NX Fuels H2 Shot Incubator Phase I

Cooperative Research and Development Final Report

CRADA Number: CRD-22-23256

NREL Technical Contacts: Todd Deutsch,
Kevin Topolski, and Jamie Kee

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Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5900-88983
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Cooperative Research and Development Final Report

Report Date: February 22, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: NX Fuels, Inc.

CRADA Number: CRD-22-23256

CRADA Title: NX Fuels H2 Shot Incubator Phase I

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen Fuel Cell Technologies Office (HFCT)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$50,000.00
TOTALS	$50,000.00

Executive Summary of CRADA Work:

NX Fuels will work with NREL to perform Life-Cycle Analysis (LCA) and Techno-Economic Analysis (TEA) for NX Fuels' solar H_2 system. TEA/LCA modeling developed early on will provide insight on the most critical parameters related to the green H_2 cost and environmental impacts and help us create the business case at scale. This project will advance the Nation's decarbonization goals by demonstrating the economic feasibility of NX Fuels clean hydrogen production pathway and evaluate its impact on CO_2 emissions.

Summary of Research Results:

Task 1: Solar H2 System Model

TEA and LCA seek to forecast the unit cost and environmental impact of industrial-scale processes by using mathematical formulas based on smaller, prototype versions with capital and operating inputs. In order to perform TEA and LCA, both the performance specifications and the components that constitute the solar hydrogen system must be known. The prices of these photoreactor constituents are used as inputs in the TEA to calculate the hydrogen production costs. The composition and quantity of each component are used to calculate embodied emissions in the LCA. NX Fuels shared schematics and the bill of materials for their prototype photoreactor allowing NREL to perform the following tasks.

Task 2: Conduct TEA and LCA

NREL performed TEA and LCA based on the model defined in Task 1. TEA was based on the publicly available H2A discounted cash flow rate of return analysis tool using existing case studies as a starting point. The LCA used the publicly available Greenhouse Gases, Regulated Emissions and Energy Use in Technologies (GREET) model to evaluate energy use, energy efficiency, and avoided carbon emissions compared to a hydrogen production technology baseline. The methodology and results from the TEA and LCA are detailed in Task 5.

Task 3: Design Consultation Based on Initial Results

After performing a preliminary TEA, NREL discussed the results with NX Fuels and used sensitivity factors to suggest prototype design improvements. Sensitivity analysis identifies the performance metrics, capital and operating costs that have the greatest impact on levelized cost of hydrogen. The results of the sensitivity analysis and design suggestions are described in Task 5.

Task 4: Train TEA/LCA Model Training

Because the TEA tools (H2A and H2FAST) and LCA tool (GREET) are publicly available, anyone with training and basic technical acumen should be able to use them. NREL scheduled a 2-hour virtual meeting on July 5, 2023, where they demonstrated the TEA/LCA models so NX Fuels could become proficient in their use. NREL shared copies of the spreadsheets used for calculations and demonstrated the impact of design modifications emerging from Task 3 on performance and, ultimately, the levelized cost of hydrogen produced.

Task 5: Project Final Report

NREL prepared a final project report that summarizes the TEA/LCA methodology and results from scaling NX Fuels' prototype device. The complete final report appears below.

NREL <> NX Fuels H-SHOT Phase I report

Kevin Topolski, Jamie Kee, Todd Deutsch

NREL

Introduction

This document discusses the analysis conducted by NREL under the H-Shot Phase I program. Per the agreed-upon scope established at the outset of this project, both a preliminary techno-economic analysis (TEA) and life cycle analysis (LCA) were performed. The following analyses incorporate a combination of values provided by NX Fuels, literature, and cost correlations from available models. While these analyses present a $/kg levelized cost as well as a CO_2 emissions estimate for hydrogen (H_2) production under the NX Fuels technology concept, these are still preliminary and would benefit from continued refinement as the technology advances and scale-up considerations are better understood.

System Sizing and Costing

The targeted NX Fuels system is an array of 10-panel modules capable of producing 1000 kg of H_2 per day on average. Hydrogen and oxygen are co-evolved in the NX Fuels reactor and is assumed to be produced at atmospheric pressure. A gas separation system is downstream of the NX Fuels reactor to separate the photoelectrochemical (PEC) reaction products into streams that are predominantly H_2, oxygen, and water vapor, respectively. Inputs to the overall NX Fuels systems consist of sunlight, water, and electricity. The NX Fuels system boundary is defined to include the PEC reactor as to provide a comparable analysis to the PEC systems modeled in a James et al., 2009 as shown in Figure 1.

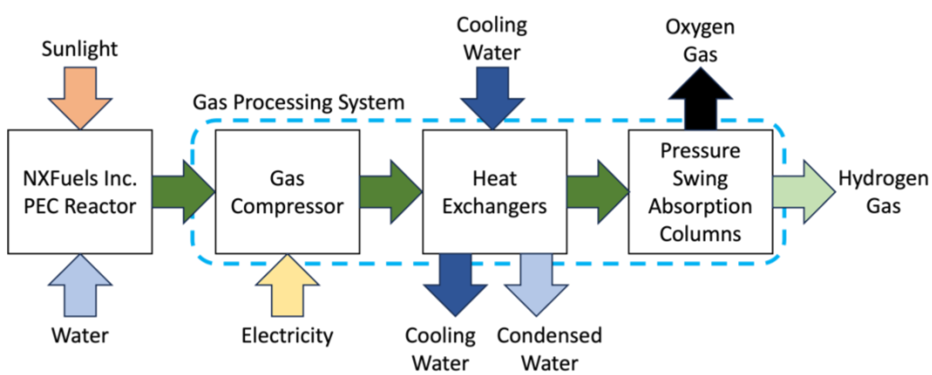

Figure 1: Block flow diagram of the NX Fuels system highlighting the equipment evaluated under this study.

It is important to note that the NX Fuels system's operation is inherently dependent on the available sunlight and does not contain built-in storage or buffers. As such, the gas processing equipment that makes up the NX Fuels system is sized to the peak H_2 production rate, which is oversized relative to the 1000 kg of H_2 per day average production rate. Equipment sizing is therefore dependent on local solar availability which informs H_2 peak production rates, in addition to the average production rate targets. This study used the solar availability in Daggett, California to present ideal environmental conditions to evaluate the techno-economic performance of the NX Fuels system upon.

Daggett is located in Southern California and is often used as a best-case location to demonstrate solar-powered system economics. This is because this location experiences high direct normal irradiance (DNI) relative to other locations in the United States. This study assessed the average annual DNI from 1998 to 2020 and determined the max DNI for that same period. The data regarding average annual and maximum DNI is presented in the Appendix. Table 1 shows aggregate statistics and analysis for DNI from 1998 to 2020.

Table 1: Aggregate statistics and analysis on Direct Normal Irradiance (DNI) data from 1998 to 2020 (Sengupta et al., 2018)

Average DNI	7,835.38	Wh/m^2-day
	326.47	W/m^2
Maximum DNI	1056	W/m^2
Shading Loss	8%	
Refractive Loss	5%	
Average DNI with Refractive and Shading Losses	6816.78	Wh/m^2-day
	284.03	W/m^2
Maximum DNI with Refractive Loss	1003.2	W/m^2
Capacity Factor	28%	
Maximum:Average Production Ratio	3.53	

The average DNI from 1998 to 2020 was assessed to be 7,835.4 Wh/m^2-day or 326.5 W/m^2, whereas the maximum DNI during this period is 1,056 W/m^2. This study applied 8% shading and 5% refractive loss factors from James et al., 2009 to these average and maximum DNI values. These losses represent the percent of solar radiation that is not absorbed by a solar collector and accounts for radiation losses due to shadowing of nearby solar collectors, other equipment, and solar collector window refraction. The shading loss is, however, only applicable to the average DNI values as the maximum DNI value assumes no shading at peak solar insolation. The resulting average and maximum DNI values were then used to compute a nominal capacity factor and maximum average production ratio. The former metric is the percentage of time the H_2 production plant is operating at capacity and the latter metric is used for up-sizing equipment in this H_2 production plant for feasible operation given local solar radiation.

NX Fuels Reactor

The cost and performance assumptions were based on the photoreactor demonstrated by NX Fuels that uses a Fresnel lens to focus the direct portion of impingent solar radiation on a semiconductor photoabsorber. NX Fuels provided a schematic of the reactor chamber that the following analysis was based on.

Gas Processing System

A gas processing system is required downstream of the PEC reactor to separate the product stream into H_2, oxygen, and water streams before storage and ultimately, consumer use. This study adapted the gas processing system modeling from James et al., 2009 to determine equipment sizes, equipment capital costs and utility requirements. Figure 2 shows the gas processing system modeled in this study consists of a condenser, a two-stage compressor with intercoolers and pressure swing absorption (PSA) columns. This study chose to model pressure swing absorption for gas separation as it is a mature technology and as James et al., 2009 identified it as a superior option compared other gas separation methods such as temperature swing absorption and membrane separation. Table *2* describes the key streams of interest in the gas separation system.

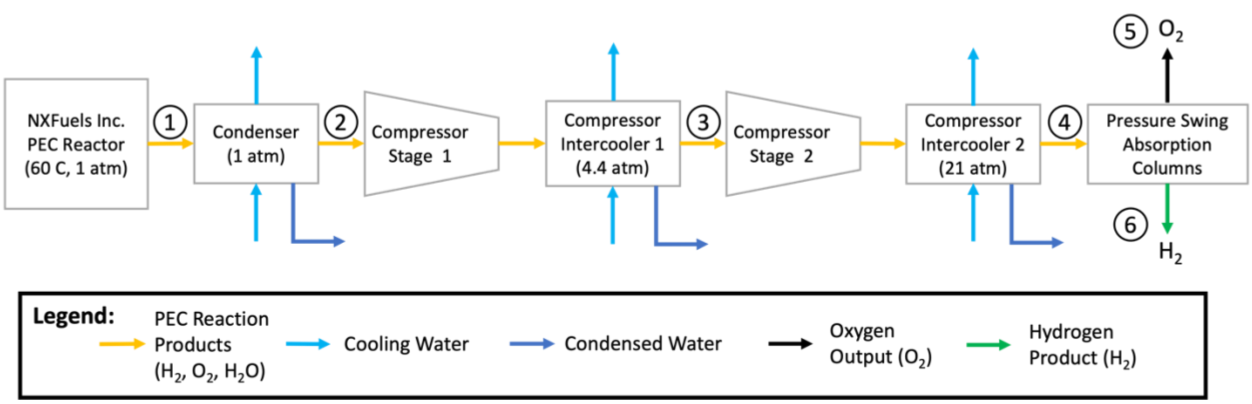

Figure 2: Visual representation of the gas processing system downstream of the NX Fuels PEC reactor with stream ID numbers

Table 2: Gas separation system stream table with average mass and mole flowrates

Stream ID	1	2	3	4	5	6
Temperature (°C)	60	40	40	40	40	40
Pressure (atm)	1	1	4.4	21	1	20
Mole Flow (kmol/d)	1,036	891	841	830	334	496
Mass Flow (kg/d)	13,699	11,083	10,182	9,983	8,983	1,000
Mole Fraction						
H2	0.5320	0.6187	0.6555	0.6643	0.0124	1
O2	0.2660	0.3094	0.3278	0.3321	0.9816	0
H2O	0.2020	0.0719	0.0167	0.0036	0.0060	0

Gas compression from ambient pressures to 305 psig (21 atm) is required to enable downstream gas separation at the PSA sub-system. This study adapted the 21:1 compression ratio, 2-stage compressor in James et al., 2009 for equipment sizing and to determine equipment costs. Stream 2 in Figure 2 is used as a basis to size the gas compressor within NX Fuels' gas processing system. This study applied a $9,519.73/(kmol gas/hr) cost factor, consistent with James et al., 2009, to determine uninstalled compressor costs. This study also used a 3.53 peak:average production rate sizing ratio derived from Daggett, CA solar DNI profiles to determine compressor size for peak process production rates. Compressor unit power requirements were determined by dividing compressor capacity by the NX Fuel process H_2 production rate. Sizing and costing results are summarized in Table 3.

Table 3: Compressor sizing, equipment, and operation cost results for the NX Fuels gas processing system

Compressor sizing, equipment, and operation cost parameters			
Compressor Average Flowrate		37.1	kmol/hr
Compressor Peak Flowrate		131.09	kmol/hr
Compressor Stage-Specific Head	**Stage 1**	6,164.21	kJ/kmol
	Stage 2	6,691.45	kJ/kmol
Power Consumption at Average Compressor Inlet Flowrate Conditions		132.54	kW
Power Consumption at Peak Compressor Inlet Flowrate		468.13	kW
Compressor Unit Power Consumption		3.18	kWh/kg
Compressor Uninstalled Cost		$1,247,948	
Installation Factor		1.3	
Compressor Installed Cost		$1,622,333	

This study used the Type 1 PEC system, described below, gas separation section in James et al., 2009 as a basis to size and cost the condenser and compressor intercoolers in the NX Fuels process system given the same modeled process conditions (temperature, pressure, and gas composition) between the two systems. As such, heat exchanger sizing in this report made the following simplified assumptions to enable equipment costing:

1. Heat exchanger operating conditions (pressures, temperature, gas composition) are the same as what is provided in James et al., 2009 for the Type 1 PEC system

2. Heat exchanger and condenser equipment have same overall heat transfer coefficients as the equipment sized in James et al., 2009 for Type 1 system

3. Given assumptions 1. and 2., heat exchanger and condenser equipment costs scale with process gas flowrate

4. Heat exchanger, condenser and water pump equipment cost scale reasonably at a 0.6 scale-up factor for extrapolation (Dysert, 2003)

The NX Fuels condenser and compressor intercooler costs computed in Table 4 below were calculated by scaling the Type 1 PEC system heat exchanger equipment costs to the condenser and compressor intercoolers flowrate data shown in Table 2.

Table 4: Heat exchanger sizing and equipment cost results for the NX Fuels gas processing system

Heat Exchanger ID	Average Mass Flowrate (kg/hr)	Peak Mass Flowrate (kg/hr)	Heat Exchanger Uninstalled Equipment Cost	Heat Exchanger Installed Equipment Cost
Condenser	571	2,016	$26,233	$29,381
Intercooler 1	462	1,631	$28,826	$32,285
Intercooler 2	424	1,498	$29,685	$33,247

Lastly, the PSA system was sized by applying the peak:average production rate ratio of the NX Fuels gas processing system to the average H_2 production flowrate. We assume a H_2 recovery fraction of 90% and a pure H_2 product stream outlet, similar to James et al., 2009. The PSA system uninstalled costs shown are calculated using PSA cost correlations and installation factors taken from Penev et al., 2018.

Table 5: Pressure swing absorption system sizing and cost results for the NX Fuels gas processing system

PSA Sizing and Capital Cost Assessment		
Average Flowrate Capacity	1,000	kg H2/day
Peak Flowrate Capacity	3,532	kg H2/day
PSA System Uninstalled Cost	$249,253	
Installation Factor	1.17	
PSA System Installed Cost	$291,626	

Techno-economic analysis

A TEA was performed on the system illustrated in Figure 1, which is inclusive of the PEC reactor, compressor, cooling system and PSA system. This TEA is delivered using both the H2A (NREL, 2018) and H2FAST (Penev et al., 2017) tools. H2A is H_2 production pathway-centric economic tool developed by NREL to assess LCOH, given economic parameter inputs such as capital expenses, operating expenses, and financing. To account for inflation the H2A inputs are in 2005 reference year dollars while outputs are currently reported using 2016 as the reference year. NREL has developed H2A case studies to include several PEC H_2 production configurations. The two most relevant production configurations are a Type I system where photocatalyst particles co-evolve H_2 and oxygen, and the Type IV system that uses a planar photoabsorber with optical concentration on a two-axis tracker. The Type IV system assumes that pure (i.e., not mixed with oxygen) H_2 is produced at an elevated pressure so no gas handling equipment is required. However, this is not the case for the NX Fuels system that produces a mixed stream of $H_2/O_2/H_2O(g)$. The analysis below used a Type IV system to evaluate the

LCOH without gas handling with Type I methodology and H2FAST to calculate the added cost of transforming a stream of mixed gases at 1 atm to pure H_2 at 300 psi. H2FAST is similar to H2A, but provides a more rigorous, generally accepted accounting principles financial analysis and can remain agnostic to the technology pathway. In both tools, the LCOH is determined as the sale price of H_2 to achieve an investor cash flow net present value of $0, while satisfying a user-defined internal rate of return.

TEA standardization requires comparing multiple scenarios at the same production rate, which H2A has established as 1 tonne per day (TPD) as the targeted output for PEC systems. Raw material and labor for site preparation is, therefore, a function of performance as a system with twice the efficiency will need half the absorbers and land area. The first step in calculating cost is to determine the capture area, defined as the surface area in m^2 that the solar photons strike, in this case Fresnel lens area, which can be found using the following equation:

$$\text{Capture area} = \frac{\text{LHV (33.33 kwh/kg}}{\text{Insolation (kwh/m}^2\text{/d} * \text{STH} * \text{Optical Efficiency} * \text{Separation Efficiency}}$$

Where the insolation is the location-specific, average daily insolation (derated for shadowing), LHV is the lower heating value of H_2, STH is the solar-to-hydrogen efficiency, optical efficiency is the combined losses off the front and back surfaces of the Fresnel lens and the front and back surfaces of the electrolyte-holding vessel, and separation efficiency is the percent recovery of H_2 from the $H_2/O_2/H_2O$ mixture (assumed to be 0.9). The semiconductor absorber area is found by dividing the capture area by the concentration factor, which was 50 for all calculations. The next cost to consider is that of the collector, which we define here as the Fresnel lenses, PEC reactor (minus the semiconductor absorber), associated piping, and tracker. These costs will also be a function of the capture area, which itself primarily depends on STH efficiency, and should be in units of $/m^2. A detailed analysis of all of these components is beyond the scope of this preliminary TEA and a value of $68/m^2 was used. This was justified by roughly estimating $100/m^2 in 2022 dollars, deflated using historical consumer price index data to the 2005 reference year used in H2A, to get $68/m^2 in 2005 dollars. In addition to capital costs, replacement costs also need to be considered and entered into H2A case studies. There are two kinds of component replacements with specific associated costs. First, the semiconductor absorber always experiences a diminished performance with time and must be periodically replaced below some performance threshold, this is a parameter is known as absorber lifetime. Second, H2A assumes a complete overhaul of the entire system at halfway through the 40-year plant lifetime. While not a replacement cost, H2A includes an annual factor (called "unplanned replacement") to account for building more subunits to counter diminished performance to maintain the constant 1 TPD output. The H2A defaults to 0.5% of total direct depreciable capital which we found to be a significant contributor to LCOH. We instead set this value to zero and manually entered a yearly capital cost of 3% (the assumed decline in PEC performance) of the total collector, absorber, and foundation/erection.

After determining capital and replacement costs enumerated above, the baseline LCOH without gas handling (collection, separation, and compression) was found to be $3.06/kg$H_2$ with the following inputs into H2A: 15% STH efficiency, $68/m^2 concentration/containment, 0.9 plant capacity factor, 86% optical efficiency, using an absorber that costs $250/m^2 and lasts 5 years.

With the baseline LCOH as a starting point, we systematically changed single parameters to perform a sensitivity analysis. Sensitivity analysis is a powerful tool to identify factors that most influence LCOH. In practice, sensitivity analyses have a low, medium, and high value for each parameter and the medium value is held constant for all other parameters not being varied. For example, in Figure 3, STH efficiency is calculated at 10, 15, and 25% for the baseline values listed above for all other parameters. The DNI for Daggett, CA (7.24 $kWh.m^{-2}.d^{-1}$ considering shadowing) was used for all scenarios except for a single calculation to estimate the LCOH in Ann Arbor, MI (3.38 $kWh.m^{-2}.d^{-1}$ with shadowing) at baseline values for all other inputs. The results indicate that STH efficiency and the cost of the concentration/containment are largest levers influencing LCOH. This is an intuitive outcome considering the influence of STH efficiency on the quantity of materials needed for balance of plant (BOP) components and the concentration/containment is the areal BOP cost that largely makes up the capital and replacement costs. It should be noted that the 50x concentration mitigates absorber costs and lifetime that would have a much greater influence on LCOH in an unconcentrated system.

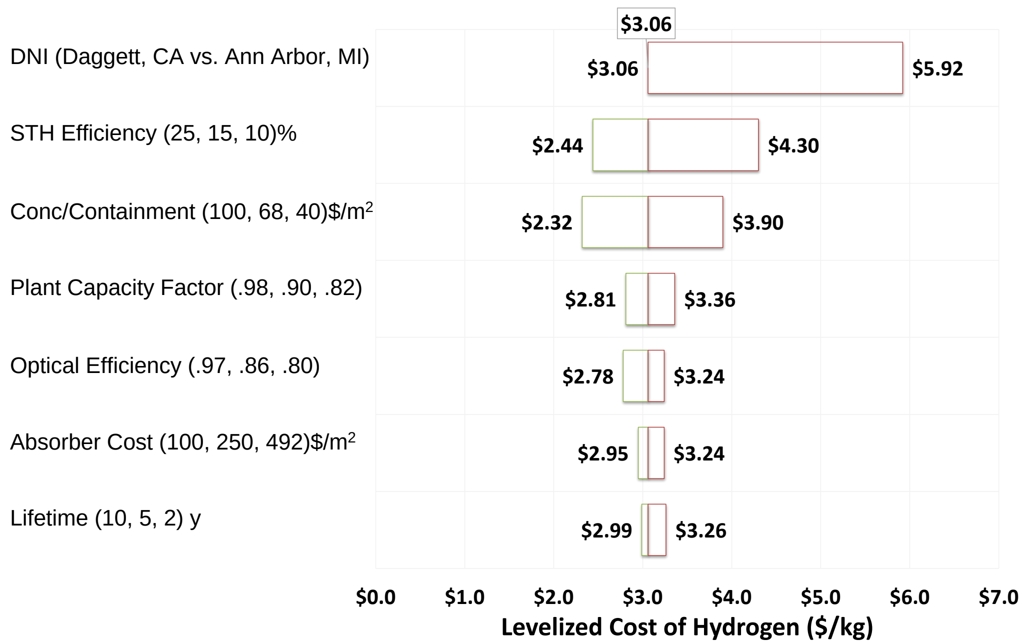

Figure 3: Sensitivity analysis showing how each factor influences LCOH from the baseline $3.06 $/kg.

The H2A analysis inputs were concurrently optimized (i.e., all values set to their most favorable) to identify conditions that would lead to <$1/kg LCOH. Maximizing all the parameters noted in the sensitivity analysis in Figure 3 yields an LCOH of $1.31. Increasing STH efficiency to 30%, lifetime to 20 years, and doubling plant capacity from 1 to 2 TPD results in $0.96 LCOH that does not include gas handling costs that would add another $1/kg. The components that account for this LCOH can be seen in Figure 4, with fixed operating costs, initial equity depreciable capital, and debt interest accounting for approximately 70%.

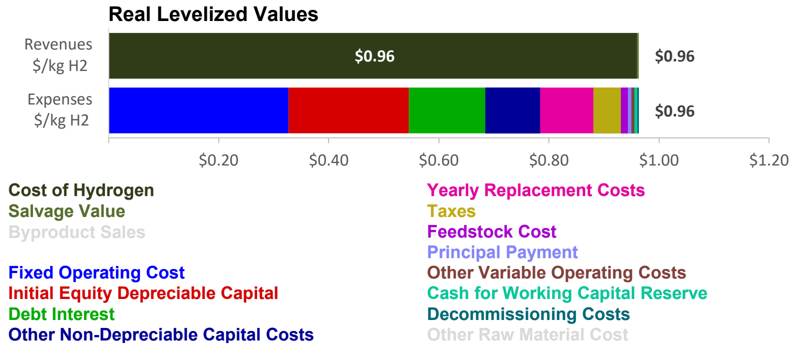

Figure 4: Breakdown of cost contributions for the fully optimized scenario that achieves <$1/kg LCOH.

To convey techno-economic results for the collective NX Fuels process system illustrated in Figure 1, this study applies "baseline" parameter values considered when projecting PEC technology development. Table 6 shows the parameter values that are defined for the subsequent results discussed in this report, along with the H2A LCOH resulting from those parameter values.

Table 6: PEC reactor system "baseline" parameters used in the TEA

PEC Reactor System Parameter	Value
Absorber Cost	$250/m2
Replacement Timeframe	5 years
STH efficiency	15%
H2A Levelized Cost of Hydrogen	$3.06/kg H2 in reactor outlet stream

Table 7 summarizes capital expenditure inputs for the gas processing system modeled in H2FAST. As could be seen below, the two-stage compressor that pressurizes the PEC reactor outlet gas from 1 atm to 21 atm represents the majority of the capital cost within the gas processing system at 80% of the subsystem capital cost.

Table 7: Capital expense inputs in TEA

Capital Expense	Value	Depreciation Schedule
Compressor	$2,182,037	20 yrs MACRS
Gas cooling system	$392,237	20 yrs MACRS
PSA system	$127,659	20 yrs MACRS
Total	$2,701,933	

Table 8 provides a summary of the feedstock unit usage and costs inputted into H2FAST. This table does not include feedstock unit usages and costs that are already captured within the H2A analysis. However, the impact of H2A feedstock unit usage and costs are represented as the levelized cost PEC reactor outlet H_2 in the first row of Table 8 titled "PEC Reactor Outlet H_2". The electricity use described in Table 8 refers to the power required by the gas processing compressors to pressurize the PEC reactor outlet stream for downstream gas separation.

Table 8: Feedstock usage and costs used in TEA

Feedstock	Unit Usage	Units	Costs
PEC Reactor Outlet H2	3.06	kg H2 in effluent/kg H2	$3.06/kg H2 in effluent
Electricity	3.181	kWh/kg H2	$0.07/kWh

Table 9 and Table 10 highlight the key design, operation, and financial parameters for the overall facility (as shown in Figure 1). The design and operation of this H_2 production facility is based on an average targeted H_2 production rate of 1 TPD. As seen in Table 9, the nameplate capacity of the facility is shown as significantly larger than the targeted production rate. This facility is sized significantly larger than the targeted production rate as to offset the facility's low capacity factor, which is a function of the peak and average solar irradiance for a given time duration. The remaining parameters in Table 9 and Table 10 define the financial structure, and have been set to match the default values set in H2FAST with exception to operating life, which is set to match the values used in H2A.

Table 9: Sales specification used in H2FAST TEA

Parameter	Value	Unit
Nameplate Capacity	3,532	kg/day
Product	Hydrogen	
Inflation	1.9	%
Operating life	40	years
Installation time	12	months
Demand ramp-up	0	years
Long-term utilization	28.31	%

Table 10: Financial parameters used in H2FAST TEA

Parameter	Value
Total tax rate	25.74%
Capital gains tax	15%
Leverage after-tax nominal discount rate	8%
Initial debt/equity financing ratio	1.5
Debt type	Bond debt
Debt interest rate	3.7%
Working capital	15%

The TEA for this study culminates in estimating the LCOH, which is given in units of \$/kg H_2. Figure 5 provides an output of H2FAST which shows a breakdown of major cost contributors to the LCOH. The LCOH could be observed as the H_2 sales value in this figure. As seen below, the cost of producing the H_2 from the PEC reactor outlet is the dominant operating expense. The discrepancy between the cost of producing H_2 at the PEC reactor outlet and the value shown in Table 8 is due to separation losses from the PSA equipment operation.

As shared before, the compressor capital cost and cost of electricity to operate the compressor serve as the highest cost contributors for the gas processing system. It should be noted that the gas processing system adds roughly an additional \$1/kg H_2 cost to the H_2 produced at the outlet of the PEC reaction. This additional cost is inclusive of all the gas processing system capital and operation expenses as well as also factoring in separation losses over the PSA equipment.

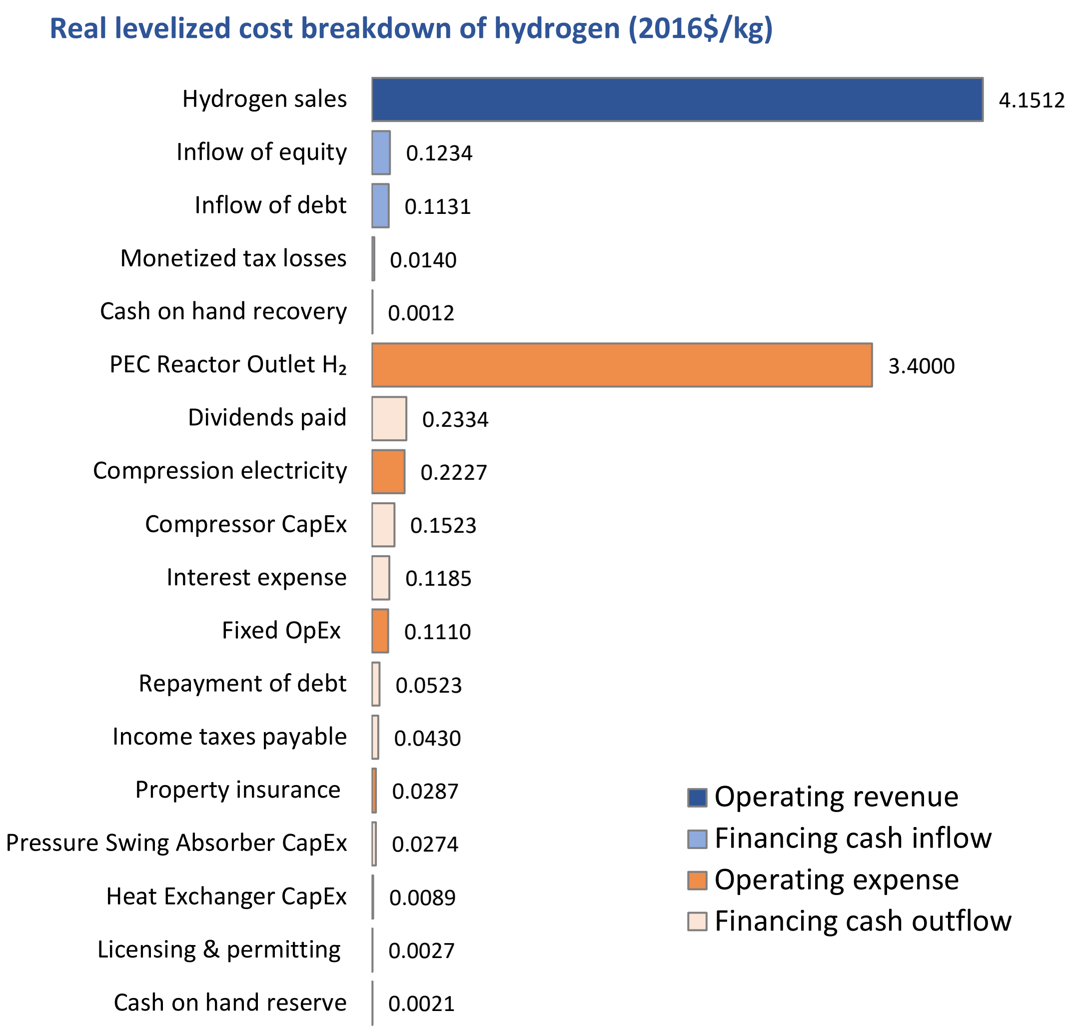

Figure 5: Levelized cost breakdown for the PEC reactor and gas processing system

Life cycle analysis

The life cycle analysis in this study is represented as emissions in units of $kgCO_2e/kgH_2$. The well-to-gate (WTG) emissions are used to qualify green H_2 production and is used in determining clean H_2 production tax credit brackets in the Inflation Reduction Act (i.e., 45V tax credit).

The WTG emissions encompass Scope 1,2, and 3 emissions. Scope 1 emissions are direct emissions from within the facility. Scope 2 emissions are embedded emissions associated with sourcing feedstocks. Scope 3 emissions are indirect emissions that occur both upstream and downstream. The WTG emissions are analyzed using the GREET tool (ANL, 2021) and grid emission rates from the EPA eGRID tool (United States Environmental Protection Agency (EPA), 2023).

The GREET model evaluates energy and emission impacts for H_2 production pathways. For solar applications as would be observed in the NX Fuels reactor, the Scope 1 emissions would be zero because there are no direct emissions coming from the facility. The Scope 2 and 3 emissions are modified from the solar electricity to H_2 production route. Regarding Scope 2 emissions, the only feedstock considered in the analysis is the electricity used in the compressor. The electricity usage for the compressor is 3.18 kWh/kg. Both the Scope 2 and 3 emissions are scaled in proportion to the electricity usage in this analysis.

The eGRID tool provides the grid emissions of each state and the resource mix of each state. Table 11 shows the grid emissions for the entire US at 0.3887 $kgCO_2e/kWh$ and California at 0.2179 $kgCO_2e/kWh$ using the CO_2 equivalent data set and year 2021 values. Note that eGRID does not account for line losses between generation and consumption which is estimated at 5%.

Table 11: Electrical grid emission for select US states

Location	Emission Intensity (kg CO2e/kWh)
US	0.3887
Florida	0.3799
Colorado	0.5554
Texas	0.3902
California	0.2179
Washington	0.0921
West Virginia	0.888

Table 12 shows the grid resource mix for California. In California, the grid is primarily powered by gas at 49.4%, followed by solar at 17.7% and nuclear at 8.4%. Many states have a renewable portfolio standard and expect to improve renewable penetration into the grid in the future.

Table 12: Electric grid resource mix in California

Resource mix	CALIFORNIA
Coal	0.1%
Oil	0.0%
Gas	49.4%
Nuclear	8.4%
Hydro	7.3%
Biomass	2.7%
Wind	7.7%
Solar	17.7%
Geo thermal	5.7%
Other Fossil	0.8%
Other Unknown	0.2%
Total	100%

Using the GREET values for Scope 1, 2, and 3 emissions scaled to the grid emissions and the electricity usage, the WTG emissions are expected to be approximately 0.817 $kgCO_2e/kgH_2$. This value uses the California 2021 grid mix as reported by the eGRID tool and the 3.18 kWh/kgH_2 electricity usage. Based on GREET, emissions from solar or wind generated electricity would be 0 $kgCO_2e/kWh$, but embodied emissions from electricity production may add emissions in the range of tens of grams of CO_2e/kWh.

Table 13: Emissions using California 2021 electrical grid

Emissions Category	Emissions Intensity (kg CO2e/kg H2)
Scope 1	0
Scope 2	0.689
Scope 3	0.085
Embodied emissions	0.044
Total	0.817

The embodied emissions for the parts and construction of the equipment for the NX Fuels reactor were estimated based on the life cycle analysis for a photovoltaic system (Fthenakis & Kim, 2013). Even though the technologies are not the same, this analysis provides an initial estimate of the life cycle emissions for the NX Fuels system. The study by (Fthenakis & Kim, 2013) provides equivalent CO_2 emissions per equipment item. The present analysis scaled the reported emissions to the size of the NX Fuels system and the production rate of H_2 to estimate a kg CO_2e/kg H_2. The total in Table 14 is scaled by the NX Fuels collector area (42000 m^2), the project lifetime (40 years), and H_2 production rate (1000 kg/day) to arrive at 0.037 kg CO_2e/kg H_2 for embodied emissions.

Table 14: Embodied emissions per component in units of m2 of collector area

Collector Area Component	Embodied emissions intensity (kg CO2e/m2)
Cells	1.75
Foundation	1.23
Frame	48.03
Fresnel lenses	25.92
Heat sink	88.99
Tracker	89.64
Hydraulic Drive	25.42
Motor	0.32
Cables	0.76
Controller	1.42
Anemometer and sensor	0.12
Assembly/Installation	0.03
Operation/Maintenance	7.03
Transportation	12.78
End-of-life	1.31
Total	307.77

Technical/Scientific recommendations

Because many of the inputs in TEA and LCA were estimates from hypothetical long-term operating conditions and performance, we recommend NX Fuels continues to build and test prototypes. By updating TEA and LCA models with empirically determined inputs, LCOH can be estimated with greater confidence. These prototypes should include not only the PEC reactor component but also gas handling equipment. Special attention should be paid to verify operation at 50x optical concentration and to accurately determine STH efficiency and absorber lifetime under such conditions. We also suggest NX Fuels persists in their effort to develop a continuous (vs. batch) mode of operation.

Summary/Conclusions

NREL used performance specifications and a bill of materials from a water-splitting photoreactor developed by NXFuels Inc to perform TEA to determine LCOH and LCA to evaluate the emissions intensity of the hydrogen produced. The analysis results suggest that a LCOH around $4/kg could be achieved if the “baseline” performance targets can be met.

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Appendix

Table: Direct Normal Irradiance (DNI) per year from 1998 to 2020 (Sengupta et al., 2018)

Year	Average Annual DNI		Max DNI (W/m^2)
	Wh/m2-day	W/m2	
1998	7853	327	1030
1999	8013	334	1031
2000	7843	327	1020
2001	7627	318	1001
2002	8085	337	1036
2003	7505	313	1011
2004	8075	336	1039
2005	7496	312	1013
2006	7712	321	1032
2007	8023	334	1023
2008	7837	327	1015
2009	7738	322	1009
2010	7753	323	1022
2011	7993	333	1028
2012	7773	324	1015
2013	7844	327	1043
2014	7796	325	1015
2015	7622	318	1013
2016	7896	329	1022
2017	7688	320	1027
2018	8057	336	1056
2019	7724	322	1036
2020	8261	344	1041

Task 6: Additional Tasks

No additional tasks were performed.

Task 7: CRADA Final Report

This report encompasses the completion and deliverable of the Article X requirement for the CRADA Final Report.

Subject Inventions Listing: None.

ROI #: None.