High Temperature Steam Electrolysis Process Performance and Cost Estimates

Daniel S. Wendt
L. Todd Knighton
Richard D. Boardman

Idaho National Laboratory

Idaho National Laboratory

Project Overview

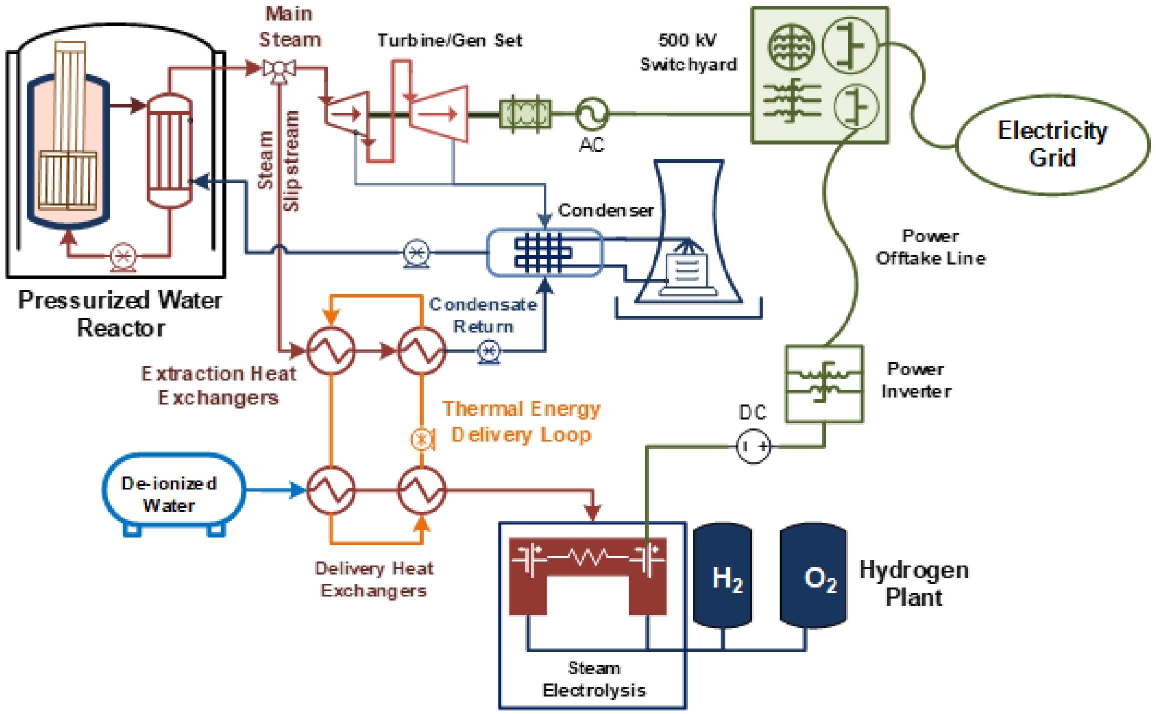
- Purpose: The purpose of this project was to develop a performance and cost baseline that can be used to benchmark the levelized cost of hydrogen (LCOH) for future high temperature steam electrolysis (HTSE) plant installations against that of alternate hydrogen production technologies, and to determine the parameters that have the greatest influence on achieving the Department of Energy hydrogen production cost target of less than $2/kg by 2025 and approaching the Earthshot goal of $1/kg by 2030.
- Goal/targets: The goal of the analysis was to estimate the LCOH for a nuclear-integrated, gigawatt-scale, modular construction HTSE process design, based on use of current solid oxide electrolysis cell (SOEC) technology under a scenario in which the manufacturing capacity, technology deployment rate, and construction schedules support startup of an Nth-of-a-Kind (NOAK) plant by year 2025.
- Approach: The general approach for this analysis involved development and use of high temperature steam electrolysis process model (using AspenTech HYSYS software) to determine system mass & energy balances for a nuclear-integrated, gigawatt-scale HTSE plant. Equipment sizing parameters were then obtained from the process model, and AspenTech Process Economic Analyzer software and data from previous HTSE system cost analyses were used to determine balance-of-plant capital costs, while stack cost estimates consistent with a 1,000 MW/yr manufacturing rate were obtained from a recent Strategic Analysis, Inc. bottom-up stack cost analysis. Finally, the DOE H2A model was utilized as the basis for calculating the LCOH based on the process modeling energy requirements, capital cost analysis, and specification of relevant financial parameters.
- Accomplishments: Accomplishments include development of nuclear-integrated modular construction HTSE process and economic models capable of evaluating process performance and costs at various production capacities and with different technology horizon assumptions. Performed LCOH comparison of NOAK, GW-scale HTSE process and conventional Steam Methane Reforming (with and without carbon capture and sequestration) as functions of electricity and natural gas price. Completed HTSE LCOH sensitivity analysis and developed a waterfall chart to illustrate a potential scenario that could result in achievement of the Earthshot goal of $1/kg hydrogen.
- Future plans: Proprietary versions of the INL HTSE process model have previously been developed in collaboration with CRADA partners, and it is expected that requirements of ongoing and future projects will continue to drive refinement of this model. Updates to the public version of the INL HTSE techno-economic analysis are expected as publicly available cost and/or performance data becomes available, based on the needs of DOE and INL’s project partners/collaborators.

Introduction

- Technology readiness levels (TRLs) of water-splitting electrolysis systems have dramatically increased in recent years as the interest in clean hydrogen production and decarbonization of transportation, industry and other sectors increases around the globe.
- Idaho National Laboratory (INL) has been involved in collaborative materials research and modeling of High Temperature Steam Electrolysis (HTSE) components and systems for several years. Process modeling on a large variety of projects has led to foundational knowledge supporting technoeconomic assessments (TEAs) of hydrogen production plants.
- Several INL evaluations have been performed on behalf of commercial vendors under DOE Strategic Partnership Projects. The INL reference design and cost analysis can be used to determine steps to reducing the levelized cost of hydrogen (LCOH) to disruptive levels that will meet the Department of Energy cost target of producing hydrogen for less than $2/kg by 2025 and approaching the Earthshot goal of $1/kg by 2030.
- This slide deck summarizes the highlights of a recent HTSE process analysis completed by INL in which a light water reactor (LWR) nuclear power plant (NPP) provides the energy input for a gigawatt-scale installation. Complete details of the analysis are provided in:

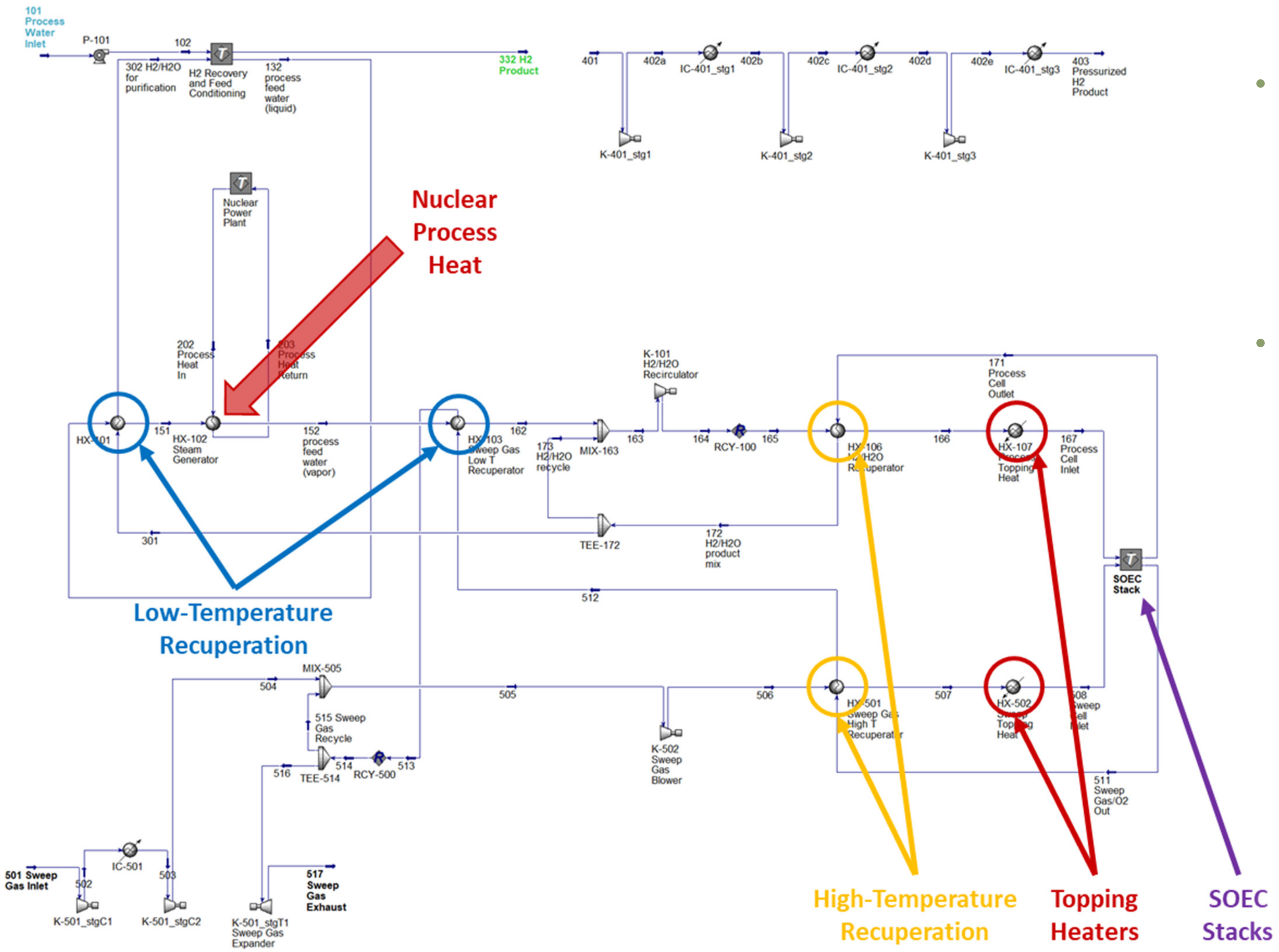
  Wendt, D.S., Knighton, L.T., and Boardman, R.D. “HTSE Process Performance and Cost Estimates.” Idaho National Laboratory, 2022. INL/RPT-22-66117

LWR-HTSE System Overview

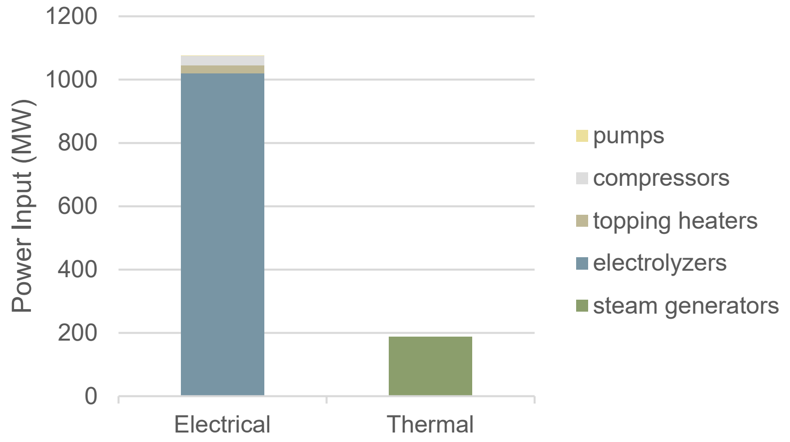


- In a gigawatt-scale LWR-HTSE system, the LWR NPP is used to generate electrical power for HTSE process, as well as to provide heat input for vaporizing HTSE process feedwater
- A thermal energy delivery loop is used to transport heat from the LWR NPP to the HTSE process (distance of 1 km assumed for risk mitigation purposes)
- In the LWR-HTSE configuration, the LWR can be operated at full power output, while the HTSE plant can be operated as a dispatchable load to enable the net power output to the electrical grid to vary in response to fluctuations in electrical market demand (and electricity prices)
- This analysis considers only the case of steady-state hydrogen production, with a constant hydrogen production rate. Process performance and cost estimates for this operating scenario are provided.
- Evaluation of dynamic operating mode performance and economics are evaluated in separate current and previous studies performed by INL and collaborators.

HTSE Process Flow Diagram



- A gigawatt-scale LWR HTSE process design model was developed and used to evaluate steady state constant hydrogen production scenarios
- An HTSE process utilizing all energy output from an LWR NPP would require approximately 5% of the LWR total steam flow to provide the process-heat input, while the balance of the LWR steam flow would continue to be used to drive the steam turbines/generator that produce the electrical power used to meet the HTSE process electrical power demands.
- Heat from LWR is used for vaporizing HTSE process feedwater at moderate temperature (<200°C); the SOEC stack operating temperature is achieved through use of recuperation (heat exchange with HTSE product stream) and high-temperature topping heat (provided by electrical resistance heaters)



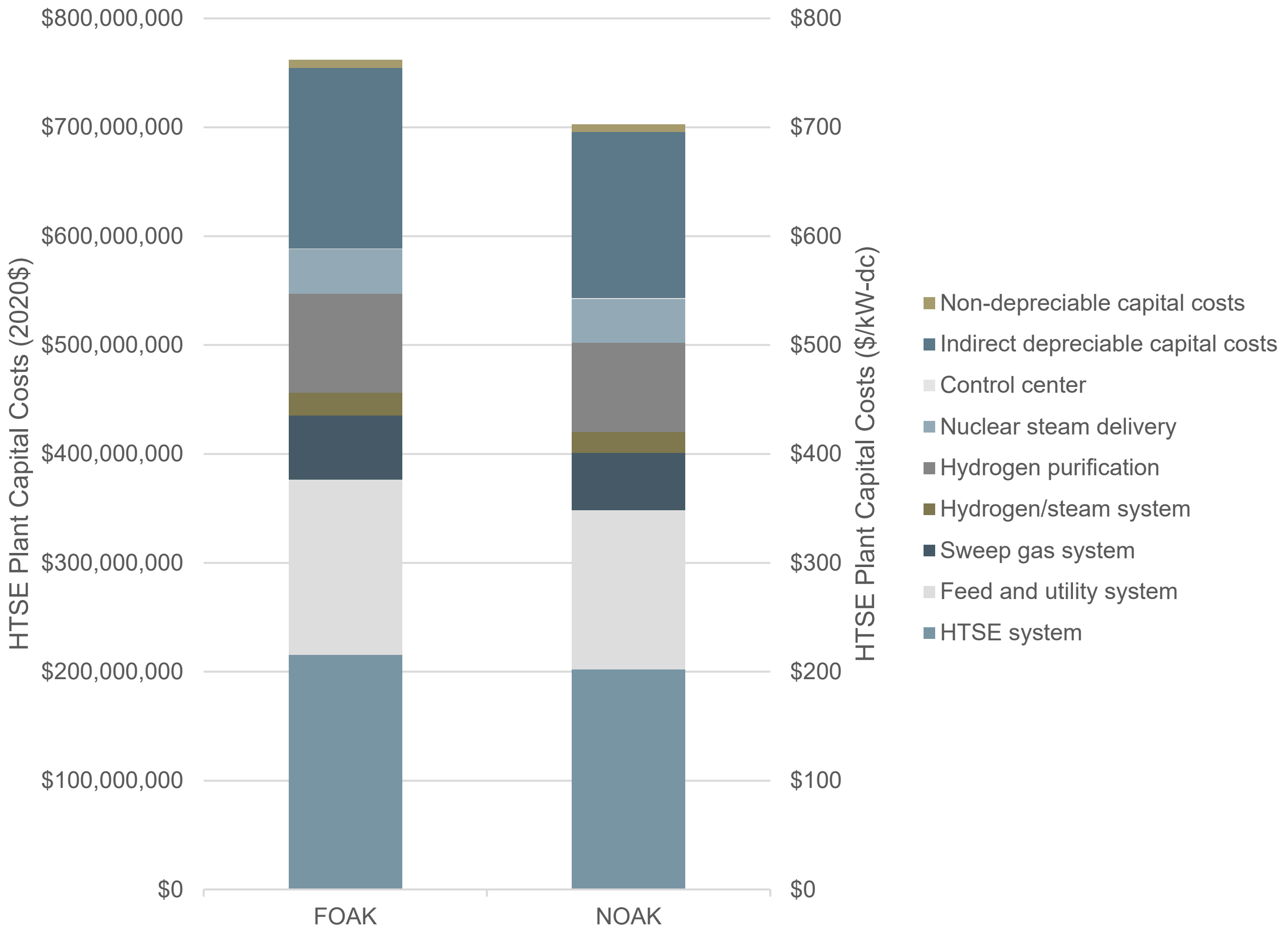
HTSE Performance and Cost Summary

- The table at right summarizes the HTSE process design basis, performance calculations, and cost estimates from steady state process analysis completed by INL.
- This baseline design and cost analysis provides INL's estimate of the operational parameters and costs for an Nth-of-a-Kind (NOAK) HTSE plant. Individual commercial HTSE suppliers will have performance and cost data that differs from that used in this analysis.
- All cost information for this analyses was calculated in 2020$. No attempt was made to quantify recent price inflation due to the COVID pandemic and/or other global factors.
- The integration with an LWR plant included basic cost estimates for nuclear process heat delivery equipment such as piping and heat exchangers to transfer thermal energy to the HTSE process for use in vaporizing the process feedwater. No allowance was made to estimate costs of equipment modifications inside the nuclear plant boundary, specific nuclear permitting, nuclear code compliance etc.

Description	Value	Note
Plant Design Capacity	702 tonnes/day	99.9 mol% hydrogen at 20 bar
Power Requirements	1076 MW_e 188 MW_t	Electrical power corresponds to total AC power requirement, including inverter power to provide 1000 MW-dc to SOEC stacks
Operating Capacity Factor	87.1%	Accounts for plant shutdowns as well as cell degradation
Actual Hydrogen Production Rate	611 tonnes/day	
Efficiency (HHV)	90.2%	Includes both thermal- and electrical-energy consumption
Stack Operating Pressure	5 bar	Based on maximizing system efficiency by trending operating pressure and steam utilization versus system efficiency
Steam Utilization (conversion of reactant steam)	80%	
Electricity Required	36.8 $kWh_e/kg\text{-}H_2$	
Thermal Energy Required	6.4 $kWh_t/kg\text{-}H_2$	
Technology Horizon	NOAK, 95% learning rate	Nth-of-a-Kind defined as 2.5 GW-e of previous HTSE plant installations
Stack Cost	$78/$kW_{dc}$	Electrode-supported with 1,000 MW/yr manufacturing rate
Stack Service Life	4 years	Assumes annual stack replacements to restore the HTSE plant design-capacity rating at the start of each operating year.
Direct Capital Cost	$544/$kW_{dc}$	GW-scale NOAK Plant
Total Capital Investment	$703/$kW_{dc}$	GW-scale NOAK Plant
Levelized Cost of H_2 (HTSE)	$1.86/kg	At $30/MWh electricity cost; excludes application- and/or site-specific product storage and transport costs. Does not include high-pressure product hydrogen compression beyond 20 bar

GW-Scale LWR-HTSE Plant CAPEX

- A summary of the HTSE plant capital cost estimates for first-of-a-kind and Nth-of-a-kind plant types are provided in the chart on the right.
- The capital cost estimates include the SOEC stacks and HTSE balance of plant equipment (25 MW_{dc} modular block construction basis), as well as the capital costs for the nuclear process heat delivery system, utility systems, control center, etc.
- Costs are provided in terms of total capital costs in 2020$ (left vertical axis), as well as unit costs in 2020$/$kW_{dc}$ (right vertical axis)
- The indirect capital costs include site preparation (2%), engineering & design (2.3%), process & project contingency (8.8%), contractors fee (10%), legal fee (5%), and land (1%). Values are percentages of the HTSE process direct capital cost.



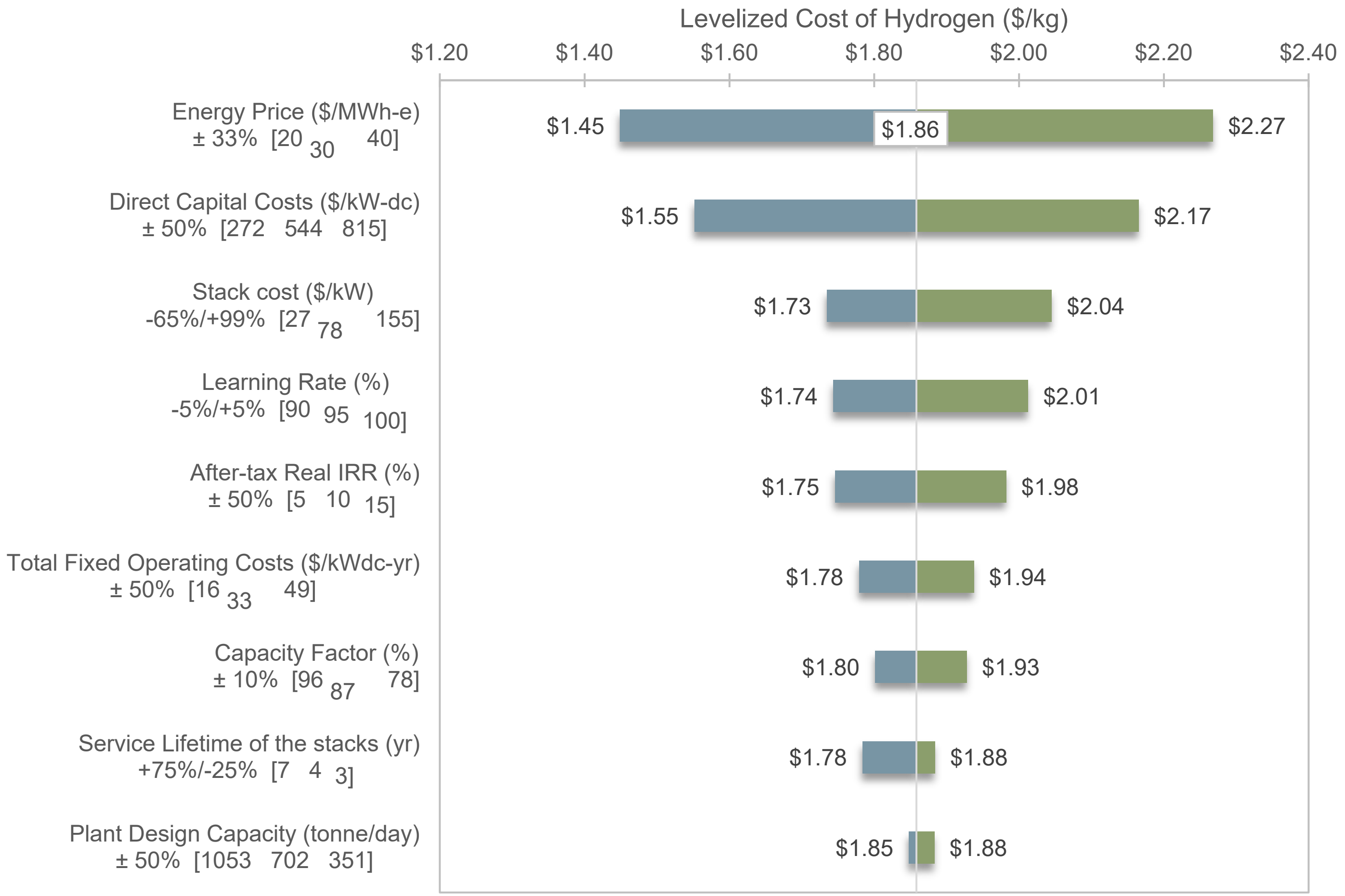
NOAK GW-Scale LWR-HTSE Levelized Cost of Hydrogen Analysis

- A levelized cost of hydrogen (LCOH) analysis was calculated in the DOE H2A model using the process and cost estimates from the INL HTSE process evaluation.
- Financial input parameters are provided in the table below; A breakdown of the LCOH cost components is provided in the chart at right
- The projected $1.86/kg LCOH for a NOAK GW-scale LWR-HTSE plant does not include product transportation or storage costs. Potential revenues from oxygen byproduct sales, capacity payments, or clean hydrogen production credits are similarly not included

Start-up year	2025
Length of construction period	1 year
Start-up time	1 year
Plant life	20 years
Depreciation schedule	20-year MACRS
% Equity financing	40%
Interest rate on debt	3.7%
Debt period	20 years
% of fixed operating costs during start-up	100%
% of revenues during start-up	50%
% of variable operating costs during start-up	75%
Decommissioning costs (% of TDC)	10%
Salvage value (% of TCI)	10%
Inflation rate	1.9%
After-tax real internal rate of return (IRR)	10%
State taxes	6%
Federal taxes	21%

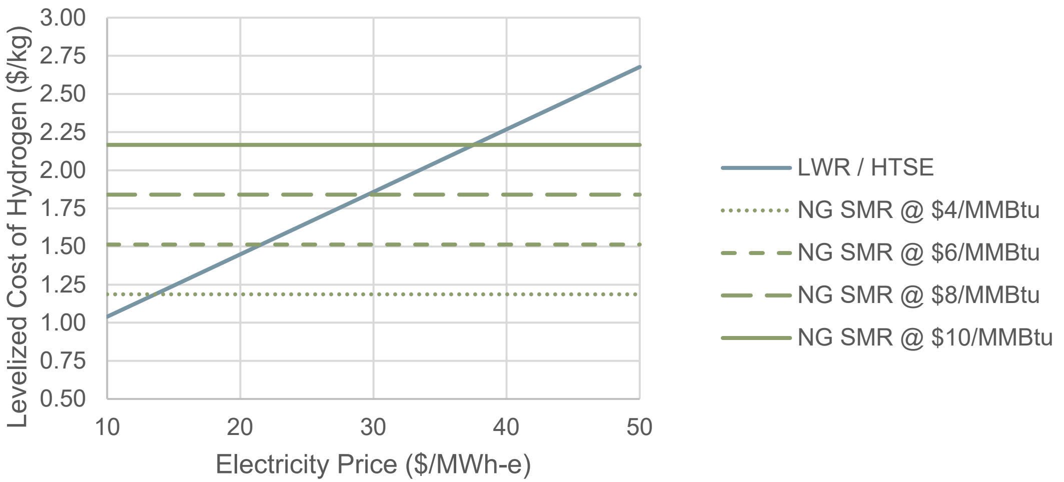
HTSE Levelized Cost of Hydrogen

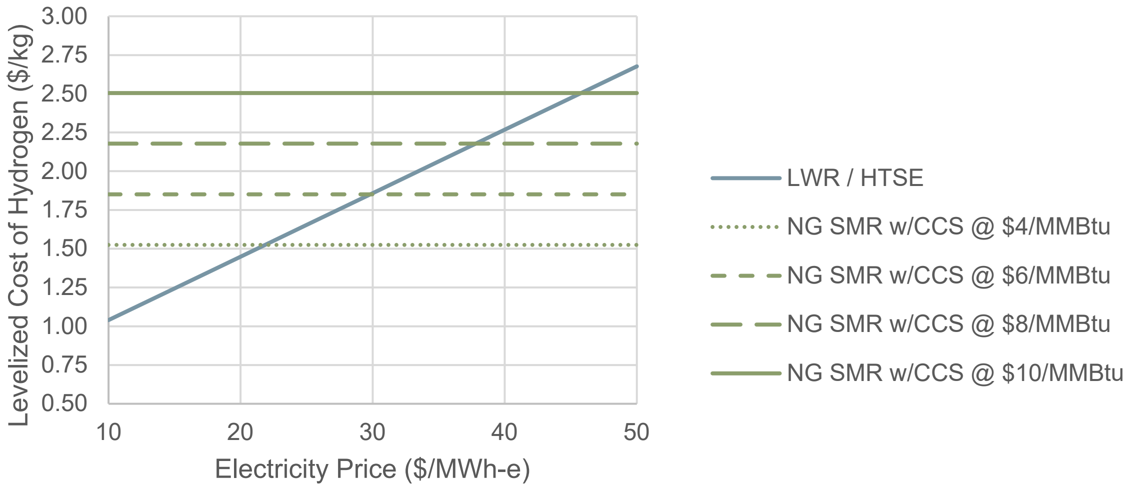
- Sensitivity analysis was performed to evaluate the impact of energy price and other key variables on the LCOH production
- Electricity price and HTSE plant DCC are the parameters with the greatest impact on LCOH. \$30-40/MWh_e is representative of estimated NPP power sales revenue into unregulated markets; \$20/MWh_e is lower bound for expected NPP O&M costs (and minimum price for NPP generated power).
- A second set of variables including the stack cost, learning rate, IRR, total fixed operating costs, stack service life, and capacity factor have a medium impact on the LCOH.
- Once NOAK plant status has been achieved and defined as the previous deployment of N = 100 count of 25 MW_{dc} modular blocks, or 2.5 GW_e of production capacity, and a base plant capacity of several hundred MW is considered, perturbations to these variables have a less-pronounced impact on LCOH than the sensitivity variables identified above.



HTSE LCOH vs Electricity Price; Comparison with NG SMR LCOH

- As identified by the sensitivity analysis, electricity price is a major cost driver for LWR-HTSE LCOH. The plots at right show LWR-HTSE LCOH as a function of electricity price.
- The LWR-HTSE LCOH is compared with the LCOH of hydrogen production via the Steam Methane Reforming (SMR) process with comparable production capacity, product purity, and product pressure specifications. The SMR LCOH is a strong function of natural gas price; the SMR LCOH at several selected natural gas prices are included in the comparison plots.
- SMR is characterized by large CO_2 emissions. The upper plot provides estimates of SMR LCOH with unabated CO_2 emissions while the lower plot provides estimates of SMR LCOH with CO_2 capture and sequestration (calculated in H2A for an SMR plant with similar production capacity to the HTSE plant).
- The SMR CCS costs are a function of plant capacity due to economies of scale in the capture and transport equipment; CCS costs for SMR would increase for an SMR hydrogen production rate less than 612 tpd, which is the basis for the CCS cost estimates presented in the plot at the bottom right.
- The plots at right suggest that in the absence of a clean hydrogen production credit, LWR-HTSE with an electricity price of \$20-40/MWh-e would be cost competitive with SMR with a natural gas ranging from \$6-10/MMBtu (SMR w/o CCS) or \$4-8/MMBtu (SMR with CCS)





Hypothetical Scenario to Achieve $1/kg DOE Hydrogen Cost Target

- To show a potential path to reach a hydrogen production cost of $1/kg, a hypothetical scenario informed by the sensitivity analysis was constructed and added to the 'waterfall' chart in the figure at right; note that the value of the CAPEX specified in the waterfall chart differs from the lower bound specified in the tornado chart.
- In addition to the reductions in energy price, operating parameters, and capital and operating costs, it may also be possible to obtain an additional source of revenue from oxygen byproduct sales or clean hydrogen production credits that could maintain the prospect of $1/kg hydrogen from HTSE in the event challenges are encountered in achieving the parameter specifications detailed in the waterfall chart.