Electrolysis Technology and Hydrogen Production Costs

FPOG Stakeholder Meeting

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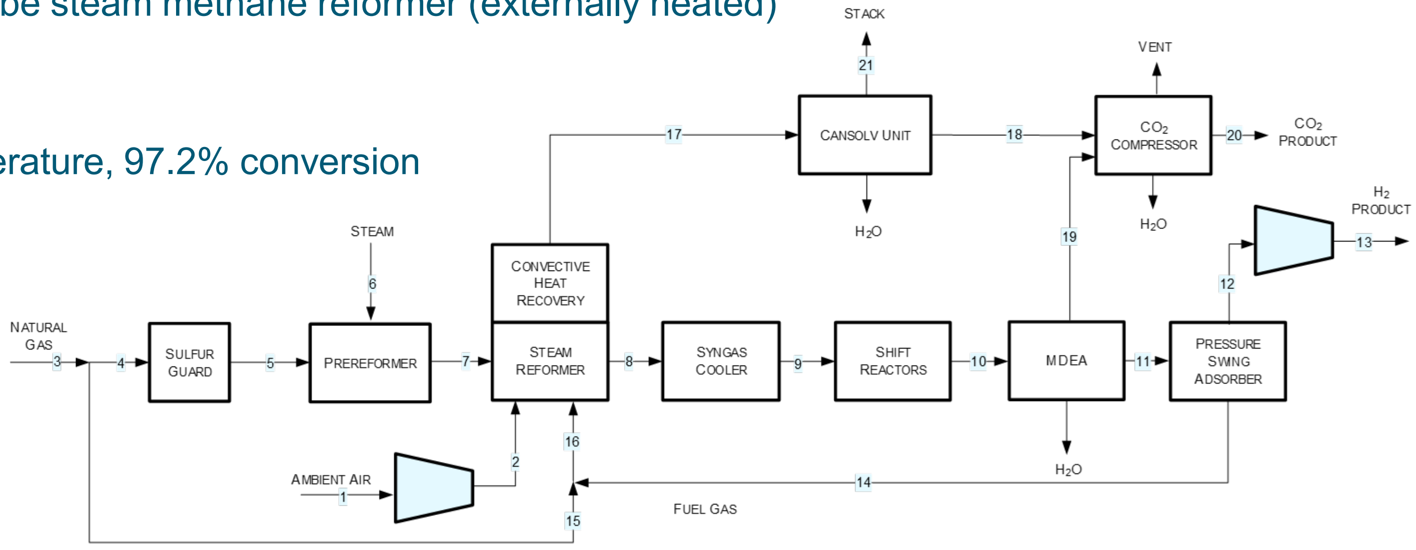
Hydrogen Production via Natural Gas SMR w/CCS

- Feedstock: Natural Gas
- Reforming: Pre-reformer and single-train, vertical tube steam methane reformer (externally heated)
- Plant Capacity: 483 metric tonnes H_2 per day
- H_2 Product Purity: 99.90 vol%
- Water Gas Shift: 2x3 train configuration, high-temperature, 97.2% conversion
- H_2 Purification: Pressure Swing Adsorption
- PSA Off-Gas: Recycled as reformer fuel
- Sulfur Control: Zinc Oxide Guard Bed
- NO_x Control: Low-NO_x Burners
- Particulate Control: N/A
- Mercury Control: N/A
- CO_2 Control: MDEA and Cansolv
- CO_2 Storage: Off-site Saline Formation



Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

Key parameters

Steam/carbon ratio (mol/mol)	2.451		
Feed rate (kJ/h)	3,562,464,762	3,946,977,698	LHV, HHV
Feed rate (kW)	989,574	1,096,383	LHV, HHV
Feed rate (mmBTU/h)	3,377	3,741	LHV, HHV
Product rate (kJ/h)	2,407,863,465	2,846,011,654	LHV, HHV
Product rate (kW)	668,851	790,559	LHV, HHV
Product rate (kg/day)	483,000		
Carbon feed rate (mol/h)	4,538,952		
Carbon sequestering rate (mol/h)	4,370,814		
Carbon sequestration fraction (%)	96.3%		
SMR carbon reforming rate	78.9%		
Shift CO conversion rate	97.2%		
Fuel use (mmBTU, LHV/kg H_2)	0.1678		
Raw water withdrawal (gal/min)	2,727		
Raw water withdrawal (gal/kg H_2)	8.1302		
Electricity use (kW)	30,240		
Electricity use (kWh/kg H_2)	1.5026		

Pre-reformer

$$C_2H_6 + 2H_2O \leftrightarrow 2CO + 5H_2;\ \Delta H^\circ_{rxn} = 346.4\ \mathrm{kJ/mol}$$

$$C_3H_8 + 3H_2O \leftrightarrow 3CO + 7H_2;\ \Delta H^\circ_{rxn} = 498.6\ \mathrm{kJ/mol}$$

$$C_4H_{10} + 4H_2O \leftrightarrow 4CO + 9H_2;\ \Delta H^\circ_{rxn} = 651.0\ \mathrm{kJ/mol}$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O;\ \Delta H^\circ_{rxn} = -205.8\ \mathrm{kJ/mol}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2;\ \Delta H^\circ_{rxn} = -41.2\ \mathrm{kJ/mol}$$

Steam Methane Reformer

$$CH_4 + H_2O \leftrightarrow CO + 3H_2;\ \Delta H^\circ_{rxn} = 205.8\ \mathrm{kJ/mol}$$

Water-Gas Shift

$$CO + H_2O \leftrightarrow CO_2 + H_2;\ \Delta H^\circ_{rxn} = -41.2\ \mathrm{kJ/mol}$$

Source: Lewis, E. et al. Comparison of Commercial, State of the Art, Fossil Based Hydrogen Production Technologies. April, 2022. DOE/NETL-2022/3241

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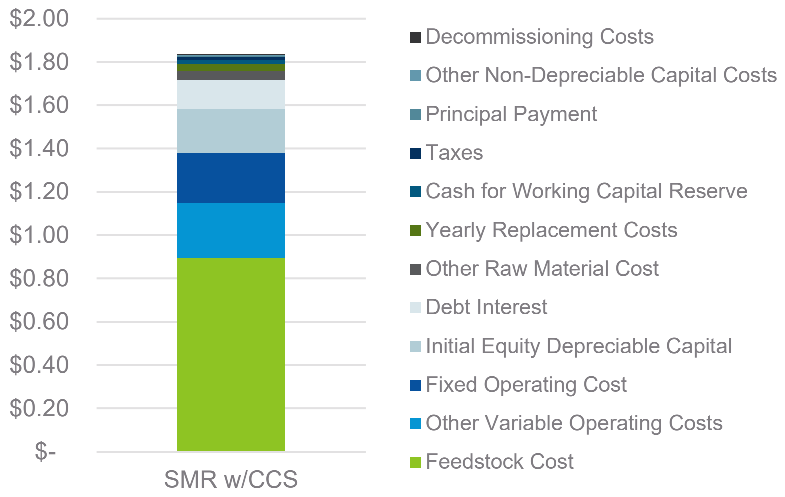
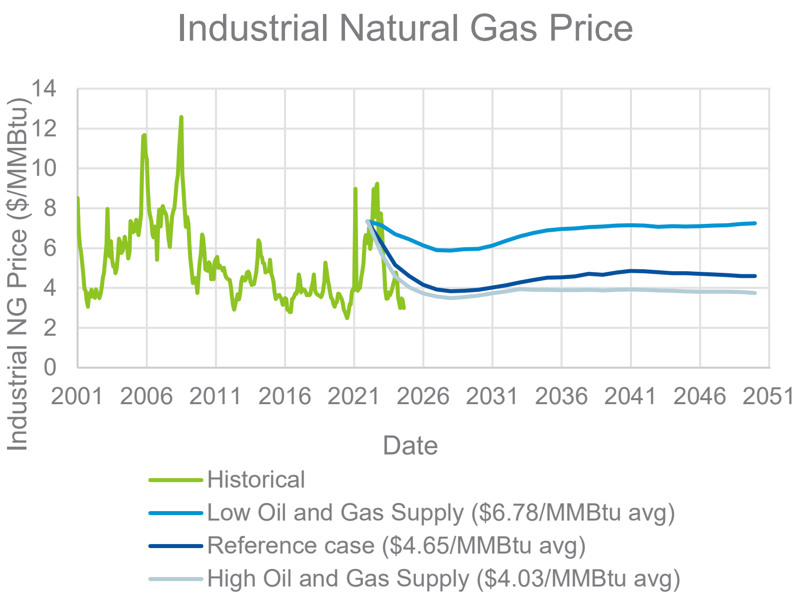
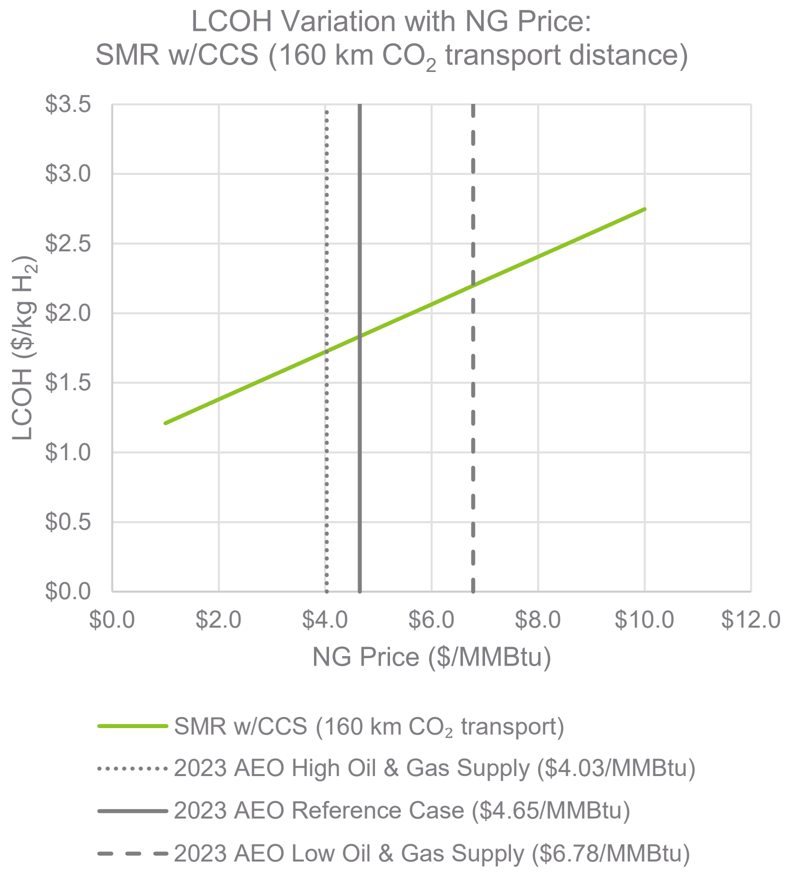
SMR LCOH Sensitivity to NG pricing





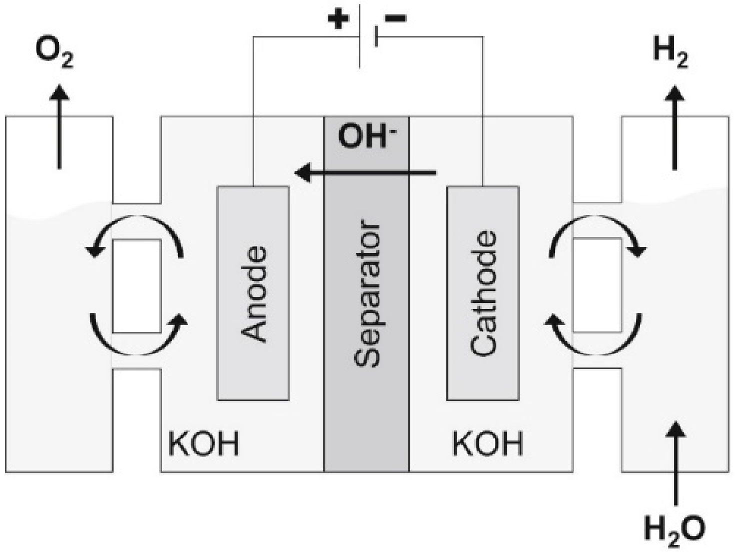
- LCOH of H_2 production via SMR is a function of natural gas fuel price.
- NG Feedstock is largest LCOH cost component (top left)
- Historical industrial NG prices show considerable variation as well as a large uncertainty in future pricing, as indicated by range of EIA AEO Case projections (bottom left)
- Plot at right shows variation in LCOH for SMR w/CCS as function of NG price.



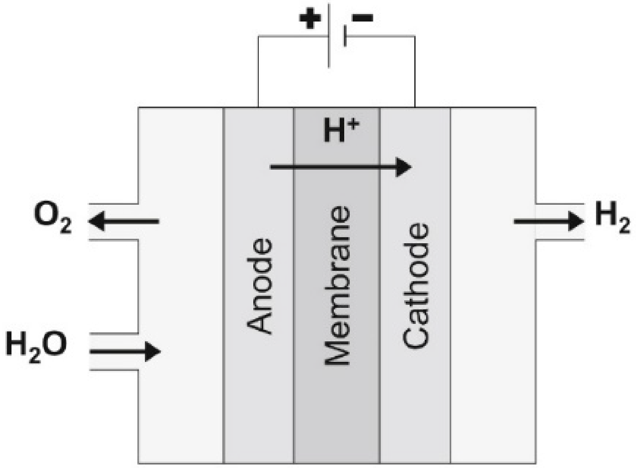
Electrolysis Hydrogen Production Technology

$2\ H_2O \rightarrow 2\ H_2 + O_2$

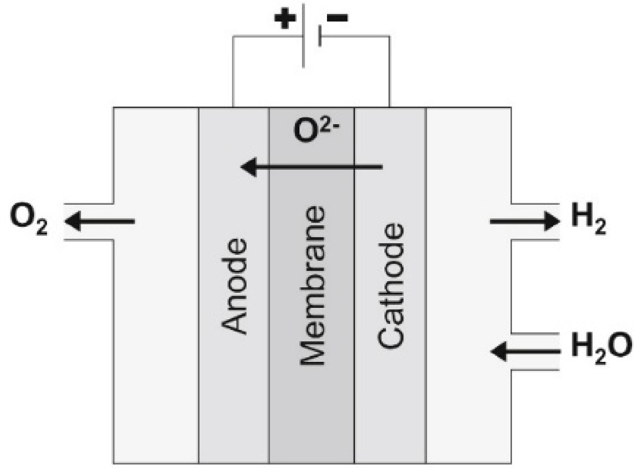
AEC



PEMEC



SOEC



Cathode: $2\ H_2O(l) + 2e^- \rightarrow H_2(g) + 2\ OH^-(aq)$

Anode: $2\ OH^-(aq) \rightarrow \frac{1}{2}O_2(g) + 2e^- + H_2O(l)$

- Well-established and commercialized
- Lower capital cost
- Less operational flexibility

Anode: $H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+\ (aq) + 2e^-$

Cathode: $2H^+(aq) + 2e^- \rightarrow H_2(g)$

- Rapid response time
- Wide operating range
- Lower durability
- Membrane materials include rare earths, e.g. platinum, iridium, gold

Cathode: $H_2O(g) + 2e^- \rightarrow H_2(g) + O^{2-}$

Anode: $O^{2-} \rightarrow \frac{1}{2}O_2(g) + 2e^-$

- High efficiency
- Lower energy cost
- Usage of cheaper transition metal catalysts as electrode materials
- Lower TRL than low temp technologies

Electrolysis Energy Requirements

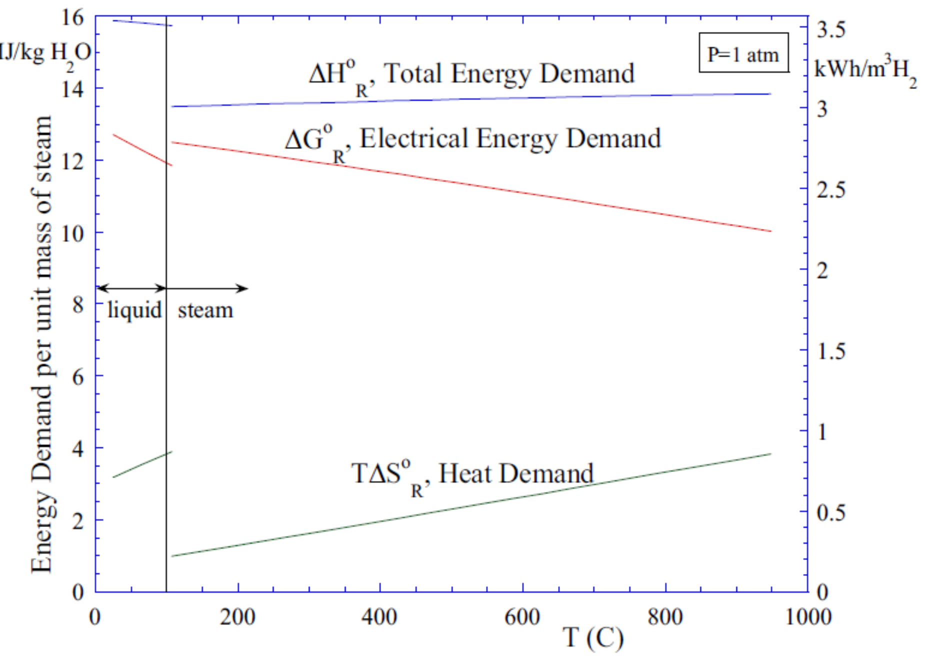
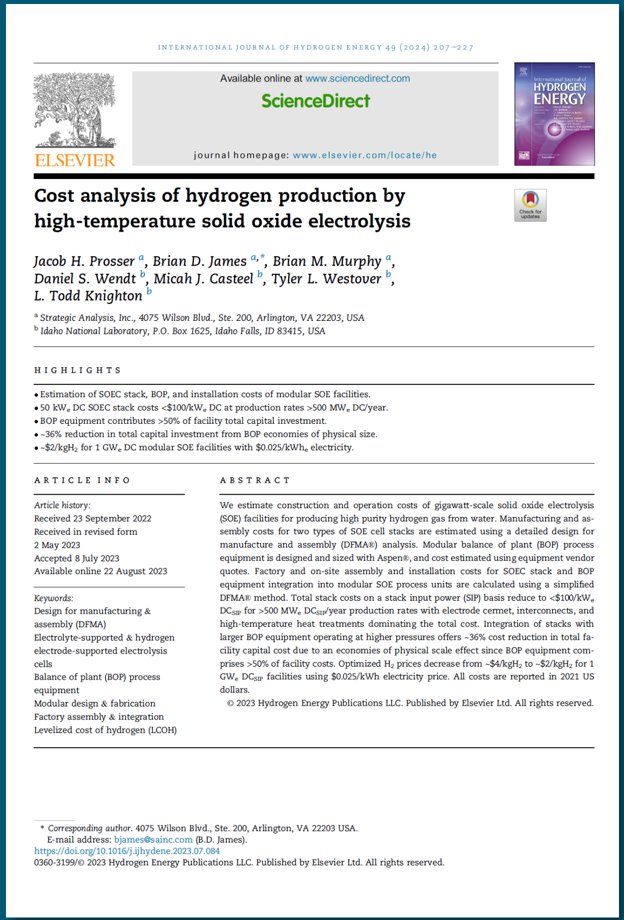


Figure 6. Standard-state energy requirements for electrolysis as a function of temperature.

- Electrolysis electrical power requirements decrease with temperature
- Use of a low-cost heat source for vaporizing electrolysis process feedwater can reduce energy costs

Cost Analysis of Hydrogen Production by High-Temperature Solid Oxide Electrolysis

- Estimated construction and operation costs of gigawatt-scale solid oxide electrolysis (SOE) facilities for producing high purity hydrogen gas from water
- Manufacturing and assembly costs for two types of SOE cell stacks are estimated using a detailed design for manufacture and assembly (DFMA®) analysis
- Modular balance of plant (BOP) process equipment is designed and sized with Aspen®, and cost estimated using equipment vendor quotes
- Factory and on-site assembly and installation costs for SOEC stack and BOP equipment integration into modular SOE process units are calculated using a simplified DFMA® method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Cost analysis of hydrogen production by high-temperature solid oxide electrolysis

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HIGHLIGHTS

- Estimation of SOEC stack, BOP, and installation costs of modular SOE facilities.
- 50 kW_e DC SOEC stack costs <$100/$kW_e$ DC at production rates >500 MW_e DC/year.
- BOP equipment contributes >50% of facility total capital investment.
- ~36% reduction in total capital investment from BOP economies of physical size.
- ~$2/$kgH_2$ for 1 GW_e DC modular SOE facilities with $0.025/$kWh_e$ electricity.

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Levelized cost of hydrogen (LCOH)

ABSTRACT

We estimate construction and operation costs of gigawatt-scale solid oxide electrolysis (SOE) facilities for producing high purity hydrogen gas from water. Manufacturing and assembly costs for two types of SOE cell stacks are estimated using a detailed design for manufacture and assembly (DFMA®) analysis. Modular balance of plant (BOP) process equipment is designed and sized with Aspen®, and cost estimated using equipment vendor quotes. Factory and on-site assembly and installation costs for SOEC stack and BOP equipment integration into modular SOE process units are calculated using a simplified DFMA® method. Total stack costs on a stack input power (SIP) basis reduce to <$100/$kW_e$ DC_{SIP} for >500 MW_e DC_{SIP}/year production rates with electrode cermet, interconnects, and high-temperature heat treatments dominating the total cost. Integration of stacks with larger BOP equipment operating at higher pressures offers ~36% cost reduction in total facility capital cost due to an economies of physical scale effect since BOP equipment comprises >50% of facility costs. Optimized H_2 prices decrease from ~$4/$kgH_2$ to ~$2/$kgH_2$ for 1 GW_e DC_{SIP} facilities using $0.025/kWh electricity price. All costs are reported in 2021 US dollars.

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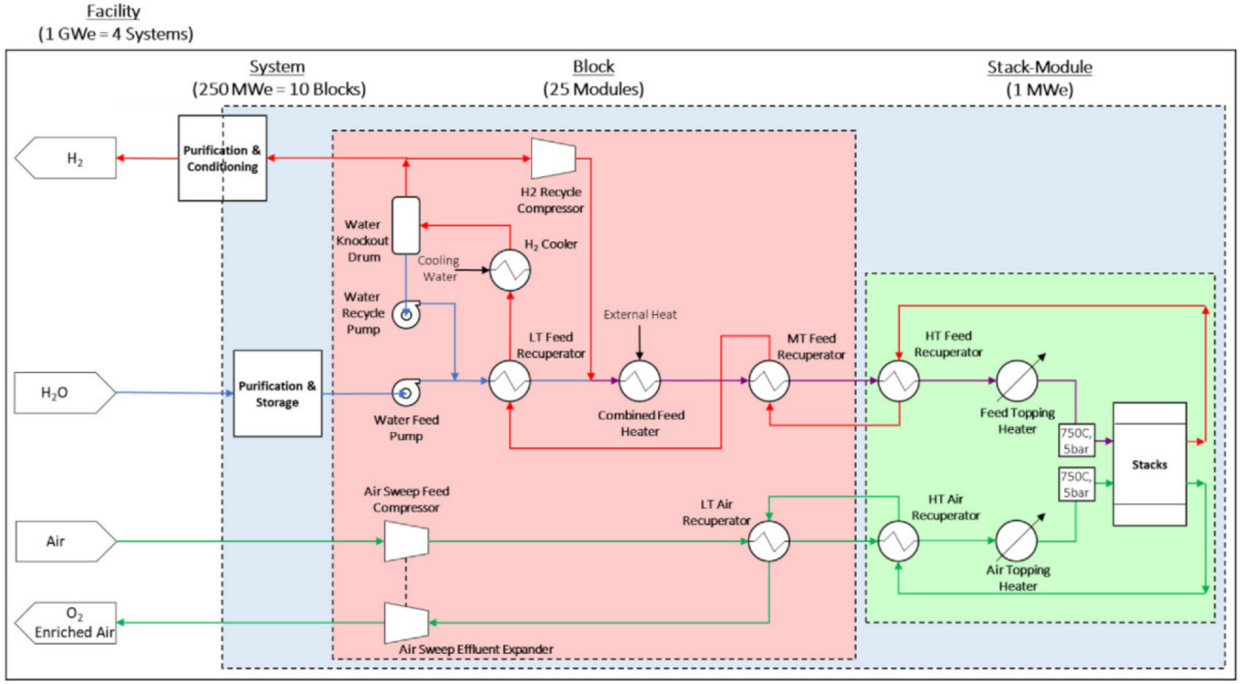
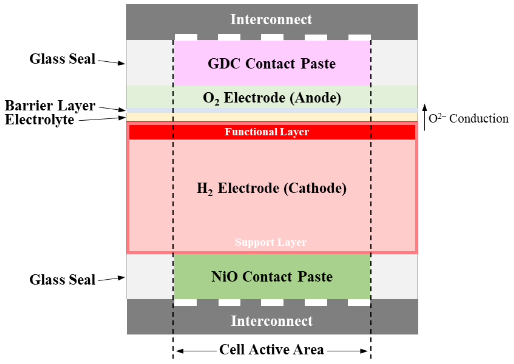
High Temperature Solid Oxide Electrolysis (SOE): Near Atmospheric Pressure Stack Design

- Design Case: Near Atmospheric Pressure (NAP)
- Technology Maturity: Nth-of-a-Kind (NOAK)
- Feedstock: Water and Electric Power
- Plant Capacity: 703.5 metric tonne H_2 per day
- Facility Power: 1000 MWe
- Stack Pressure: 1.3 bara
- Stack Operating Temperature: 750°C
- Cell Architecture: Cathode Supported
- Cell Current Density: 1.5 A/cm²
- Stack Life: 4 years
- Stack Steam Utilization: 80%
- H_2 Purification: Steam condensation and Pressure Swing Adsorption
- Sulfur Control: N/A
- NOx Control: N/A
- Particulate Control: N/A
- Mercury Control: N/A
- CO_2 Control: N/A
- CO_2 Storage: N/A
- Specific Electricity Consumption: 38.7 kWhe/kgH_2
- Specific Thermal Consumption: 7.3 kWht/kgH_2
- Specific H_2O Consumption: 11.2 kgH_2O/kgH_2
- H_2 Product Purity: 99.99 mol%
- Total Capital Cost ($2021 USD): $668 MM ($668/kWe)

Source: https://doi.org/10.1016/j.ijhydene.2023.07.084



Cathode-Supported Cell



Anode: $2\,O^{2-} \rightarrow O_2 + 4\,e^-$

Cathode: $H_2O + 2\,e^- \rightarrow H_2 + O^{2-}$

Net Reaction: $2\,H_2O \rightarrow 2\,H_2 + O_2$

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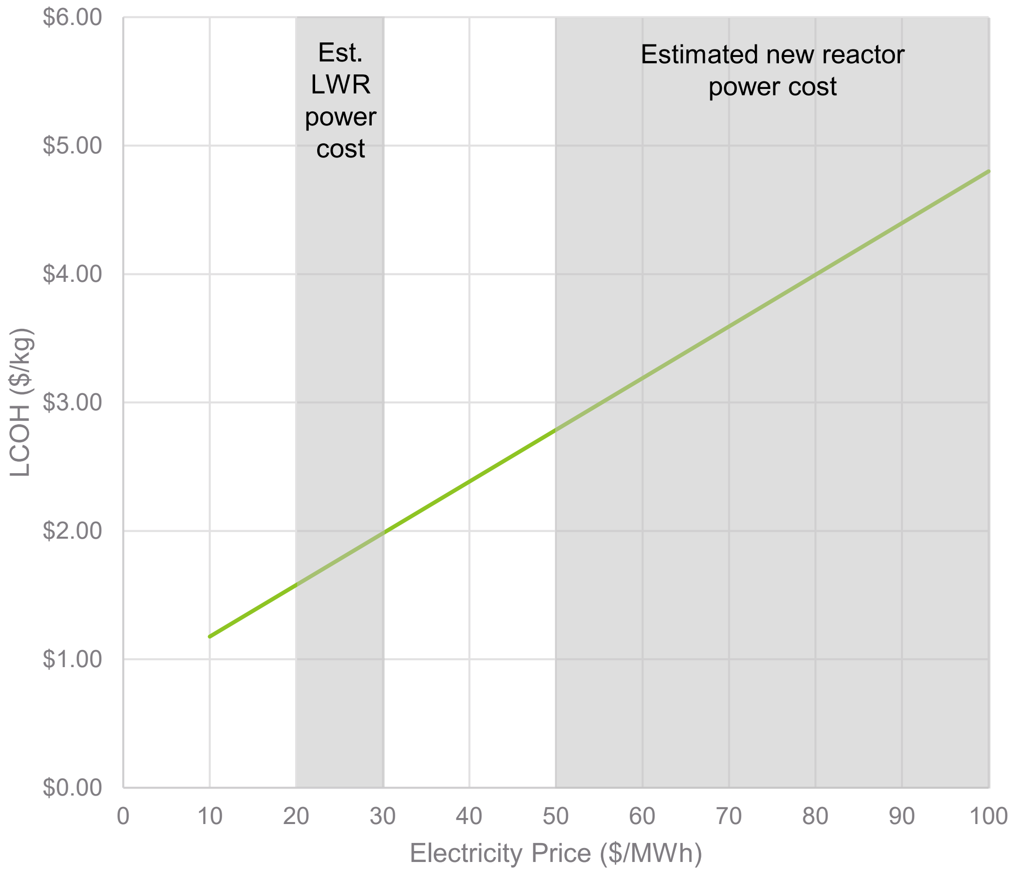
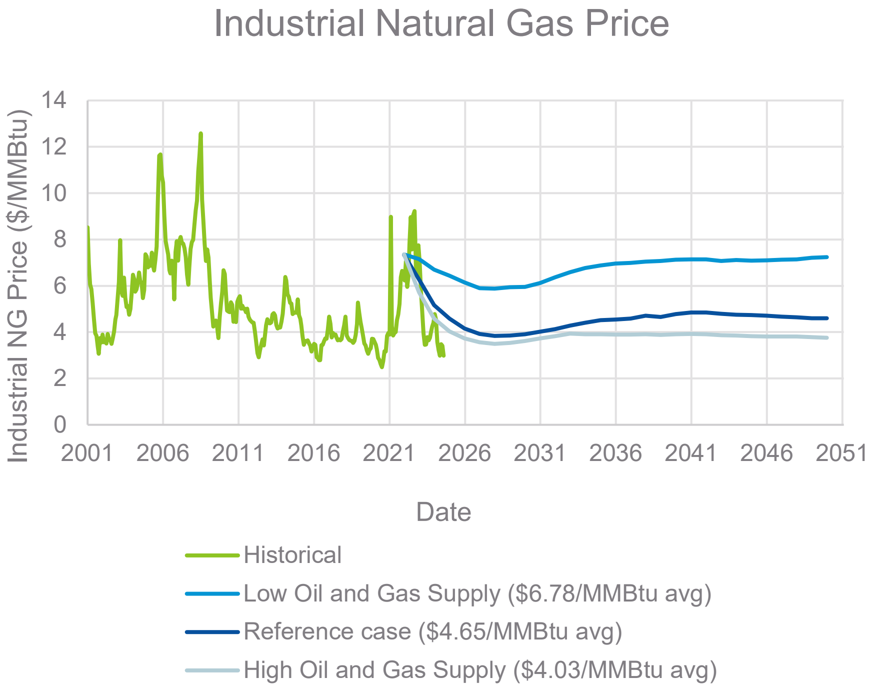
SOE LCOH: Near-Atmospheric Pressure Stack Design Case

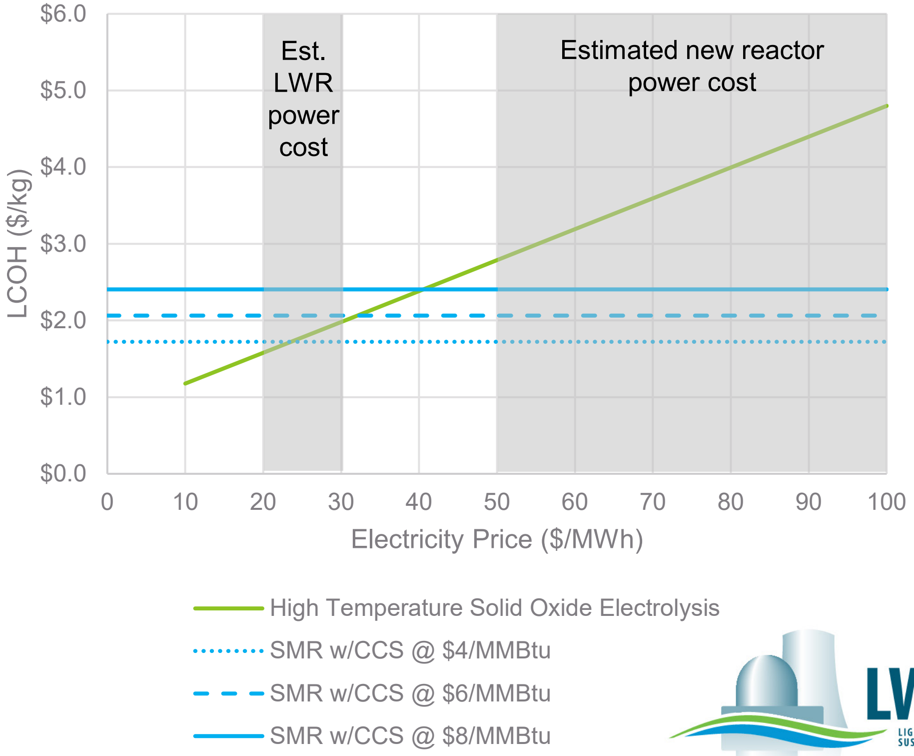
- LCOH of SOE H_2 production is a strong function of energy price
- Existing fleet LWRs have power production costs in the range of $20-30/MWhe, while next generation small modular nuclear reactors are expected to have power production costs in the range of $50-100/MWhe.
- With an electric power price of $30/MWhe and a thermal power price of $9/MWht (approximate cost of nuclear-based low pressure industrial steam production), a GW-scale NOAK SOE plant could produce H_2 at a cost of <$2/kg



LCOH Comparison of NG SMR w/CCS and Nuclear HT SOE

- Nuclear-based high temperature electrolysis is most competitive with electricity prices <$30/MWhe (well-aligned with existing fleet LWR power production costs) and natural gas prices >$6/MMBtu (which is at the mid- to high-end of the recent historical NG price range).
- Analysis does not consider Inflation Reduction Act of 2022 clean hydrogen production tax credits of $3/kg-$H_2$ (based on GHG of <0.45 kg-CO_2e/kg-H_2) applicable to 200 MWe of hydrogen production from eligible LWR power plants





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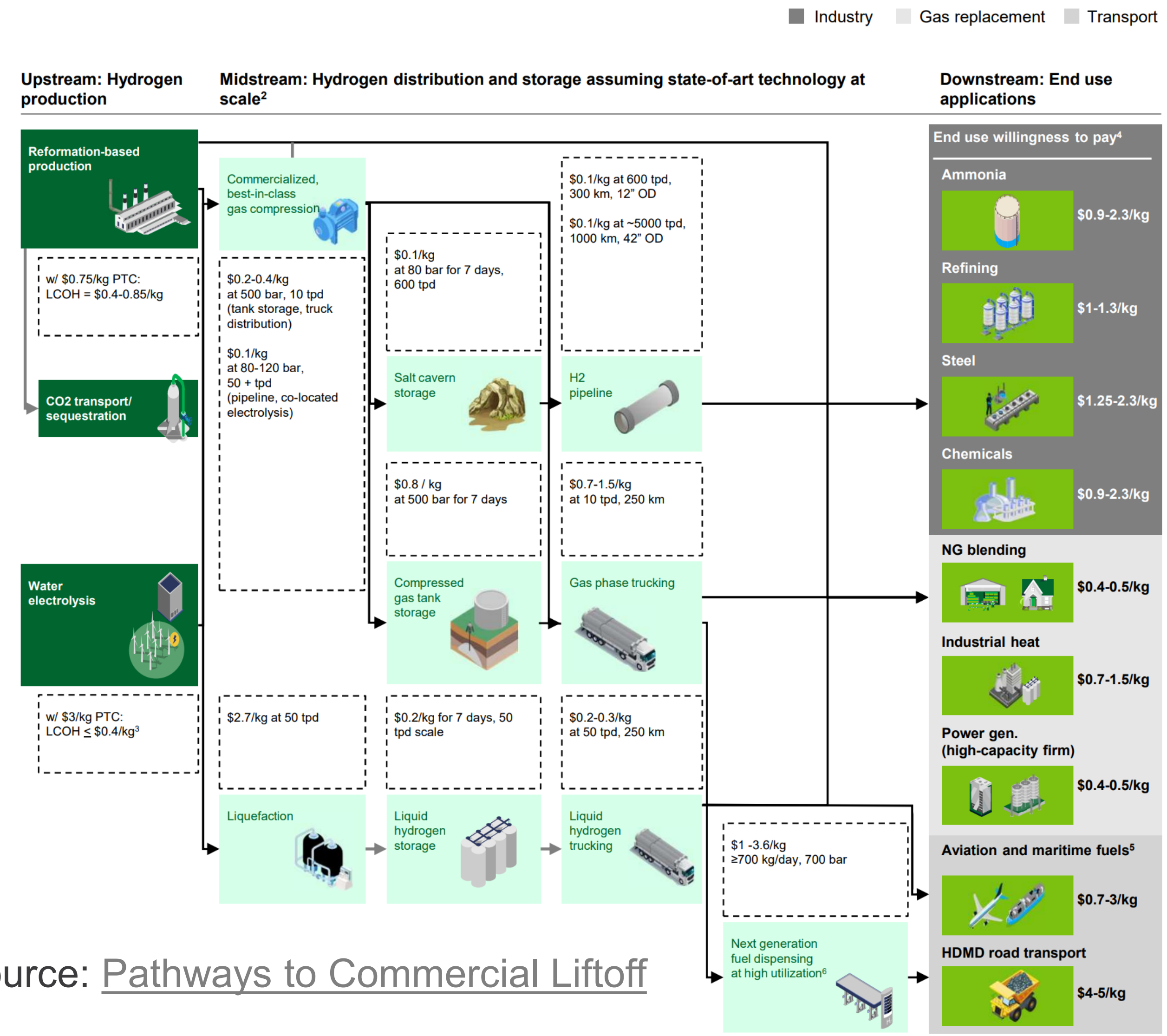
Matching H_2 Production and Transportation Costs with Price for Selected End Use Applications



Source: Pathways to Commercial Liftoff

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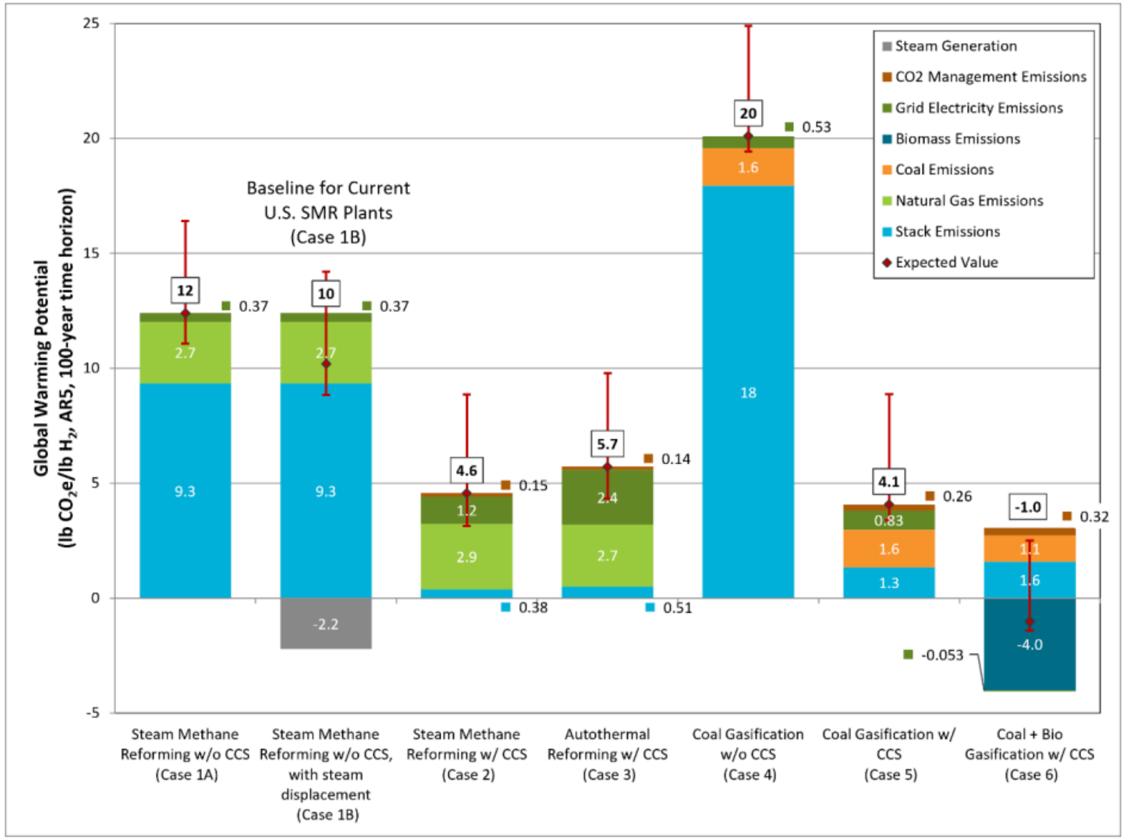
Sustaining National Nuclear Assets

lwrs.inl.gov

Steam Methane Reforming Hydrogen emissions

Exhibit 5-5. CO_2e life cycle emissions for all cases



- Baseline for Current U.S. SMR Plants: 10 kg_CO_2/kg_H_2
- Source: Comparison Of Commercial, State-Of-The-Art, Fossil-Based Hydrogen Production Technologies, page 270. https://netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf

Nuclear-based hydrogen emissions

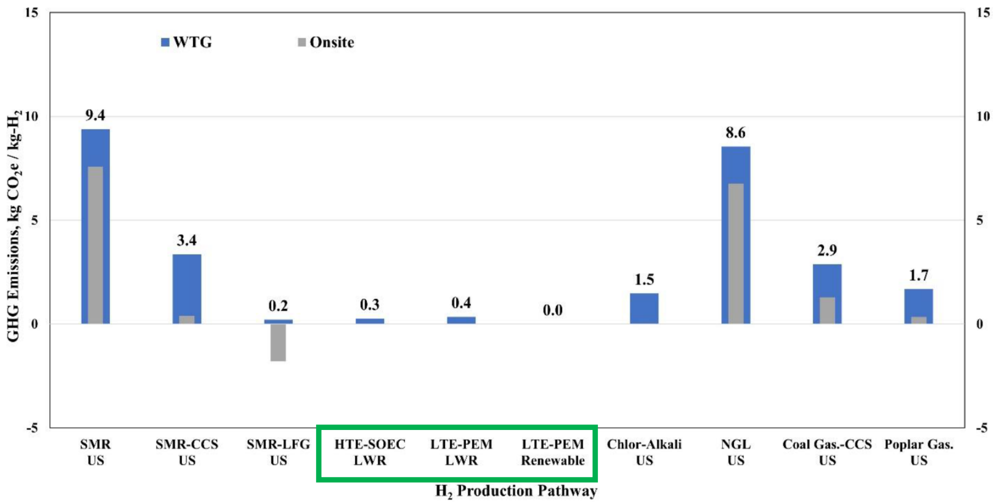


Figure 2. Well-to-gate GHG emission results for various energy sources and H_2 production technology pathways*

- HTE-SOEC LWR = 0.3 kg-CO_2e/kg-H_2
- LTE-PEM LWR = 0.4 kg-CO_2e/kg-H_2

Source: Elgowainy et al. "Hydrogen Life-Cycle Analysis in Support of Clean Hydrogen Production." ANL/ESIA-22/2. October 2022.