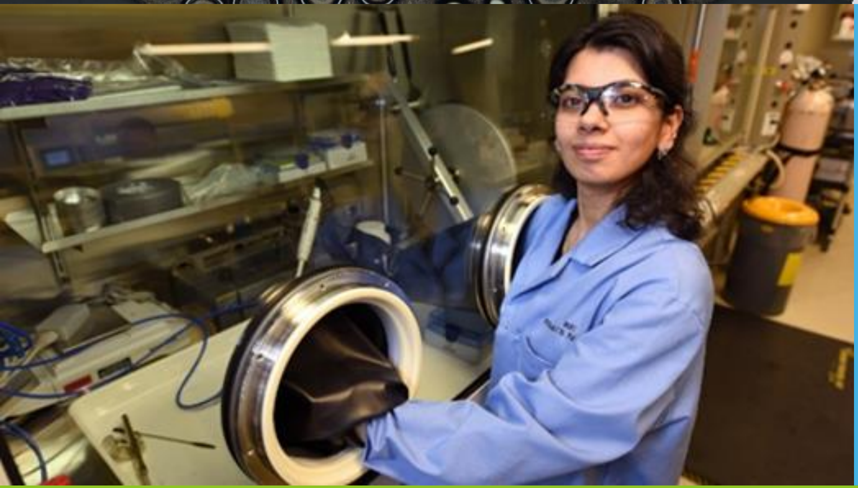


Richard Boardman, Ph.D. ChE



Ammonia: A New Business for Nuclear Energy

Idaho National Laboratory

Summary

- Advanced Nuclear Reactors
  - Small, Medium, and Large
  - Coolant: Light Water: ~325 °C; Liquid Metal: ~450-550 °C,
  - Molten Salt ~600-750 °C; High Temperature Gas 750 - 900°C
- Hydrogen production at an existing nuclear plant: Electrical AND Thermal power integration
- Four demonstration projects announced with cost-share from

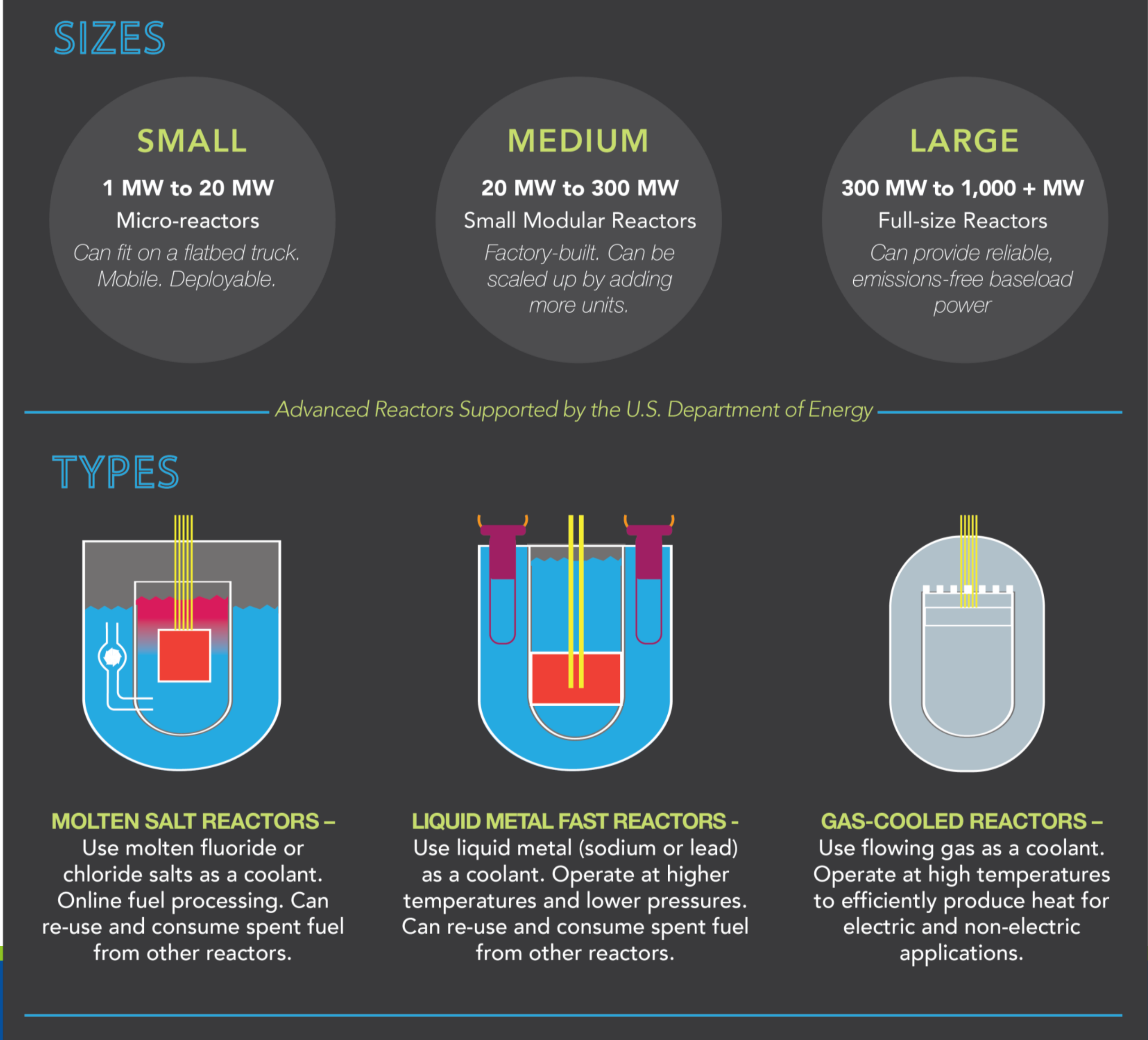
  US Department of Energy
  - Small-scale demonstrations
  - Technical & Economic Assessment (TEA)
  - Scale up to commercial operations
- Integration of nuclear reactors with ammonia plants
  - Conventional ammonia plant
  - Electrolysis for production of hydrogen (two options)

Advanced Reactor Design Concepts

Benefits:

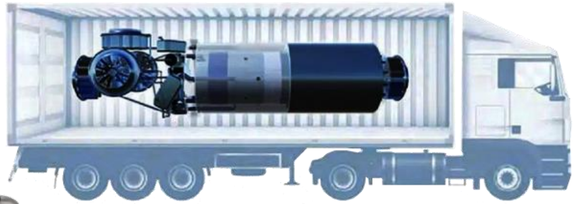
- Enhanced safety
- Versatile applications
- Reduce waste
- Use advanced manufacturing to save money

60+ private sector projects under development



Accelerating advanced reactor demonstration and deployment

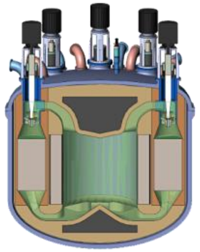
MARVEL
DOE
2022-2023



Project Pele Microreactor
DoD
2023-2024

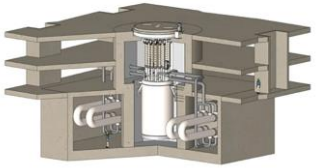
DOME Test Bed
NRIC
2023-2024

LOTUS Test Bed
NRIC
2024



MCRE
Southern Co. & TerraPower
2025

TerraPower
Southern Company

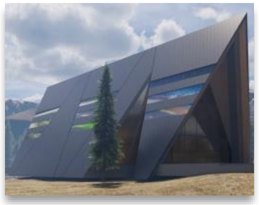


Hermes
Kairos
2026

Kairos Power

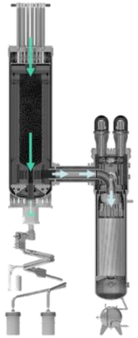
Aurora
Oklo Inc.
TBD

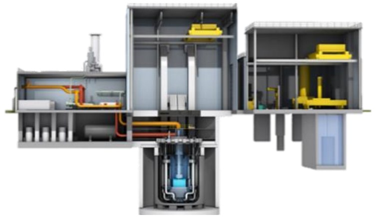
OKLO



Xe-100
X-energy
2027

energy





Natrium Reactor
TerraPower & General Electric
2028

TerraPower
HITACHI

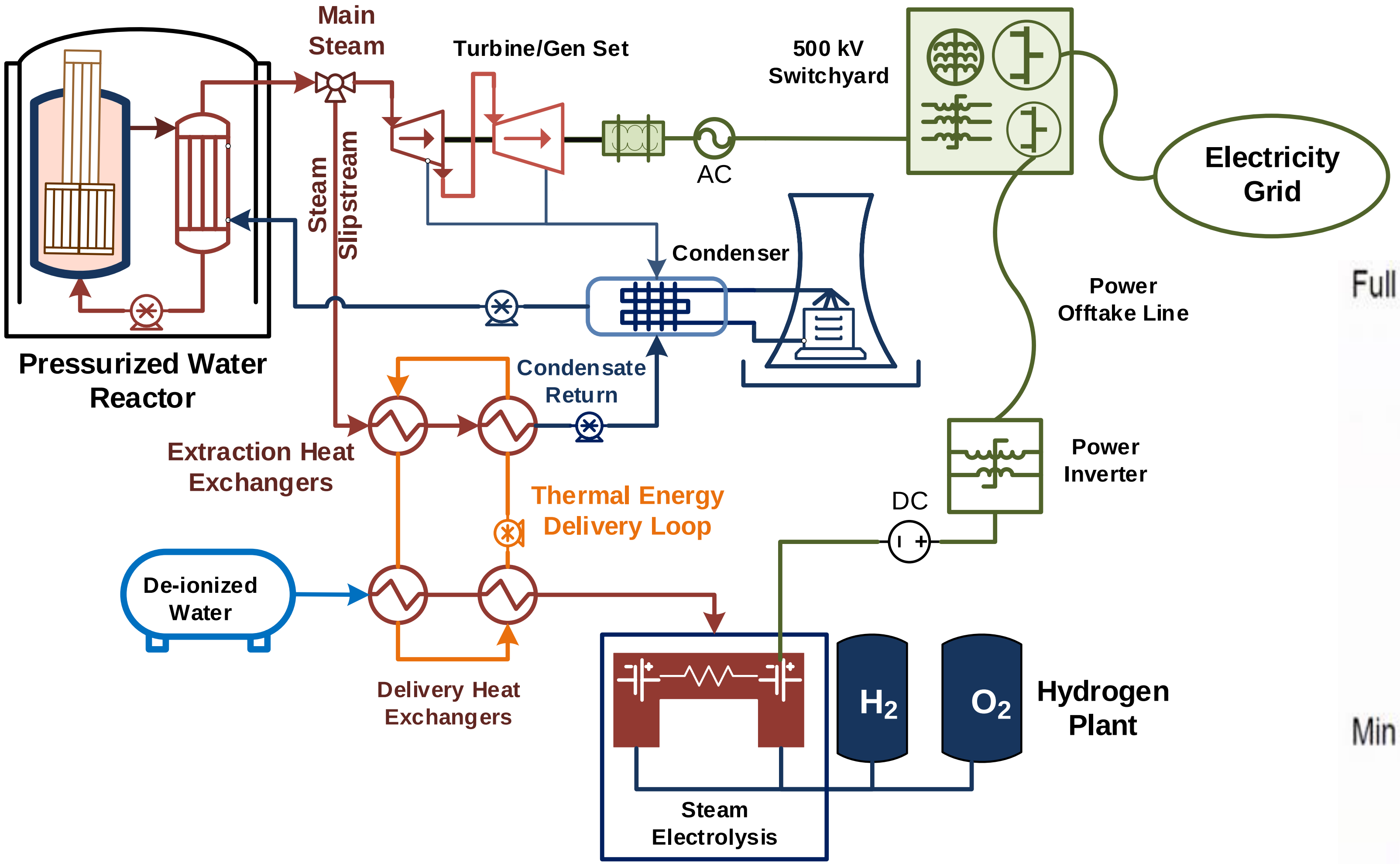
2030

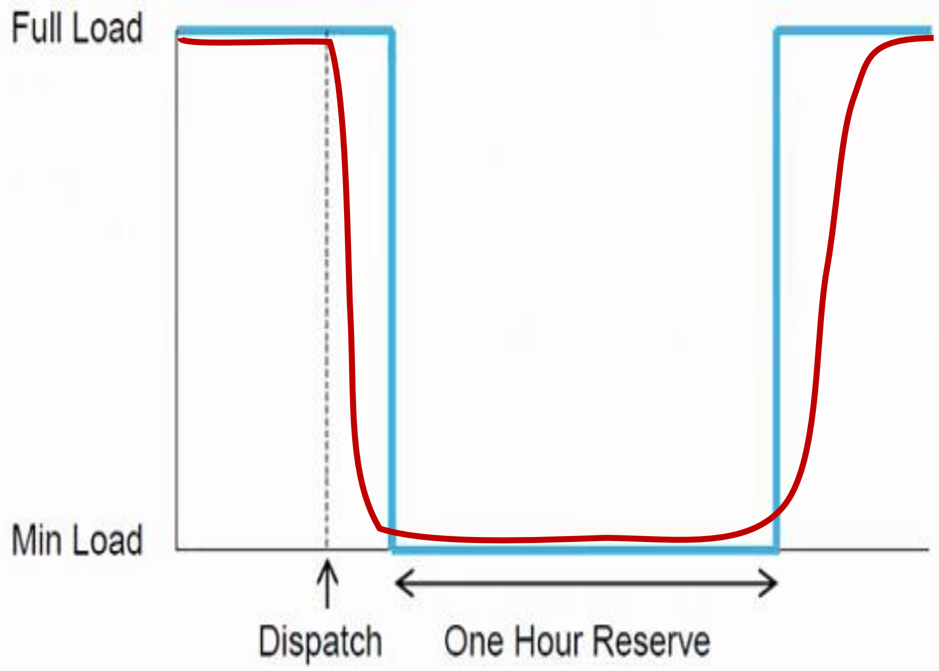
SMR
UAMPS &
NuScale
2029

UAMPS
NUSCALE

NRIC National Reactor Innovation Center

Electrolysis while dispatching as spinning or non-spinning reserves





Dynamic Energy Transport and Integration Laboratory (DETAIL)

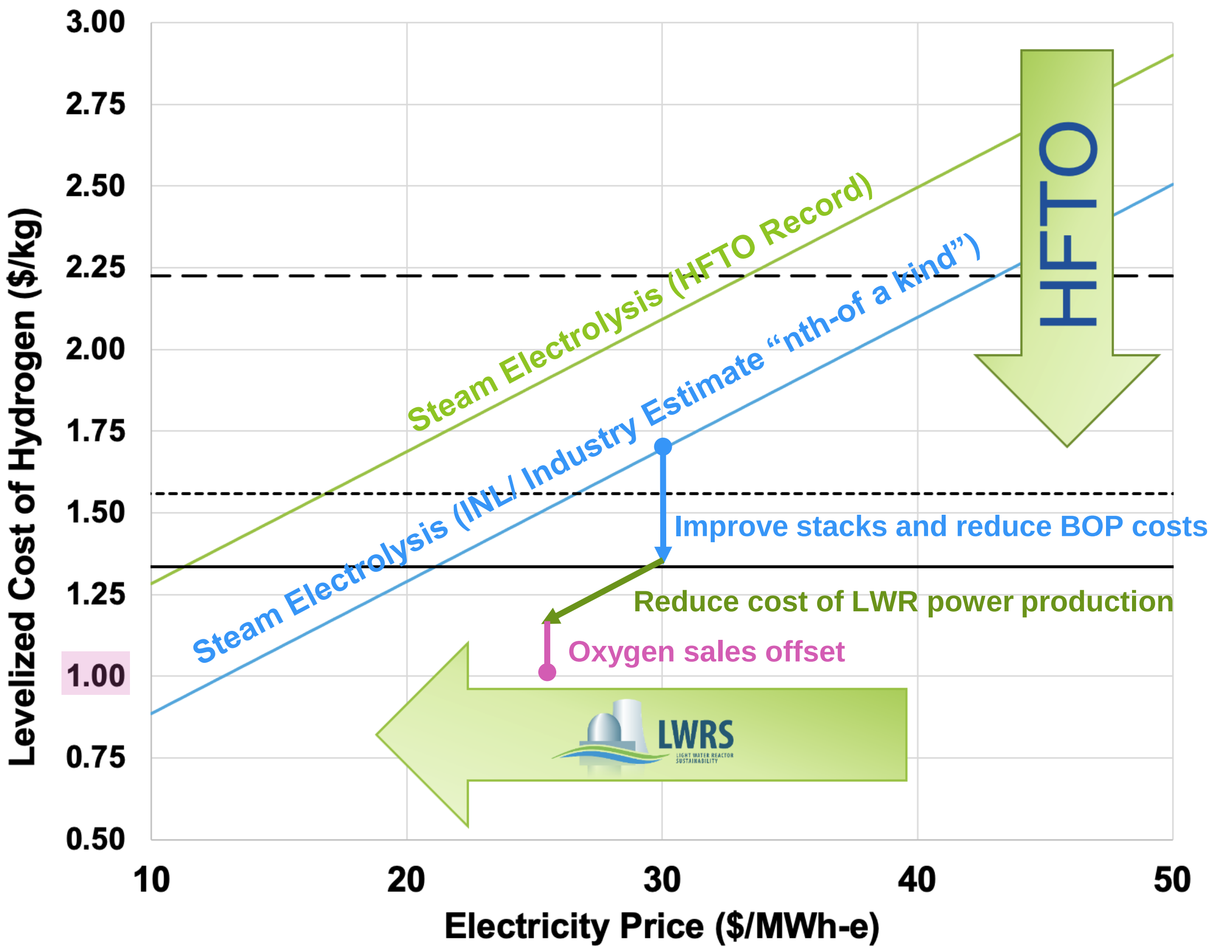
Integrated Plant Simulator with Human-in-the-Loop

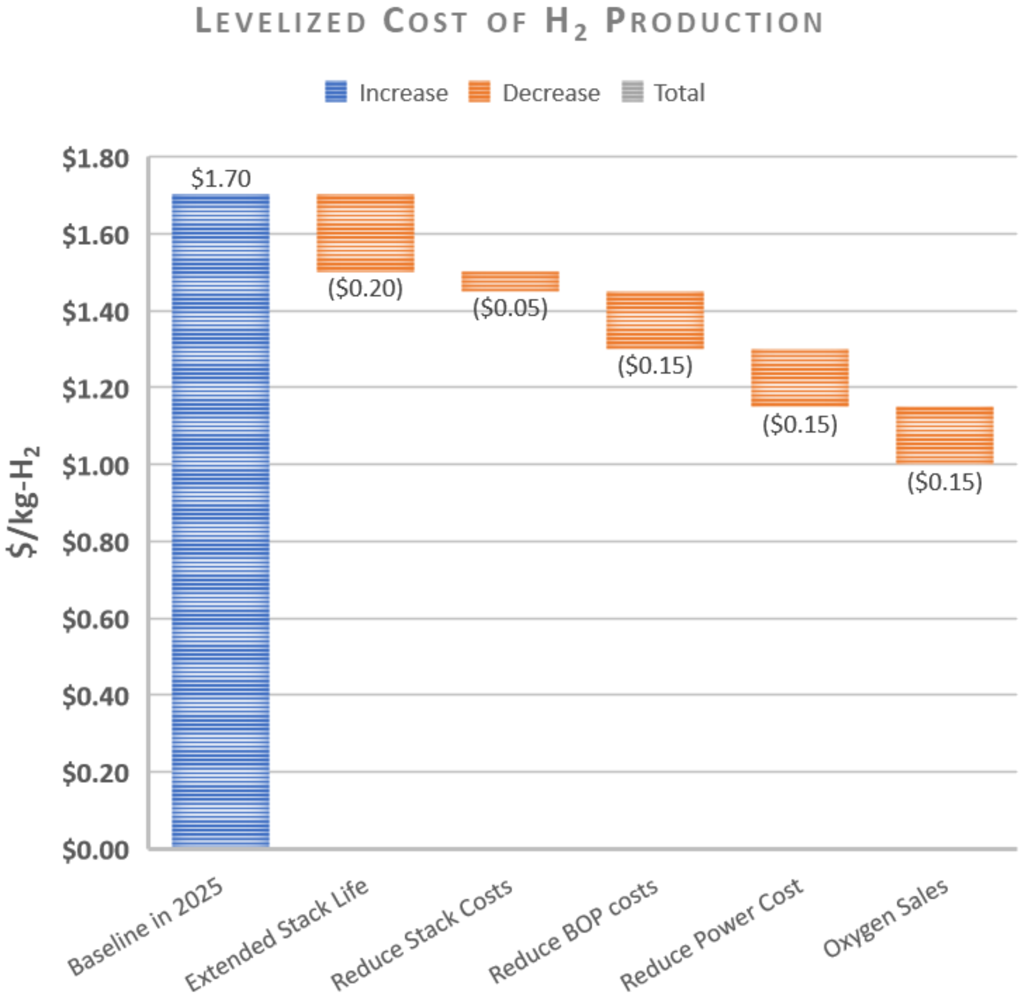
Power Hardware and Grid-in-the-Loop

Dynamic Hydrogen production

Thermal Energy Generation and Transport

Two paths to H_2 Earthshot Target
($1/kg-$H_2$ within a decade)





Joint EERE-NE H_2 Production Demonstration Projects

Four projects have been selected for demonstration of hydrogen production at nuclear power plants

- Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant
- Develop monitoring and controls procedures for scaleup to large commercial-scale hydrogen plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce hydrogen for captive use by NPPs and first movers of clean hydrogen

Projects:

- Exelon: Nine-Mile Point NPP; LTE/PEM Vendor 1; using “house load” power; PEM skid testing is underway at NREL; H2 production beginning ~Jan. 2022
- Energy Harbor; LTE/PEM Power provided by completing plant upgrade with new switch gear at the plant transmission station; installation to be made at next plant outage; contract start anticipated by Oct. 2022
- Xcel Energy: HTE/SOEC Project negotiations are being finalized. Tie into plant thermal line engineering is being planned; Project start anticipated around Jan. 2022.
- Pinnacle West Hydrogen: LTE/PEM with hydrogen combustion; demonstration of synfuels production.

Davis-Besse Nuclear Power Plant LTE-PEM

Nine Mile Point Nuclear Power Plant LTE/PEM

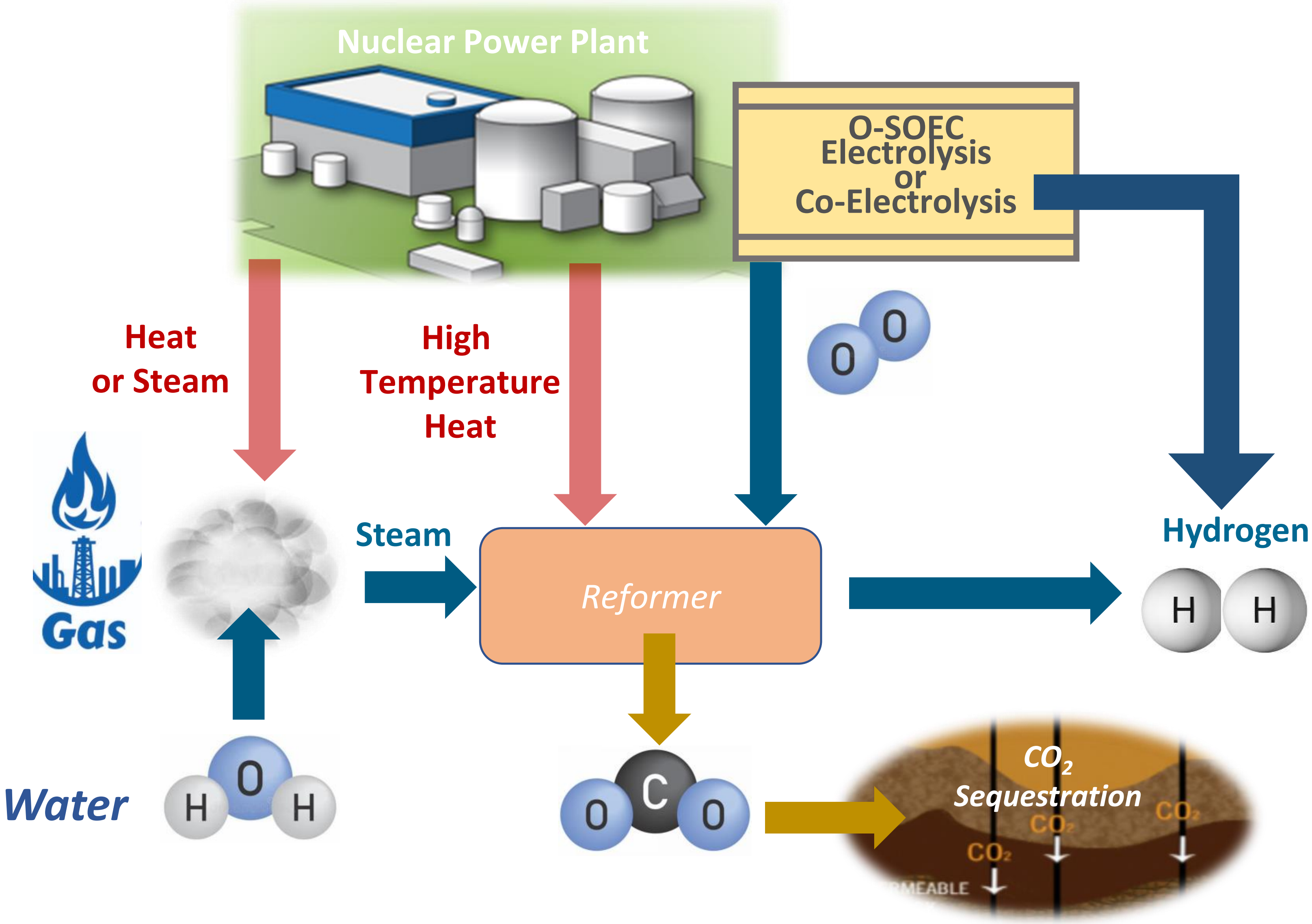
Thermal & Electrical Integration at an Xcel Energy Nuclear Plant

Prairie Island

Monticello

Hydrogen Production for Combustion and Synthetic Fuels

Synergies between nuclear and steam-methane reforming



- Steam generation
- Preheat natural gas
- Flameless reformer with very high temperature gas-cooled reactor (>900°C ROT)

- Oxygen from high temperature steam electrolysis
- Power for CO_2 compression and sequestration

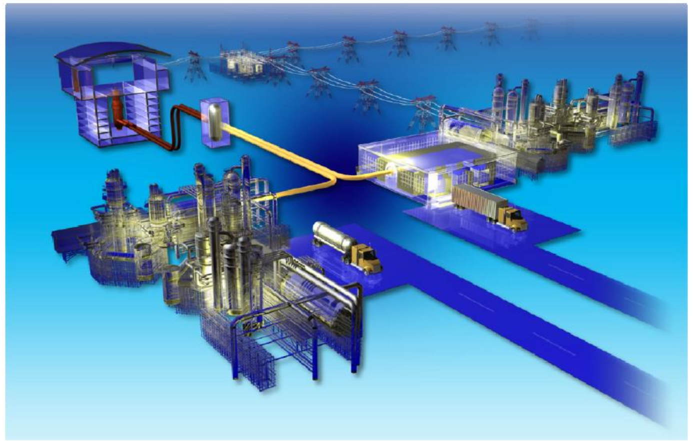
- GAPS:
  - Heat integration
  - Efficient CO_2 separation

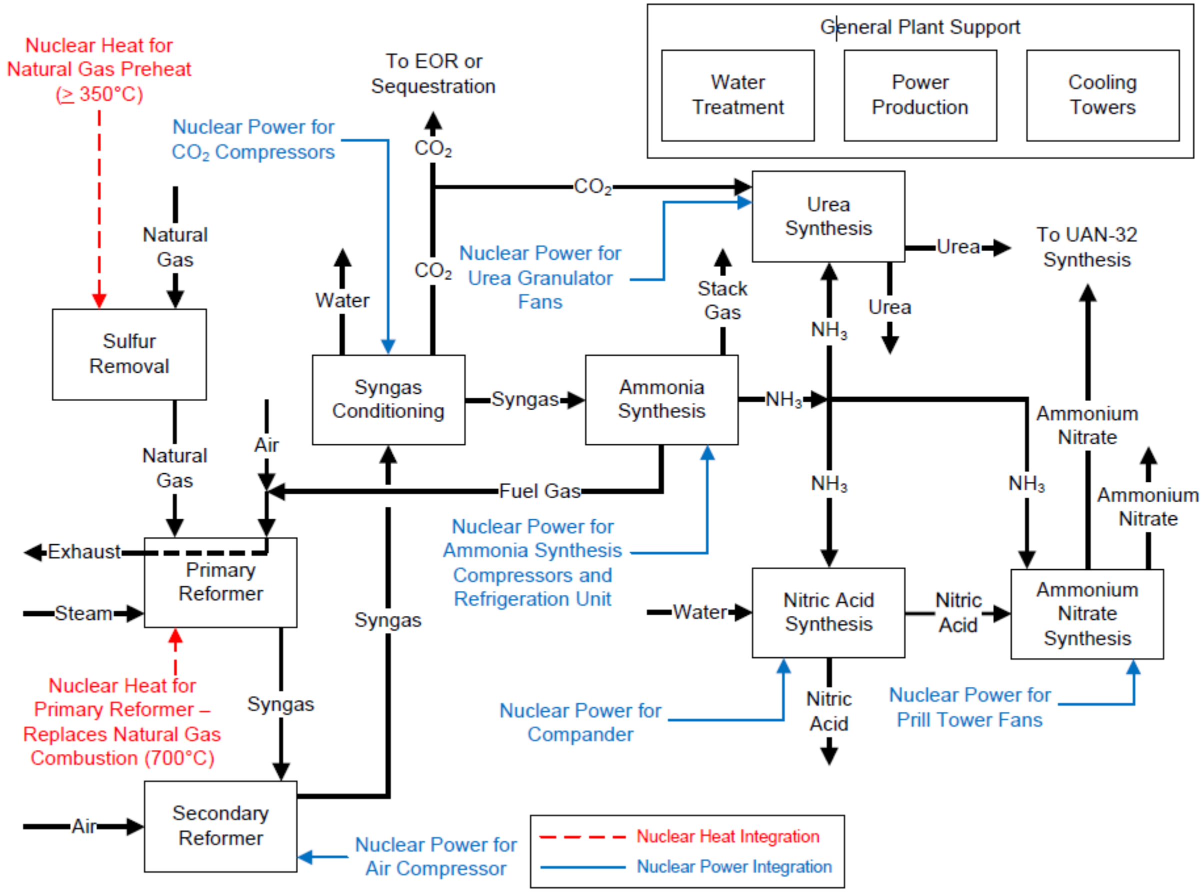
Ammonia Production with a Very High Temperature Gas-Cooled Reactor / Steam Methane Reforming Process Block-Flow Diagram

Technical Evaluation Study

Project No. 23843

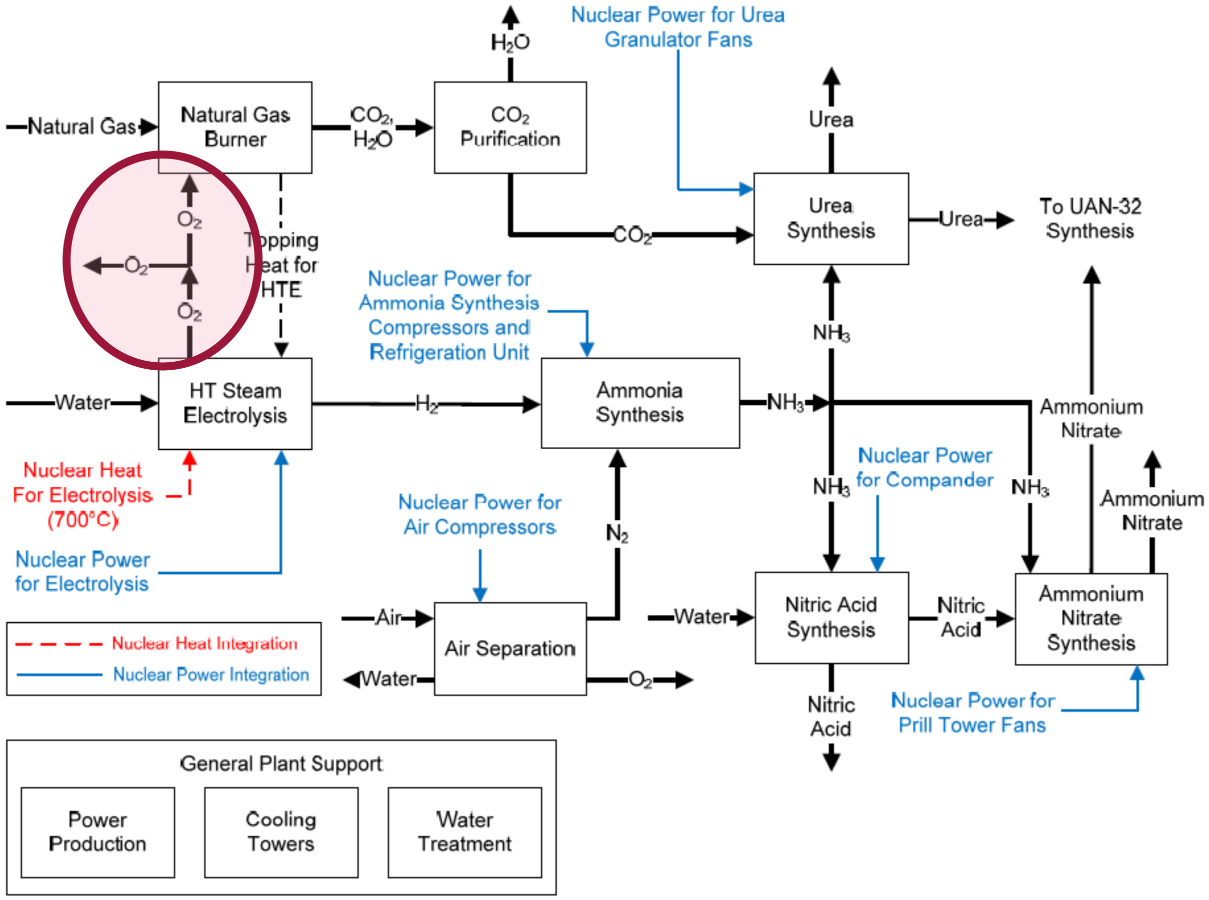
Nuclear-Integrated Ammonia Production Analysis



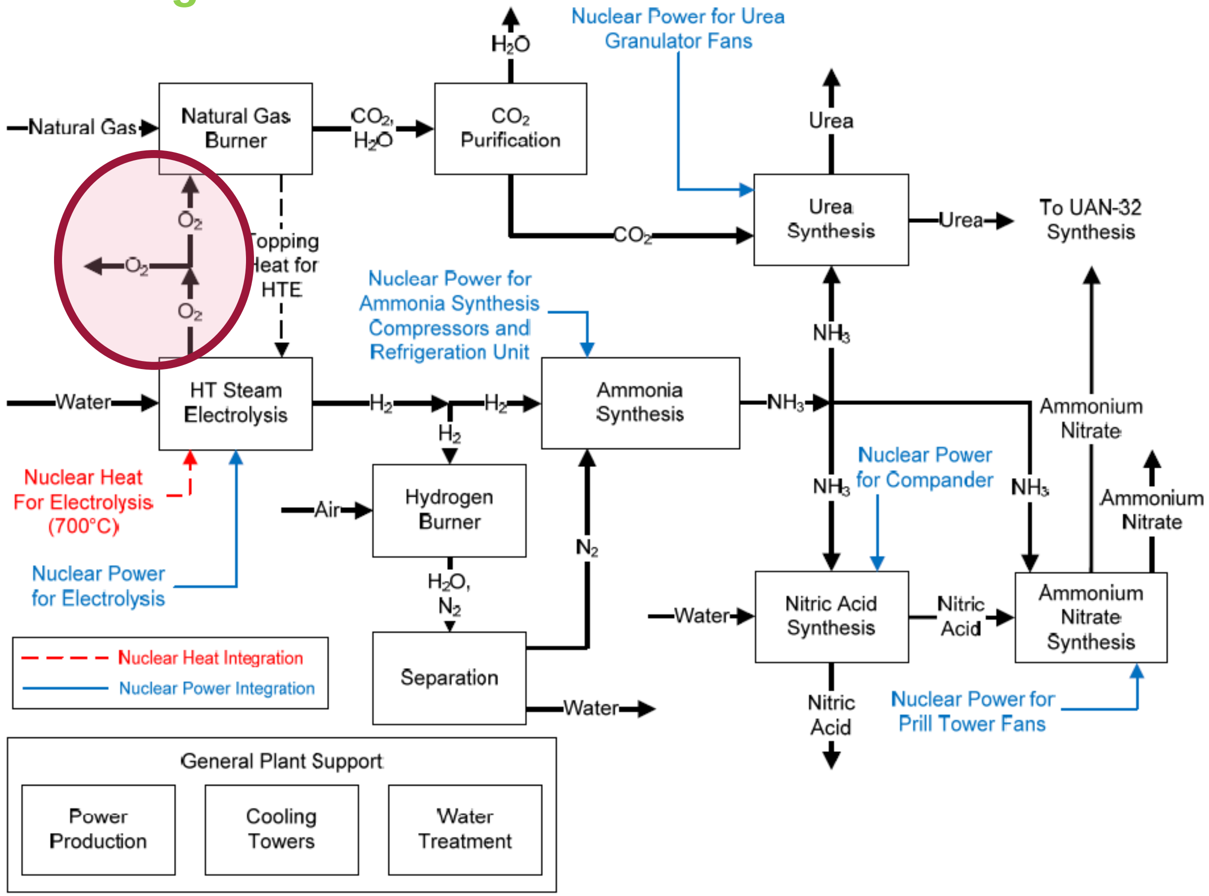


High Temperature Steam Electrolysis for Hydrogen Production

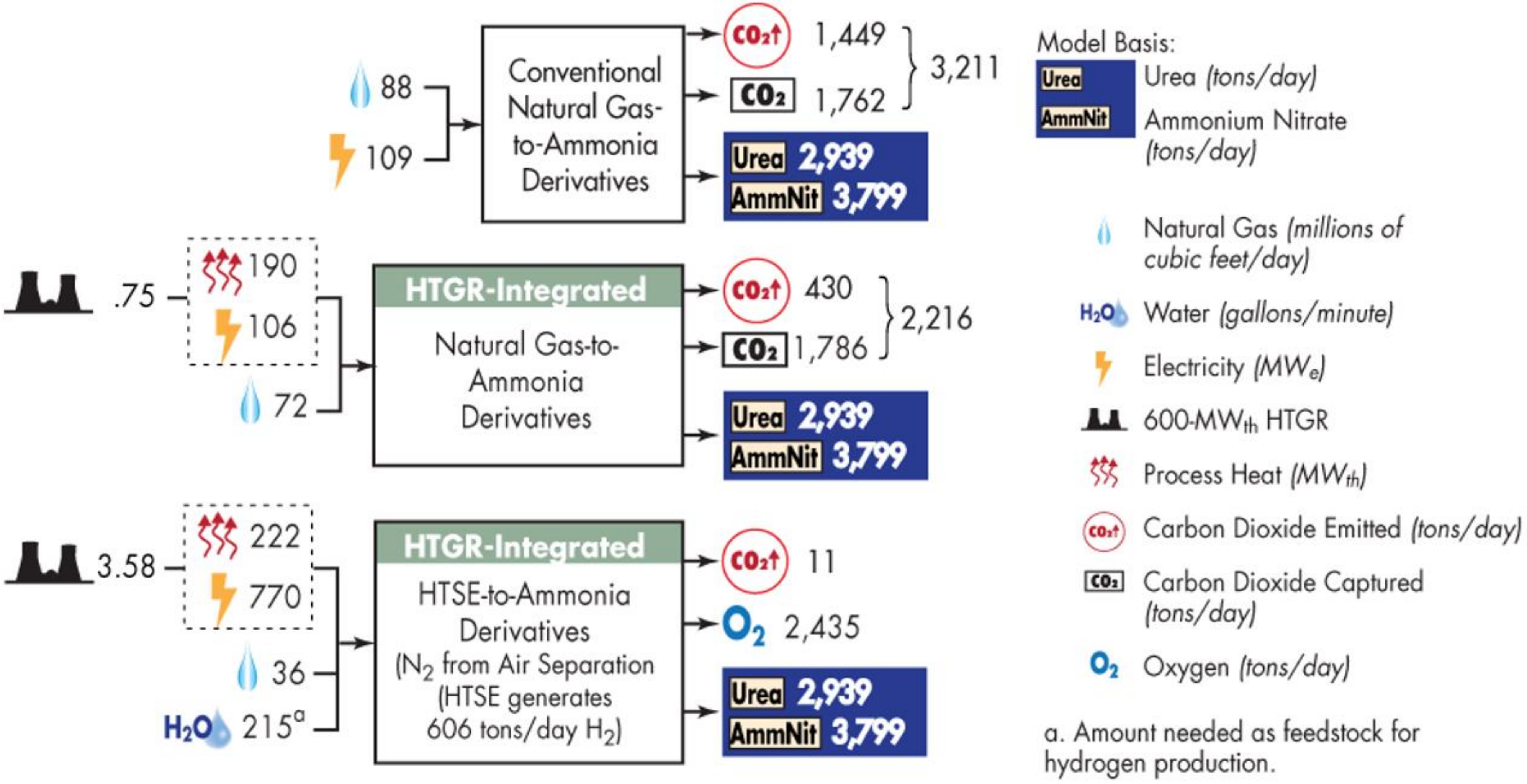
HTSE with Traditional Air Separation Unit



HTSE with Hydrogen Combustion for Nitrogen Production



Comparison of Inputs and Outputs



Urea Production Cost Comparison

Option	Urea Price ($ t^{-1})					
	No CO_2 Tax			50 $ t^{-1} CO_2 Tax	100 $ t^{-1} CO_2 Tax	200 $ t^{-1} CO_2 Tax
	Low NG	Mid. NG	High NG	Low NG	Low NG	Low NG
Urea Price Range in 2020 (DTN, 2020)	225-275			255-305	285-335	345-395
INL - Conventional Gas-to-Ammonia	244	272	348	274	304	363
HTGR Integrated Gas-to-Ammonia 2,000 ($ kW^{-1}) HTGR	263	286	348	293	304	345
HTGR Integrated Gas-to-Ammonia 1,400 ($ kW^{-1}) HTGR	249	272	335	270	291	332
HTGR Integrated Gas-to-Ammonia 700 ($ kW^{-1}) HTGR	236	259	321	257	277	318
High Temp Electrolysis Integrated Gas-to-Ammonia N_2 from ASU 700 ($ kW^{-1}) HTGR	365	369	377	368	374	377

- Cost of HTGR $ kW^{-1} thermal (600 MW_t total)
- HTGR supported hydrogen production is cost competitive when supplying heat for traditional ammonia synthesis processes
- High Temperature Steam Electrolysis is competitive with:
  - (a) low-cost manufacturing of a high temperature gas-cooled reactor
  - or (b) high price of natural gas
- Avoided CO_2 cost is a key consideration for "flameless" ammonia and urea production

CO_2 Tax	50 $·$t^{-1}$	100 $·$t^{-1}$	200 $·$t^{-1}$
High NG	378	408	467

Mini Ammonia Plant Design

Objective of Research

- Evaluate a novel configuration for small-scale production of ammonia using low temperature electrolysis
- Local ammonia production
- Use locally sourced heat and electricity (i.e. small nuclear reactor)
- Eliminate the need for storage of large amounts of ammonia (ammonia on demand)

Outcomes of Aspen Model of Mini-Ammonia Plant Concept (1 MWe input)

Electrolysis Options

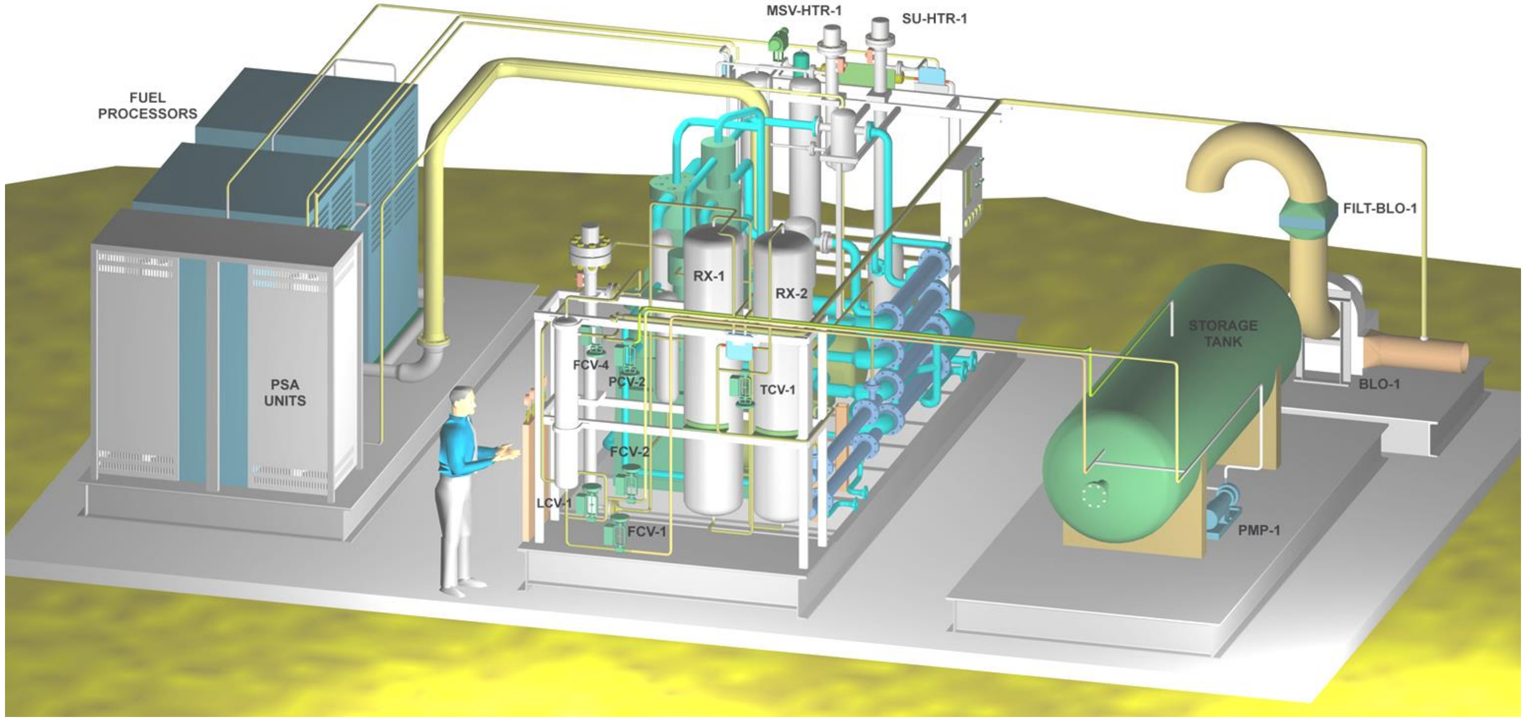
	Production Factor	Ammonia Production Efficiency (Tons / Day-MW)
Low Temperature Electrolysis: Electrolyte Solution	1.5	2.4
High Temperature Steam Electrolysis*	2.23	3.6

* ~10% to 15% Heat, 85% to 90% Electricity

Modular Ammonia Plants

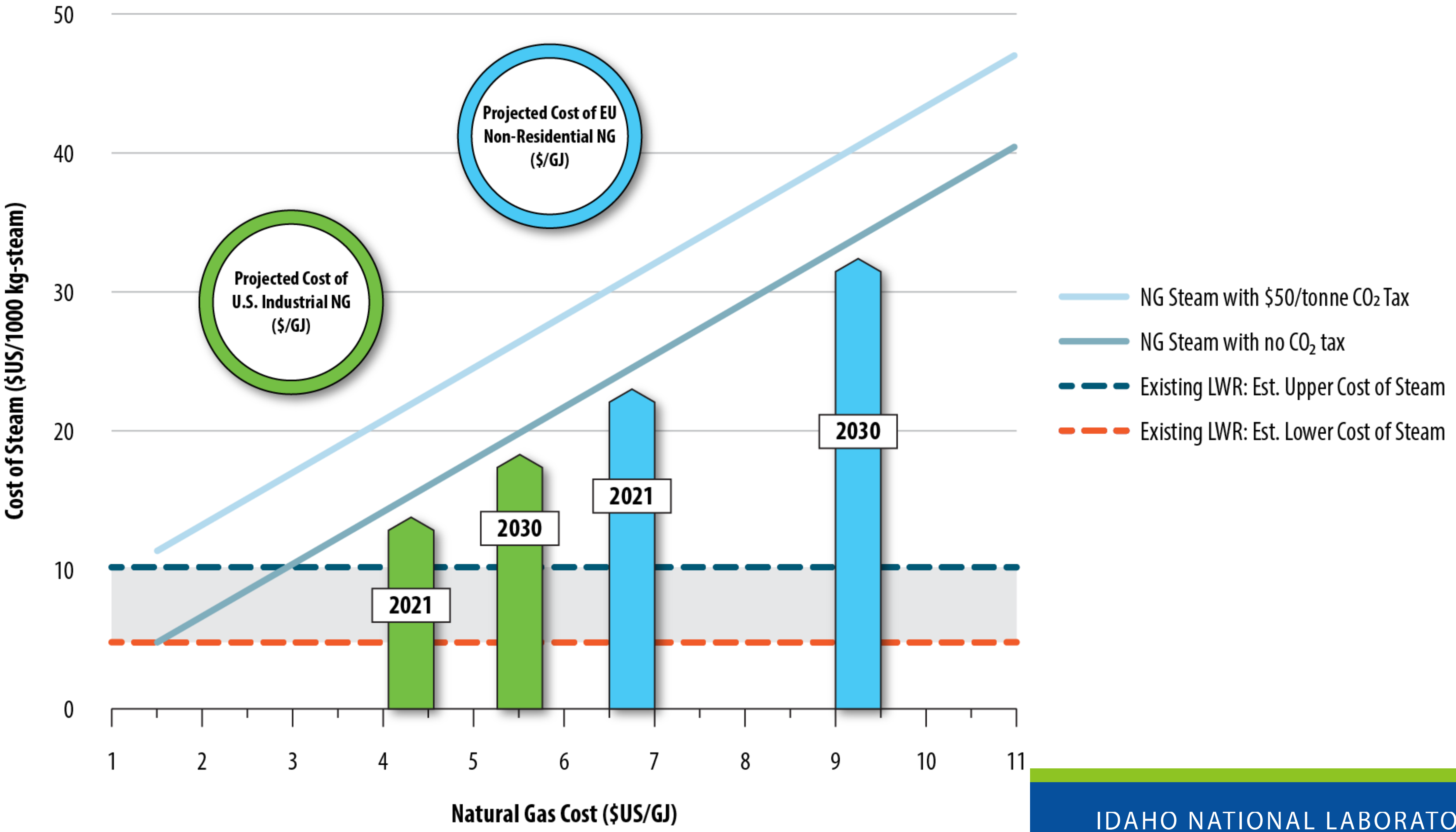
3.0 tonne/day skid-mounted production system

- Hydrogen production from electrolysis
- Small scale application ~ 1 MW
- Simplify process to minimize capital costs



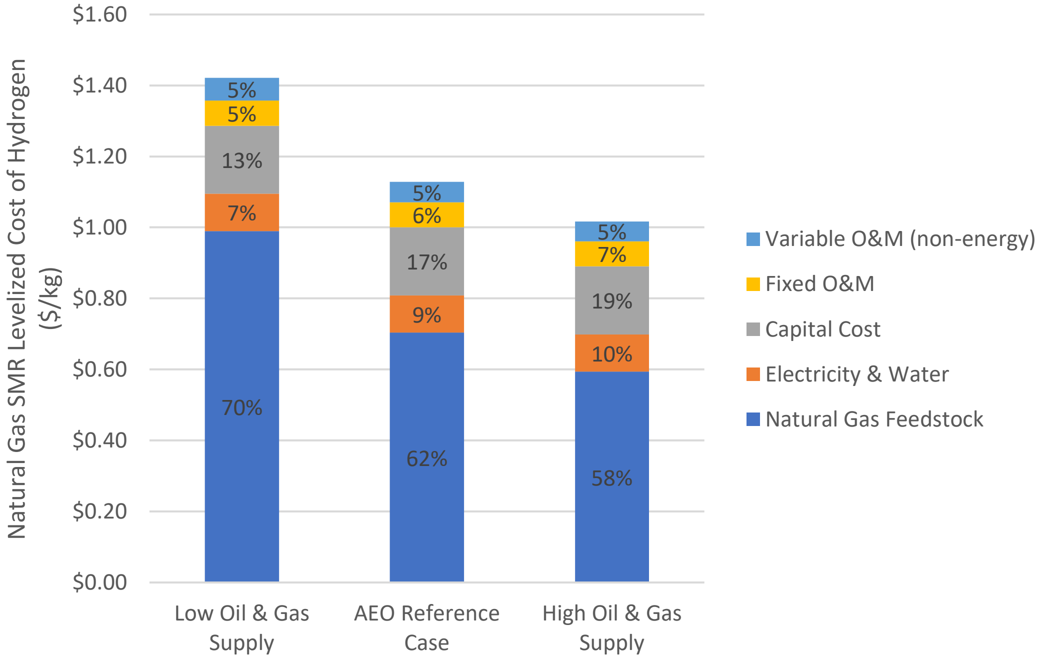
Idaho National Laboratory

Can Nuclear Compete? Natural Gas vs Nuclear LWR



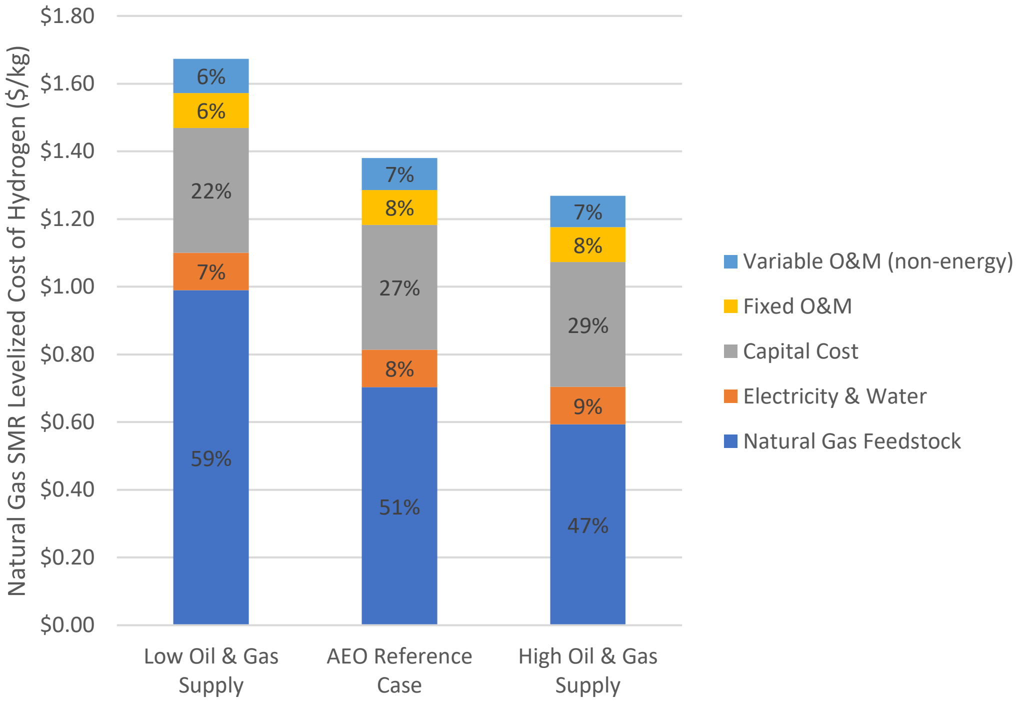
Cost of Natural Gas Steam Reforming

Conventional Auto-thermal



Natural Gas Steam Methane Reforming LCOH for selected EIA 2021 AEO NG Price Projection Cases based on SMR plant capital costs reported in NETL Hydrogen Production Facilities Plant Performance and Cost Comparisons

Hydrogen purification for ammonia production

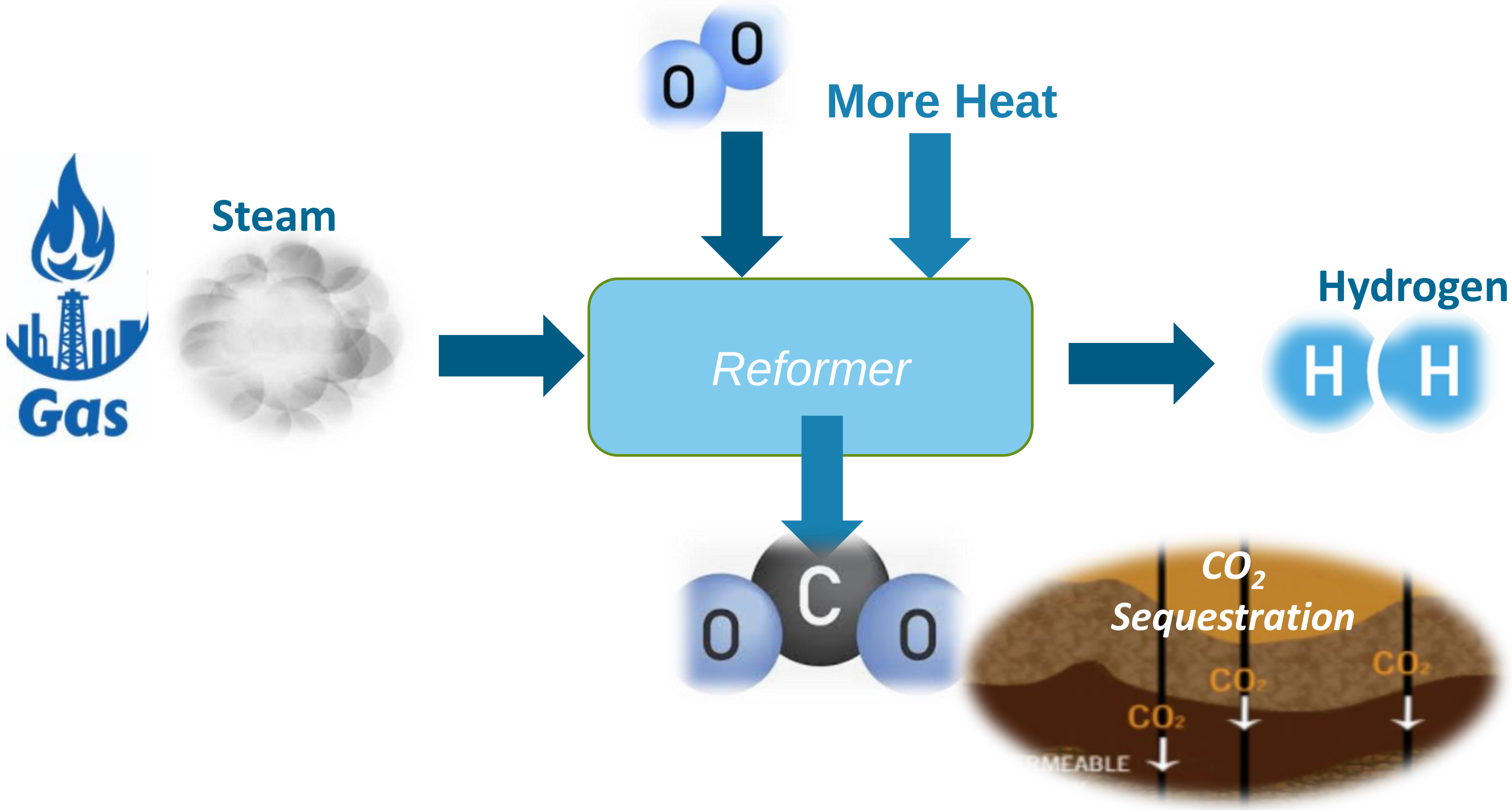


Natural Gas Steam Methane Reforming LCOH for selected EIA 2021 AEO NG Price Projection Cases based on SMR plant capital costs reported in INL TEV-954

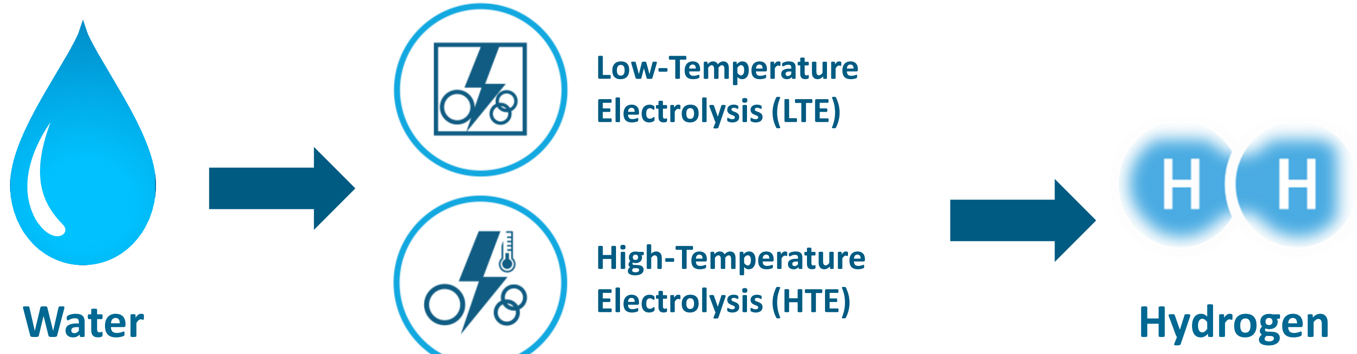
Capital Cost Increases for gas clean-up

How to produce clean hydrogen

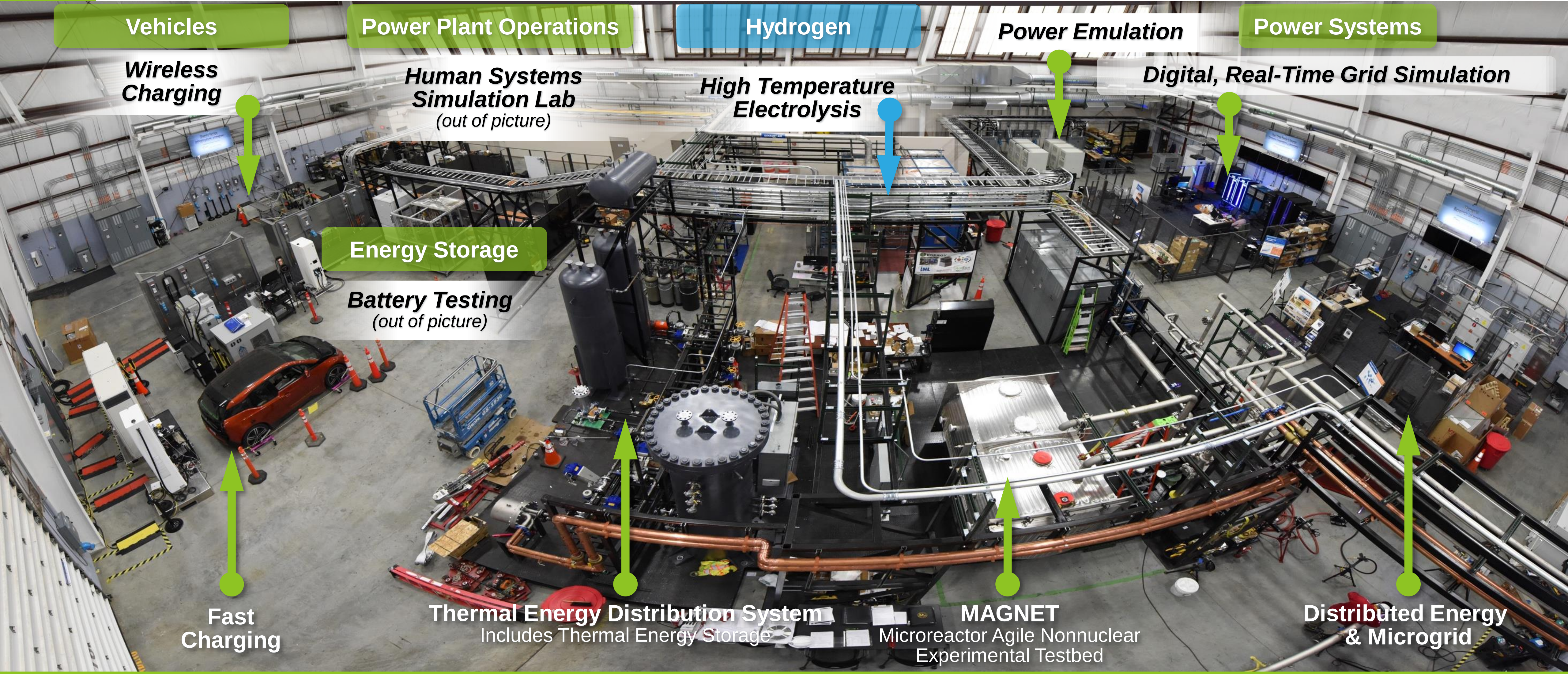
Steam / Methane Reforming

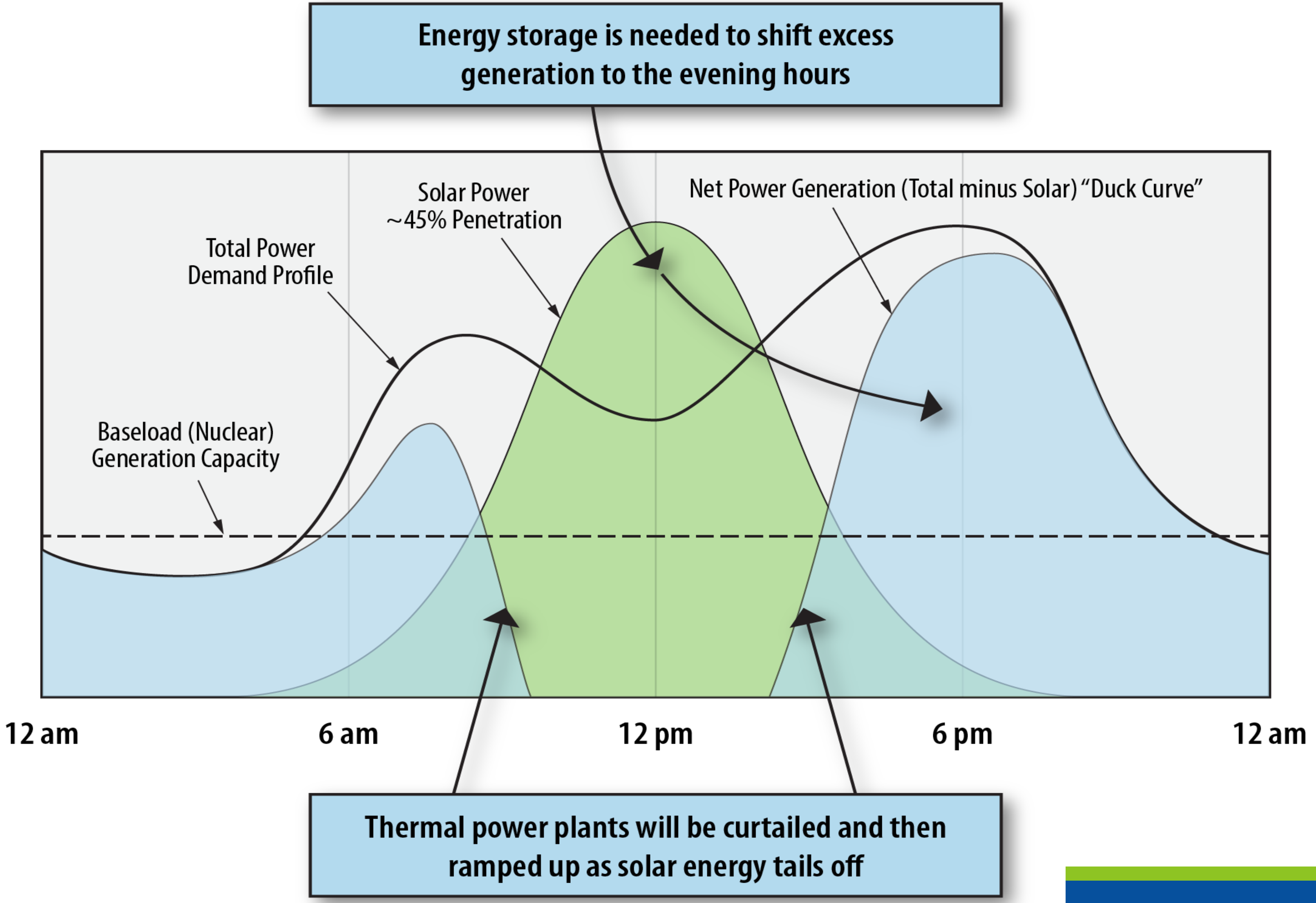


Electrolysis

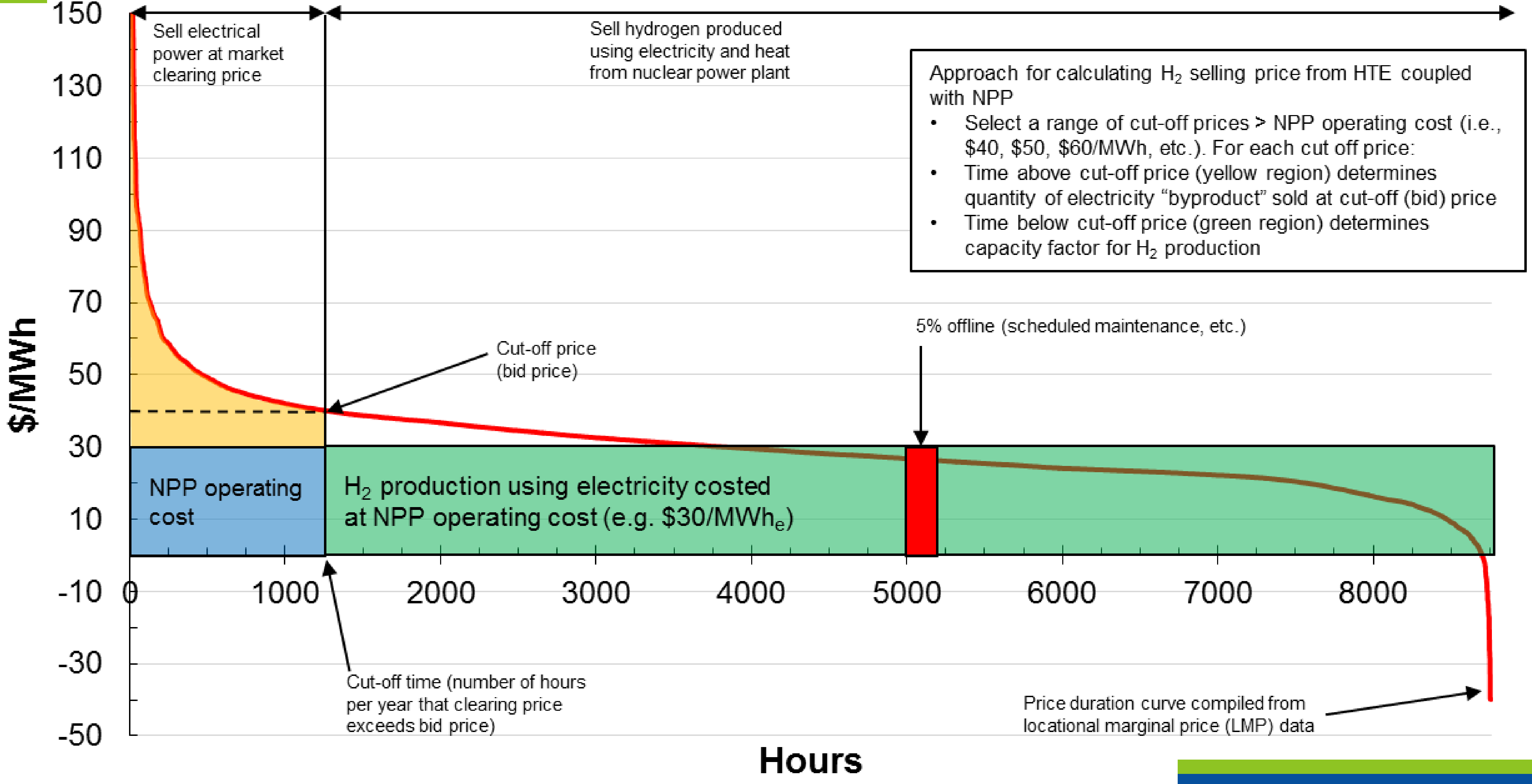


Integrating systems for the nation’s net-zero future

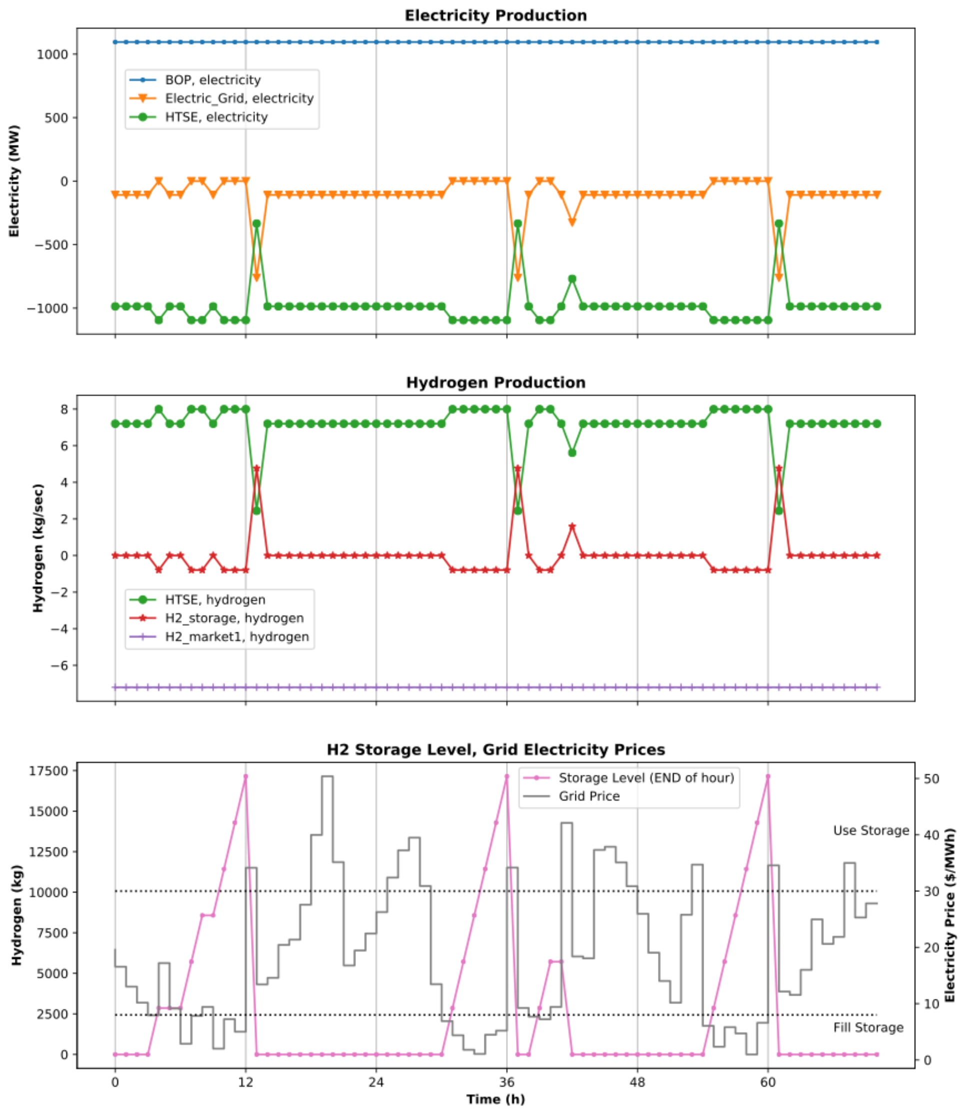


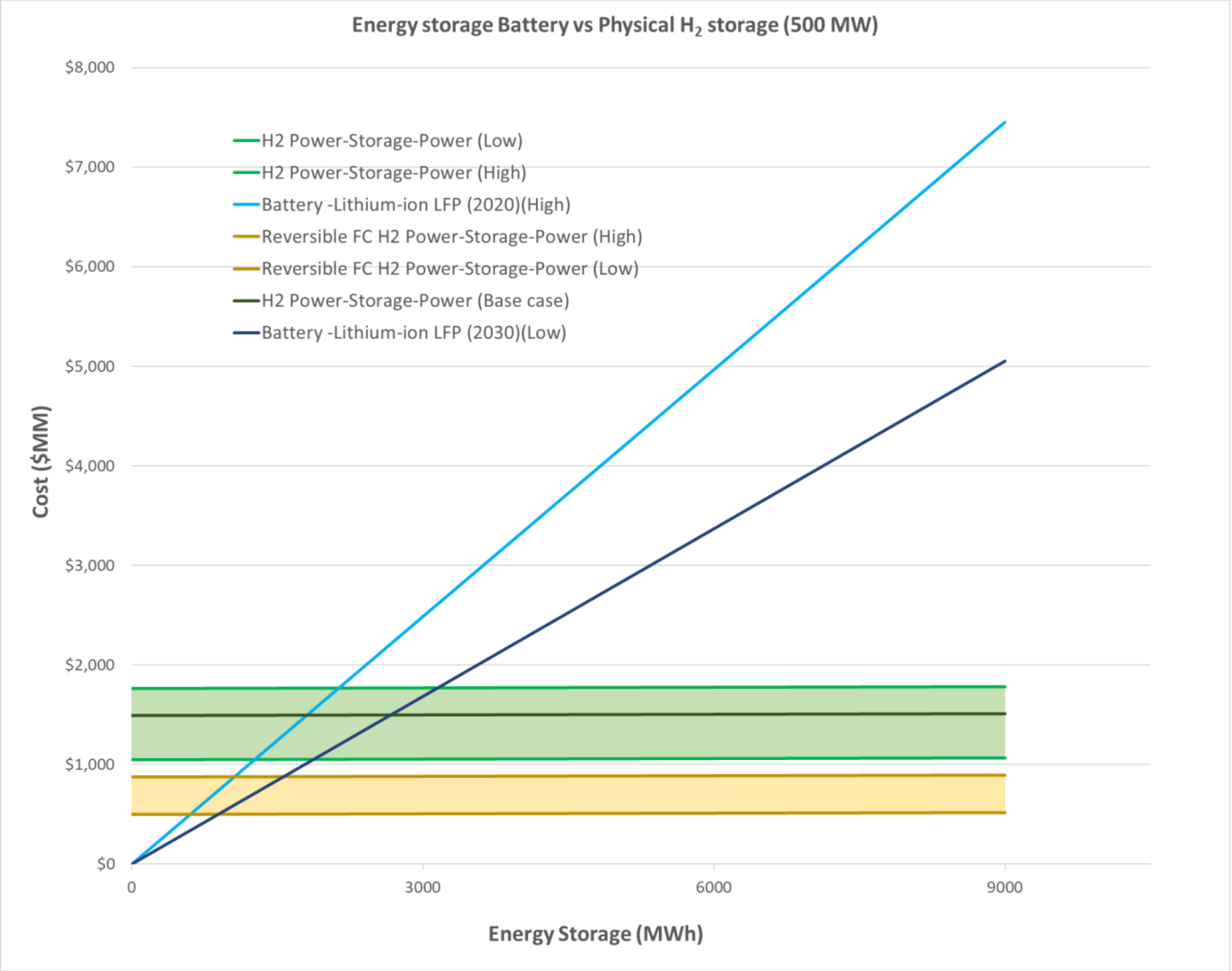

Energy storage is needed to shift excess generation to the evening hours
Solar Power ~45% Penetration
Net Power Generation (Total minus Solar) "Duck Curve"
Total Power Demand Profile
Baseload (Nuclear) Generation Capacity
12 am
6 am
12 pm
6 pm
12 am
Thermal power plants will be curtailed and then ramped up as solar energy tails off

Switching between electricity and hydrogen markets

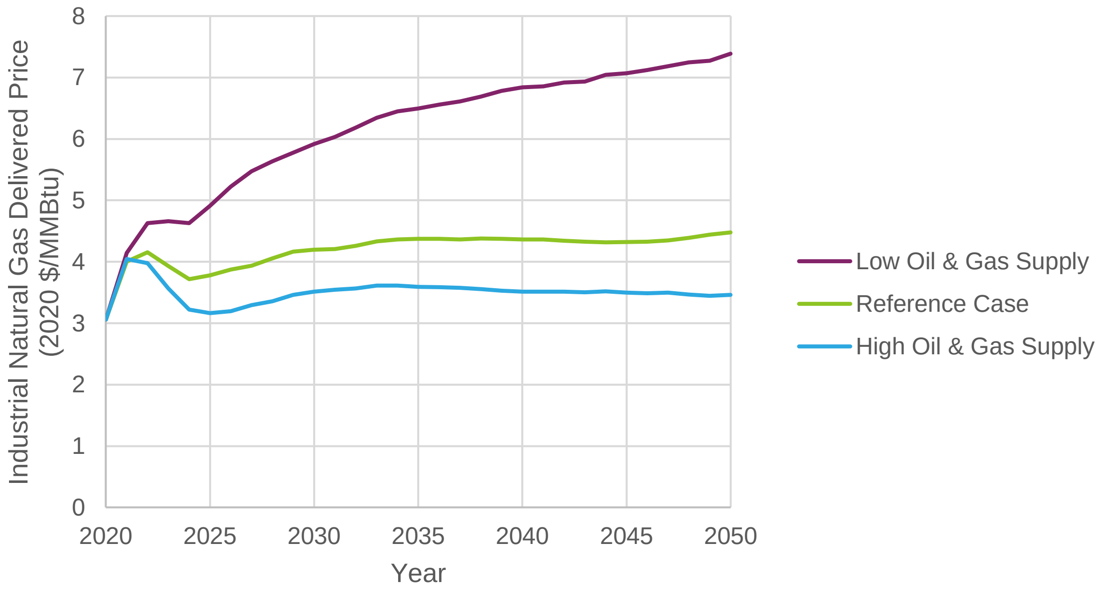


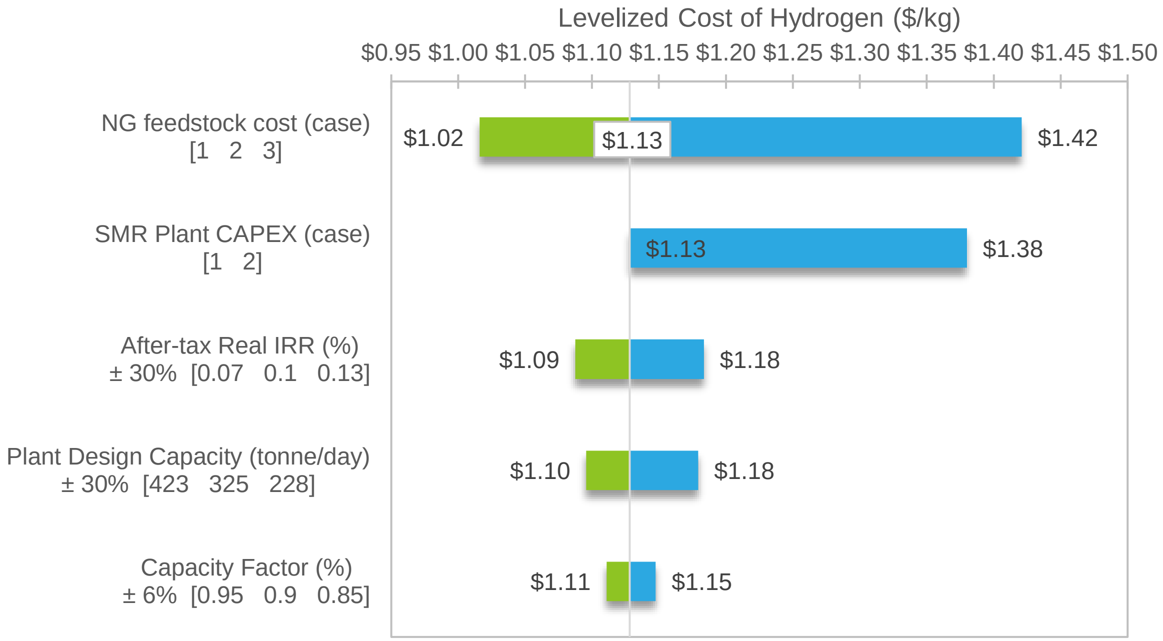
Market Arbitrage: Buy low, Sell high





Cost of producing hydrogen with conventional steam/methane reforming





Business Sensitive

IDAHO NATIONAL LABORATORY