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Estimating the Value of Nuclear Integrated Hydrogen Production and the Dependency of Electricity and Hydrogen Markets on Natural Gas

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EXECUTIVE SUMMARY

Producing low carbon Hydrogen at a competitive price is one of the challenges to hydrogen being part of the solution to reach net-zero emission targets set by the U.S. Department of Energy (DOE) by 2050 [1]. With projected near-term improvements in technology, the U.S. DOE Light Water Reactor Sustainability (LWRS) program is researching hydrogen production via solid oxide electrolysis cell (SOEC) / high-temperature steam electrolysis (HTSE) integrated with existing light water reactor (LWR) Nuclear Power Plants (NPP)-HTSE that can produce carbon-free hydrogen competitively. In the near-term, a 10-year production tax credit (PTC) found in the Inflation Reduction Act (IRA) [2] has been passed, which will catalyze the development and improvement of hydrogen production technology to be competitive. The “1-1-1” target set by the U.S. DOE is to reduce the cost of carbon-free hydrogen by 80% to $1 per kilogram in 1 decade [3].

Several models are available to analyze the profitability, opportunity, and technical capability of NPP-HTSE systems. In order of complexity from most complex to least complex some of these models include RAVEN/HERON [4], process models using Aspen HYSYS [5] and capital expense estimations using Aspen Process Economic Analyzer (APEA) and levelized cost of hydrogen (LCOH) calculation using the H2A model (Hydrogen Analysis Model) [6], and custom spread sheets built by the interested party. Though some of the more advanced existing models provide detailed analysis of complex grid-integrated problems, they also can take considerable time to setup and run. These advanced models are well suited to complex grid-integrated analysis and the consideration of flexibility and variability of regulated and deregulated electricity prices and advanced estimation of capital and operating expenses and heat and material balances.

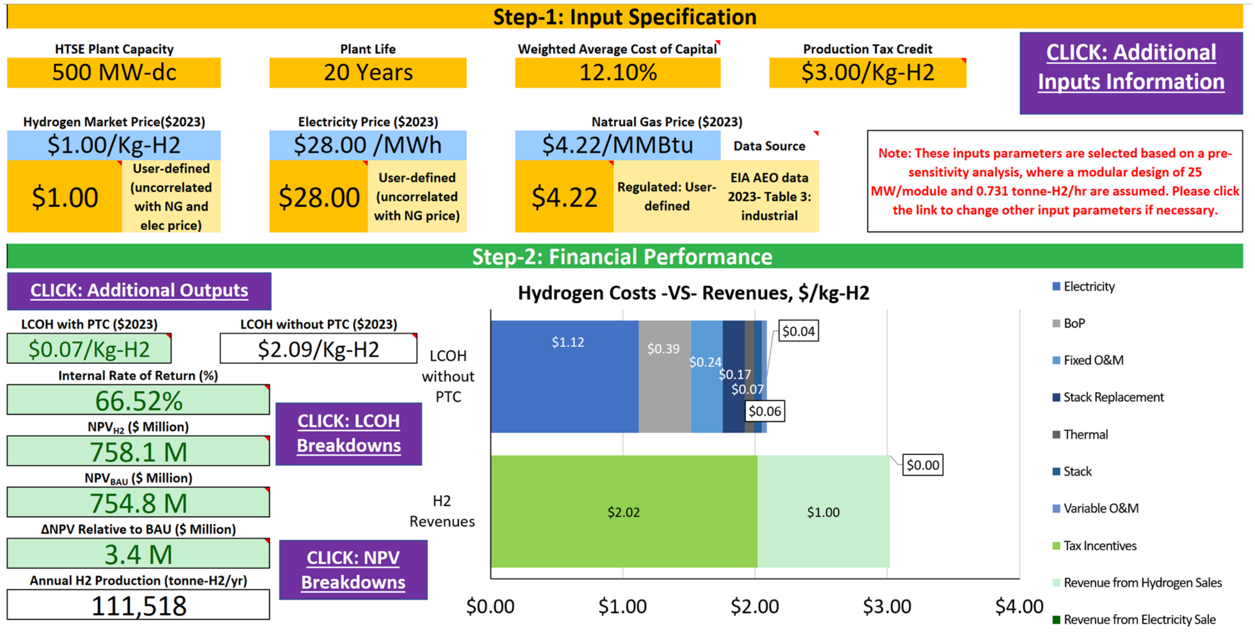
The purpose of this work reported herein was to specify, design, build, demonstrate, and deploy a simplified user-friendly NPP-HTSE hydrogen profitability analysis tool to provide utility companies operating NPPs with a quick and semi-intuitive interface to evaluate the opportunity of integrating HTSE hydrogen production with existing LWR NPPs. It is recognized that this tool has some limitations in that it cannot deal with the complex statistical variability of some grid-integrated problems for which the reader is referred to the more complex models referenced. However, it is expected that this tool will be useful in helping decision-makers to efficiently evaluate the hydrogen opportunity for existing LWR NPPs. It is important to note that this tool leverages and incorporates some correlations built from the existing, more complex models. As technology changes, some modifications to the process models and therefore to these correlations may be needed. It was decided to build this simplified tool in Microsoft Excel to maximize the usability and rapid deployment to NPP financial and technical decision-makers. The NPP-HTSE H_2 profitability tool has undergone verification against several existing models, continuous benchmark activities and beta tests with collaborating industry partners.

The NPP-HTSE H_2 profitability tool incorporates (1) discounted cash flow (DCF) and LCOH analysis, (2) sensitivity analysis with respect to the selected financial performance metrics and outputs ‘tornado’ charts, (3) profitability analysis represented by heat maps using the two most sensitive parameters, (4) electricity versus hydrogen production preference analysis by comparing the delta net present value (ΔNPV) between NPP-HTSE and business-as-usual (BAU) electricity production for the grid, and (5) competitiveness analysis by comparing the calculated LCOH for NPP-HTSE with that of SMR, which is the conventional process to produce hydrogen.

The hydrogen market price per kilogram of hydrogen production is a key input to estimate the revenue of hydrogen production. In the existing hydrogen market, most of the hydrogen is produced from steam methane reforming (SMR), which utilizes electricity and natural gas (NG) as the feedstocks. Some of the electricity used in the industry can be generated from NG. Therefore, there are dependencies between the hydrogen market price and NG price as well as the electricity price and NG price. In this report, correlation-based models are used to account for the interdependency among hydrogen market price, electricity price and NG price.

Various example cases were completed to showcase the results and capability of the tool. The following paragraphs summarize the input and output representation on the dashboard of the NPP-HTSE H_2 profitability tool for Case 2 which is described in depth in the body of the report and briefly summarized here. Case 2 includes the PTC of \$3/kg-H_2 and uses a fixed user-defined hydrogen market selling price. The electricity price is assumed to be a constant value (representing a deregulated utility that could set a ‘behind the meter’ price to a constant low value) over the years of operation.

Figure ES-1 shows the input specifications and the financial performance results for Case 2. The breakdown of LCOH without the PTC is shown as well as the breakdown of revenue from hydrogen production.



Step-1: Input Specification

HTSE Plant Capacity: 500 MW-dc

Plant Life: 20 Years

Weighted Average Cost of Capital: 12.10%

Production Tax Credit: $3.00/Kg-H2

CLICK: Additional Inputs Information

Hydrogen Market Price($2023): $1.00/Kg-H2 | $1.00 | User-defined (uncorrelated with NG and elec price)

Electricity Price ($2023): $28.00 /MWh | $28.00 | User-defined (uncorrelated with NG price)

Natrual Gas Price ($2023): $4.22/MMBtu | $4.22 | Regulated: User-defined | Data Source: EIA AEO data 2023- Table 3: industrial

Note: These inputs parameters are selected based on a pre-sensitivity analysis, where a modular design of 25 MW/module and 0.731 tonne-H2/hr are assumed. Please click the link to change other input parameters if necessary.

Step-2: Financial Performance

CLICK: Additional Outputs

LCOH with PTC ($2023): $0.07/Kg-H2

LCOH without PTC ($2023): $2.09/Kg-H2

Internal Rate of Return (%): 66.52%

NPV_{H2} (\$ Million): 758.1 M

NPV_{BAU} (\$ Million): 754.8 M

ΔNPV Relative to BAU ($ Million): 3.4 M

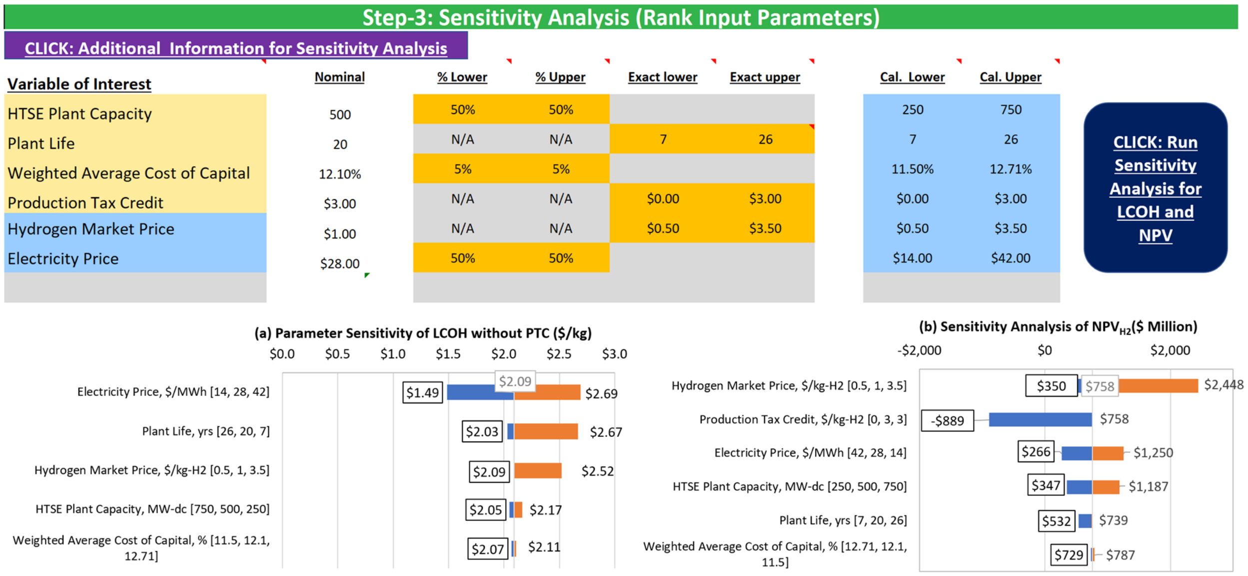
Annual H2 Production (tonne-H2/yr): 111,518

CLICK: LCOH Breakdowns

CLICK: NPV Breakdowns

Figure ES-1. The input parameters and financial performance results for Case 2 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of weighted average cost of capital (WACC), \$3/kg PTC, \$1.00/kg-H_2 hydrogen market selling price, and \$28/MWh for the electricity price.

The user can access the sensitivity of each input specification with respect to LCOH without PTC, NPV_{H2}, and NPV_{BAU} as shown in Figure ES-2. As shown, the hydrogen market price and the PTC are the most sensitive parameters affecting the NPV.



Step-3: Sensitivity Analysis (Rank Input Parameters)

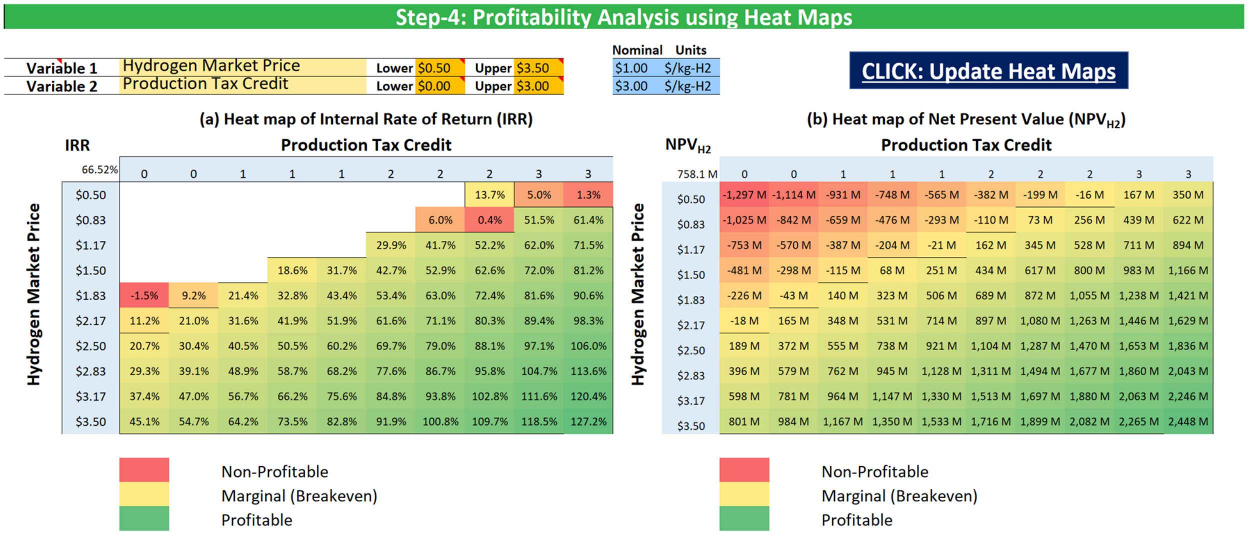
CLICK: Additional Information for Sensitivity Analysis

Variable of Interest	Nominal	% Lower	% Upper	Exact lower	Exact upper	Cal. Lower	Cal. Upper
HTSE Plant Capacity	500	50%	50%			250	750
Plant Life	20	N/A	N/A	7	26	7	26
Weighted Average Cost of Capital	12.10%	5%	5%			11.50%	12.71%
Production Tax Credit	$3.00	N/A	N/A	$0.00	$3.00	$0.00	$3.00
Hydrogen Market Price	$1.00	N/A	N/A	$0.50	$3.50	$0.50	$3.50
Electricity Price	$28.00	50%	50%			$14.00	$42.00

CLICK: Run Sensitivity Analysis for LCOH and NPV

Figure ES-2. Sensitivity analysis for Case 2 with respect to LCOH and NPV_{H2}.

The hydrogen market price and PTC are selected for the profitability analysis represented by heat maps as shown in Figure ES-3 to illustrate this feature of the tool.



Step-4: Profitability Analysis using Heat Maps

						Nominal	Units
Variable 1	Hydrogen Market Price	Lower	$0.50	Upper	$3.50	$1.00	$/kg-H2
Variable 2	Production Tax Credit	Lower	$0.00	Upper	$3.00	$3.00	$/kg-H2

CLICK: Update Heat Maps

(a) Heat map of Internal Rate of Return (IRR)

IRR — Production Tax Credit; rows: Hydrogen Market Price

66.52%	0	0	1	1	1	2	2	2	3	3
$0.50								13.7%	5.0%	1.3%
$0.83							6.0%	0.4%	51.5%	61.4%
$1.17						29.9%	41.7%	52.2%	62.0%	71.5%
$1.50				18.6%	31.7%	42.7%	52.9%	62.6%	72.0%	81.2%
$1.83	-1.5%	9.2%	21.4%	32.8%	43.4%	53.4%	63.0%	72.4%	81.6%	90.6%
$2.17	11.2%	21.0%	31.6%	41.9%	51.9%	61.6%	71.1%	80.3%	89.4%	98.3%
$2.50	20.7%	30.4%	40.5%	50.5%	60.2%	69.7%	79.0%	88.1%	97.1%	106.0%
$2.83	29.3%	39.1%	48.9%	58.7%	68.2%	77.6%	86.7%	95.8%	104.7%	113.6%
$3.17	37.4%	47.0%	56.7%	66.2%	75.6%	84.8%	93.8%	102.8%	111.6%	120.4%
$3.50	45.1%	54.7%	64.2%	73.5%	82.8%	91.9%	100.8%	109.7%	118.5%	127.2%

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

(b) Heat map of Net Present Value (NPV_{H2})

NPV_{H2} — Production Tax Credit; rows: Hydrogen Market Price

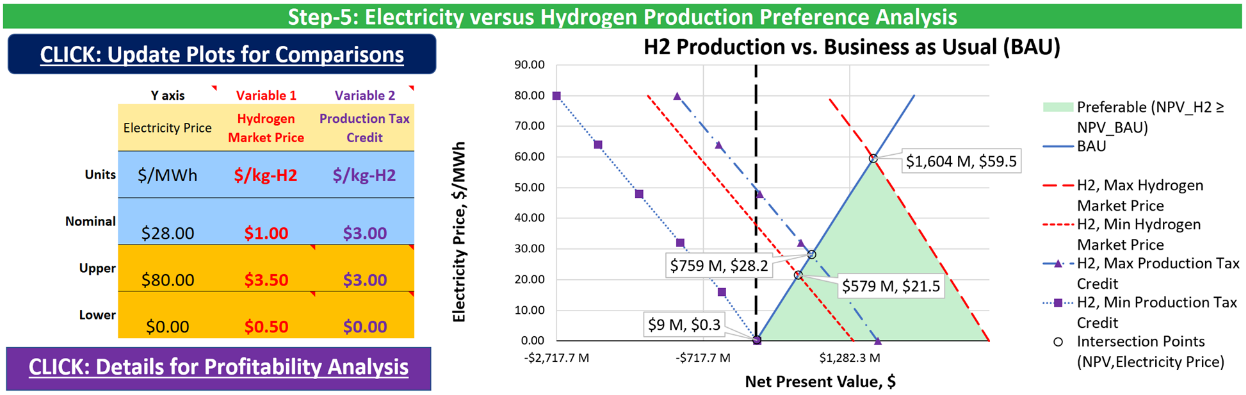
758.1 M	0	0	1	1	1	2	2	2	3	3
$0.50	-1,297 M	-1,114 M	-931 M	-748 M	-565 M	-382 M	-199 M	-16 M	167 M	350 M
$0.83	-1,025 M	-842 M	-659 M	-476 M	-293 M	-110 M	73 M	256 M	439 M	622 M
$1.17	-753 M	-570 M	-387 M	-204 M	-21 M	162 M	345 M	528 M	711 M	894 M
$1.50	-481 M	-298 M	-115 M	68 M	251 M	434 M	617 M	800 M	983 M	1,166 M
$1.83	-226 M	-43 M	140 M	323 M	506 M	689 M	872 M	1,055 M	1,238 M	1,421 M
$2.17	-18 M	165 M	348 M	531 M	714 M	897 M	1,080 M	1,263 M	1,446 M	1,629 M
$2.50	189 M	372 M	555 M	738 M	921 M	1,104 M	1,287 M	1,470 M	1,653 M	1,836 M
$2.83	396 M	579 M	762 M	945 M	1,128 M	1,311 M	1,494 M	1,677 M	1,860 M	2,043 M
$3.17	598 M	781 M	964 M	1,147 M	1,330 M	1,513 M	1,697 M	1,880 M	2,063 M	2,246 M
$3.50	801 M	984 M	1,167 M	1,350 M	1,533 M	1,716 M	1,899 M	2,082 M	2,265 M	2,448 M

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

Figure ES-3. Profitability analysis using heat maps for Case 2 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, $1.00/kg-$H_2$ for the hydrogen market selling price, and $28/MWh for the electricity price.

The profitable region (i.e., the Internal Rate of Return (IRR) is greater than WACC of 12.1% and NPV is positive) for Case 2 as shown in Figure ES-3 is located on the right and bottom of the black boundaries.

For the hydrogen production profitability analysis in Figure ES-4, the electricity price is selected for the Y-axis since it is dependent on NPV_{BAU} while PTC and hydrogen market price are selected due to the independency of the NPV_{BAU}. The upper bounds and lower bounds of the PTC and hydrogen market price are the same as those specified in Figure ES-3.



	Y axis	Variable 1	Variable 2
	Electricity Price	Hydrogen Market Price	Production Tax Credit
Units	$/MWh	$/kg-H2	$/kg-H2
Nominal	$28.00	$1.00	$3.00
Upper	$80.00	$3.50	$3.00
Lower	$0.00	$0.50	$0.00

Figure ES-4. Hydrogen production profitability analysis for Case 2 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, and fixed electricity price.

From Figure ES-34, the preferable region where NPV_H2 is greater than NPV_BAU is bounded by the NPP-BAU, maximum hydrogen market price, and the lower bound of electricity price, indicating that cases with electricity prices between $59.5/MWh and $0.3/MWh is preferred for hydrogen production.

The competitive analysis feature of the tool allows a comparison of hydrogen production with the conventional production of hydrogen via SMR as shown in Figure ES-5. The electricity price is varied from $0/MWh and $120/MWh. The upper and lower bound of PTC is the same as those in Figure ES-4. The NG price varies from $0 MMBtu to $15 MMBtu.

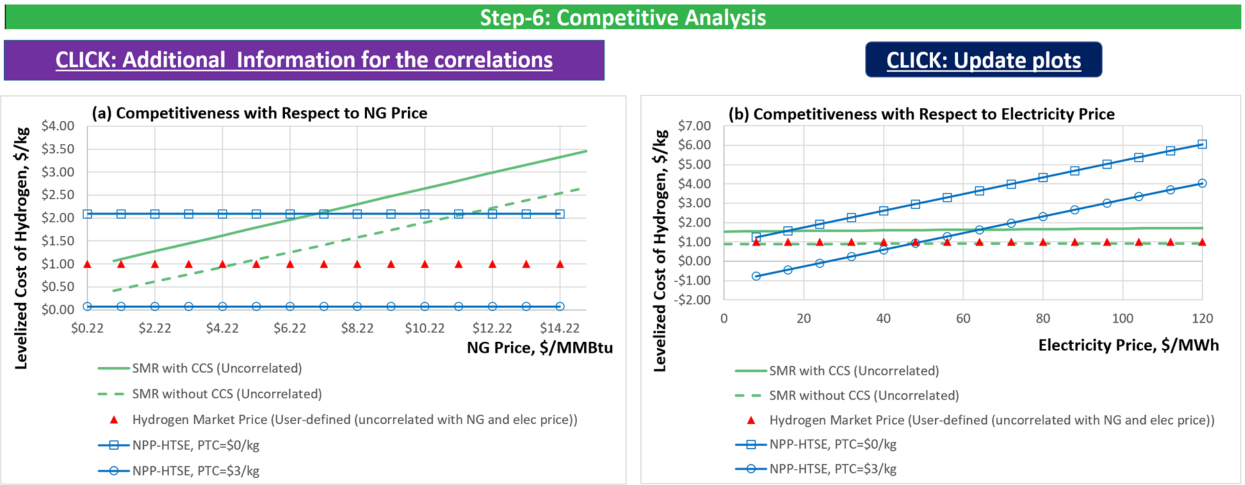


Figure ES-5. Competitive analysis for Case 2 with 500 MW-dc of HTSE design capacity, 20 yr plant life, 12.10% WACC, and $1.00/kg-$H_2$ hydrogen market price.

Figure ES-5 shows that Case 2 (NPP-HTSE with PTC) is competitive with SMR hydrogen sold by the user-defined hydrogen market price when the electricity price is less than $48/MWh regardless of NG price. The LCOH from SMR without carbon capture sequestration (CCS) is close to the user-defined hydrogen market price. When comparing the LCOH from NPP-HTSE and LCOH from SMR with CCS, the hydrogen from NPP-HTSE is competitive only when the electricity price is less than $64/MWh regardless of the NG price.

Future work could target (1) interfacing the NPP-HTSE H_2 profitability tool with other software developed in Idaho National Laboratory to expand the application, (2) developing capability to analyze advanced nuclear reactors integrated with various industries to provide heat, power, and hydrogen, (3) developing a web-based NPP-HTSE H_2 profitability tool to extend the potential usage and code capability of the tool, and (4) enhancing the features of the NPP-HTSE H_2 profitability tool.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

AEO	annual energy outlook
APEA	Aspen Process Economic Analyzer
BAU	business-as-usual
BOP	balance of plant
CCS	carbon capture sequestration
DCC	direct capital cost
DCF	discounted cash flow
DOE	Department of Energy
EIA	Energy Information Administration
FOAK	first-of-a-kind
FORCE	framework for optimization of resources and economics
HERON	Holistic Energy Resource Optimization Network
HTSE	high temperature steam electrolysis
IRA	Inflation Reduction Act
IRR	internal rate of return
LCOH	levelized cost of hydrogen
LMP	local marginal price
LTE	low-temperature electrolysis
LWR	light water reactor
MMBtu	metric million xvritish thermal unit
MMT	million metric tonne
NG	natural gas
NOAK	nth-of-a-kind
NPP	nuclear power plant
NPV	net present value
NPV_{BAU}	Net Present Value for selling all the electricity required for Hydrogen production in a HTSE plant integrated with an NPP
NPV_{H2}	Net Present Value for hydrogen production using HTSE plant integrated with an NPP
O&M	operation and maintenance
PTC	production tax credit
SMR	steam methane reforming
SOEC	solid oxide electrolysis cell
WACC	weighted average cost of capital

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1 INTRODUCTION

Hydrogen production could help meet net-zero carbon targets by 2050 [1]. However, producing carbon-free hydrogen from renewable energy sources can cost up to $5 per kilogram or more [3], much higher than the current price of hydrogen produced from the Steam Methane Reforming (SMR) without additional CCS [7]. Producing hydrogen from SMR is a mature technology and is dominant in the existing hydrogen market. Nevertheless, the hydrogen produced from SMR requires natural gas (NG) as a feedstock which leads to the production of CO_2.

Previous studies [8] showed that producing hydrogen by integrating solid oxide electrolysis cell (SOEC) and high-temperature steam electrolysis (SOEC/HTSE) with full-scale existing light water reactor (LWR) Nuclear Power Plants (NPP-HTSE) has the benefits of (1) generating carbon-free hydrogen at a relatively competitive cost given a specific range of electricity price and NG price and under realistic assumptions of improving HTSE technology in the near-term, (2) enhancing the revenue and sustainability of the NPP and (3) producing hydrogen with higher efficiency compared to low-temperature electrolysis (LTE).

In the United States, nine million metric tonnes (MMT) per year of hydrogen is produced, which is mainly used in oil refining to produce fuels and chemicals and to produce ammonia [9]. The total amount of the future potential together with existing hydrogen production was estimated as 96 MMT per year [9], which would be 10 times more than the current production.

To increase the production and to catalyze innovation, technology and manufacturing of carbon-free hydrogen, the Department of Energy (DOE) has set the “1-1-1” target to reduce the cost of carbon-free hydrogen “by 80% to $1 per 1 kilogram in 1 decade” [3]. In the near-term, a 10-year production tax credit (PTC) found in the Inflation Reduction Act (IRA) [2] has been passed to incentivize the advancement of hydrogen production technology.

Some existing models (e.g., H2A models from the National Renewable Energy Laboratory [6]) estimate the profitability of hydrogen production from different sources (e.g., SMR, solid oxide electrolysis). The performance metrics of Levelized Cost of Hydrogen (LCOH), Net Present Value (NPV), and after-tax Internal Rate of Return (IRR) are used for evaluation. An INL NPP-HTSE study [8] enhanced the H2A model by (1) incorporating the component level cost contributions for the capital cost estimation, and (2) implementing the H2A model with the inputs associated with a Gigawatt scale NPP-HTSE. However, the models contain complex input and output representation and a more user-friendly interface is desired for decision-makers who would like to test different possible scenarios.

Therefore, in this report, a user-friendly NPP-HTSE H_2 profitability tool was developed in Microsoft Excel to help the decision-makers evaluate the profitability of hydrogen production by isolating the critical inputs and outputs in a “Dashboard” format from the background calculations. Another objective of this tool is to show the results of sensitivity analysis with respect to regulated or deregulated electricity market prices, hydrogen market prices, and regulatory policy (e.g., production tax credits, etc). In addition, the results are demonstrated in graphical format for ease of interpretation. The interdependencies among hydrogen market price, electricity price and NG price are demonstrated to inform the hydrogen market or electricity price changes with respect to the NG price in the market.

The authors of the tool adapted the discounted cash flow (DCF) model from the H2A model developed by the National Renewable Energy Laboratory (NREL) with various changes and simplifications [6]. Only selected inputs and the critical financial performance metrics (i.e., LCOH, NPV, IRR) are shown on the default dashboard, representing both the critical inputs and outputs. The user has the option to investigate deeper into the inputs and outputs by navigating into different sheets in the tool. All the descriptions and assumptions are properly documented in the tool and the report. The user can change the plant-specific inputs by following the guidance of the tool (refer to Appendix A for details).

Most importantly, various example cases are included in this report to showcase the utility of the tool. Case 1 is a breakeven case, where hydrogen market price is set to the value of LCOH, resulting in zero NPV. Case 2 specifies a user-defined hydrogen market price while keeping the other inputs the same as those in Case 1. Case 3 utilizes a NG-correlated hydrogen market price and the electricity price while keeping the other parameters the same as Case 1 and 2. Case 1, 2, and 3 are evaluated within a regulated market. Case 4 applies hydrogen market price correlated with natural gas price and deregulated electricity price.

The following section explains the methodology used to estimate the hydrogen profitability in the NPP-HTSE H_2 profitability tool. Section 3 shows the verification and validation activities done during the tool development to show the validity of the tool. Section 4 demonstrates the results of the practical example cases as mentioned using the NPP-HTSE H_2 profitability tool. Section 5 summarizes draws the conclusions, recommendations, and future proposed work for the NPP-HTSE H_2 profitability tool.

For guidance on how to use the tool, please see Appendix A: User Guide.

2 METHODOLOGY FOR HYDROGEN PROFITABILITY ESTIMATION

2.1 Modeling Approach

The NPP-HTSE H_2 profitability tool was developed using standard discounted cash flow methodology, adapting the original H2A model from the National Renewable Energy Laboratory [6] and the modified H2A model from a study performed at INL [8]. The LCOH, NPV, IRR, and ΔNPV were selected as financial performance metrics and calculated based on the following equations.

LCOH

$$LCOH = \frac{(C_{ele}+C_{th}+C_{stack}+C_{BOP}+C_{fixed\ OM}+C_{var\ OM}+C_{stack\ rep.})}{S_{H2}}, \qquad \text{Equation (1)}$$

where

- C_{ele} is the electricity cost, representing the cost associated with the required electricity to meet the design capacity of hydrogen production.
- C_{th} is the thermal energy cost, representing the cost associated with the required thermal energy to meet the design capacity of hydrogen production.
- C_{stack} is the total stack cost for the SOEC/HTSE stacks.
- C_{BOP} is the total cost for the BOP. The summation of $C_{stack} + C_{BOP}$ are equivalent to the summation of capital cost including (1) initial equality depreciable capital, (2) principal payment, (3) debt interests, and (4) land costs.
- $C_{fixed\ OM}$ is the fixed operation and maintenance (O&M) costs including (1) labor costs, (2) general and administrative costs, (3) licensing, permits and fees, (4) property tax and insurance, and (5) rent, (6) material costs for maintenance and repairs, (7) production maintenance and repairs, and (8) decommissioning costs.
- $C_{var\ OM}$ is the variable O&M cost including (1) utility costs, (2) cash for working capital reserve, and (3) tax payment (if the net income is positive).
- $C_{stack\ rep.}$ is the yearly replacement cost for replacing the stacks considering the degradation and performance level.
- S_{H2} is the amount of hydrogen production during the plant life.

NPV

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+WACC)^i}, \qquad \text{Equation (2)}$$

where

- WACC is the weighted average cost of capital. This value is the same as the discount rate in the discounted cash flow analysis.
- CF_i represents the cash flow in the i^{th} year from the present year.
- n is the total plant lifetime for discounting the cash flow.

In this report, there are two different calculations of NPV: (1) NPV_{H2} and (2) NPV_{BAU}. NPV_{H2} represents the NPV of the hydrogen production by integrating HTSE with an NPP while NPV_{BAU} represents the NPV of the BAU case, where the electricity required to power HTSE is sold to the grid. Positive values of NPV_{H2} indicate that an investment of hydrogen production by integrating HTSE with an NPP is profitable.

- IRR

  The IRR is calculated using Equation (2) by solving for WACC and setting NPV=0. The case with an IRR greater than WACC indicates that the investment is profitable.

- ΔNPV

  ΔNPV is the difference between NPV estimated for NPP-HTSE and NPV for the BAU case, where the electricity is sold to the grid instead of producing hydrogen, as shown in Equation (3).

$$\Delta NPV = NPV_{H2} - NPV_{BAU}, \quad \text{Equation (3)}$$

Positive ΔNPV indicates that producing hydrogen using NPP-HTSE is more profitable than purely selling electricity to the grid.

2.2 Modeling Assumptions

The cost estimation of the integrated NPP-HTSE plant used as a baseline in the tool is based on the outputs of the SOEC/HTSE process model developed based on AspenTech HYSYS simulation software from the INL NPP-HTSE study [8]. Table 1 summarizes the critical parameters from the HYSYS simulation obtained from the INL NPP-HTSE study [8].

Table 1. HTSE and related subsystem process operating condition specifications [8].

Parameter	**Value**
Stack operating temperature	800°C
Stack operating pressure	5 bar
Operating mode	Constant V
Cell voltage	1.29 V/cell
Current density	1.5 A/cm²
Stack inlet H2O composition	90 mol%
Steam utilization	80%
HTSE modular block capacity	25 MW-dc
Sweep gas	Air
Sweep gas inlet flow rate	The flow set to achieve 40 mol% O2 in the anode outlet stream
Stack service life	4 years
Stack degradation rate	0.856%/1000 hr
Stack replacement schedule	Annual stack replacements completed to restore design production capacity

A modular design is assumed for the SOEC/HTSE stacks with 25 MW per module and 0.731 tonnes per hour of hydrogen production[8]. For example, 40 modules of SOEC/HTSE are required for an NPP-HTSE with an HTSE plant capacity of 1000 MW. Due to the modular design assumption of plant hydrogen production, the electrical and thermal power requirements are a linear function of HTSE plant capacity.

Stack cost is a function of plant design capacity, meaning that the smaller the plant design capacity, the higher the stack costs. In this study, baseline stack cost with plant design capacity below 100 MW is assumed to be $145 per kW while baseline stack cost with plant design capacity greater than or equal to 100 MWs is assumed to be $78 per kW.

Electricity price depends on whether the electricity market is regulated or deregulated. In a regulated market, a utility recovers its expenses via fixed consumer rate agreements, so we refer to “electricity price” as the constant price required to recover the cost from NPP operation. In a deregulated market, electricity price is set by the most expensive generator required to be brought online such that demand is met at any point in time. Because demand fluctuates, electricity price in a deregulated market varies over time and is referred to as the local marginal price (LMP). In the tool, the LMP fluctuates with the NG price specified by the EIA AEO data [10]. The EIA AEO data includes the average electricity price considering all the energy resources in U.S. which is approximately 1.8 times higher than the location-specific electricity price obtained when the NPP outputs are connected to the grid [11]. The user of this tool can enter their own electricity data for specific applications.

Both nth-of-a-kind (NOAK) and first-of-a-kind (FOAK) design costs are implemented in the NPP-HTSE H_2 profitability tool. FOAK considers costs associated with first-time construction while NOAK incorporates cost reductions from technology learning, increased manufacturing capacity and experience and establishment of supply lines. The NOAK design is assumed to have a 5% learning rate and with number of units produced equal to 100 (N=100).

A maximum of four years for the construction period of the SOEC/HTSE plant is assumed in the model and the corresponding percentages of capital spent in the construction period are user-defined. It is important for the user to ensure the sum of build percentages across years does not exceed 100%.

All model inputs and outputs refer to dollar values in the specified reference year (e.g., 2020 USD is the default value in the model [8]).

3 VERIFICATION AND VALIDATION OF THE NPP-HTSE H_2 PROFITABILITY TOOL

Verification and validation are important steps for tool development. Verification refers to the process of determining the accurate implementation of the model (i.e., assuring all calculations and equations are correctly implemented), while validation shows how accurate the model is compared to real-world quantities [12]. Typically, code-to-code comparison is a common approach for the verification process [12]. Validation, however, requires real-world data for comparisons. Since the technology of NPP-HTSE is still in conceptual demonstration, data is limited for real-world LCOH or NPV validation. Therefore, the NPP-HTSE H_2 profitability tool has undergone code-to-code comparisons with several existing models, continuous benchmark activities, and beta tests with collaborating industry partners.

Section 3.1 explains code-to-code comparisons by comparing sensitivity analysis with respect to LCOH with a previous INL NPP-HTSE study [8]. Section 3.2 shows code-to-code comparisons performed by comparing LCOH estimations from the INL NPP-HTSE study [8] with values produced from the NPP-HTSE H_2 profitability tool. Section 3.3 summarizes a code-to-code comparison with a financial analysis tool for hydrogen opportunities developed by APS. These verification exercises are described in turn in the following sections.

3.1 Code-to-code Comparisons with the INL NPP-HTSE Study

In the INL NPP-HTSE study [8], sensitivity analysis was performed for estimating the LCOH as shown in Figure 1, where a total of nine parameters were selected. This chart is usually referred to as a 'tornado' chart because of its cone shaped appearance with the parameter having the most effect on the key metric at the top. The baseline value of LCOH was calculated as $1.86 per kilogram of the hydrogen production. The blue and red bars represent the impact of the perturbing up and down the sensitivity parameters listed on the left. Energy price has the highest impact on the LCOH (equivalent to the "electricity price" in the NPP-HTSE H_2 profitability tool).

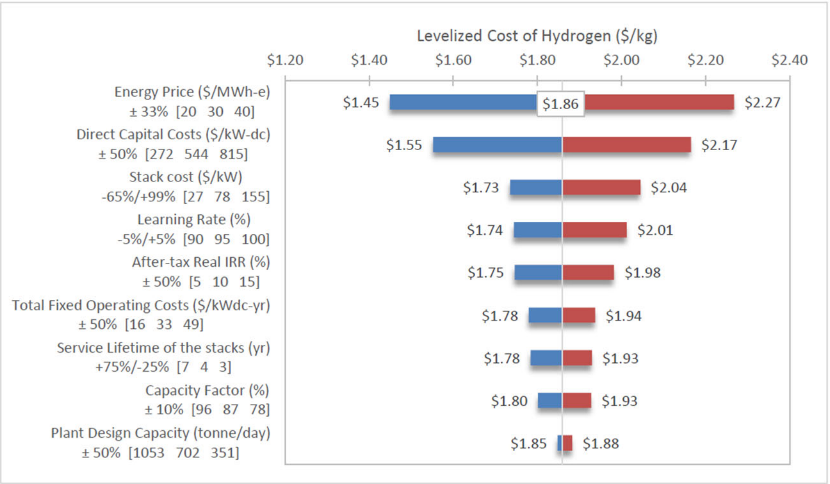


Figure 1. NPP-HTSE sensitivity analysis of the LCOH with respect to nine input parameters [8].

To verify the correct implementation of the LCOH calculations in the NPP-HTSE H_2 profitability tool, eight of the same parameters are selected to perform the sensitivity analysis using the NPP-HTSE H_2 profitability tool as shown in Figure 2. The "learning rate" is excluded from the sensitivity analysis since the current profitability tool does not have the capability of modeling the effect of the learning rate on the direct capital costs.

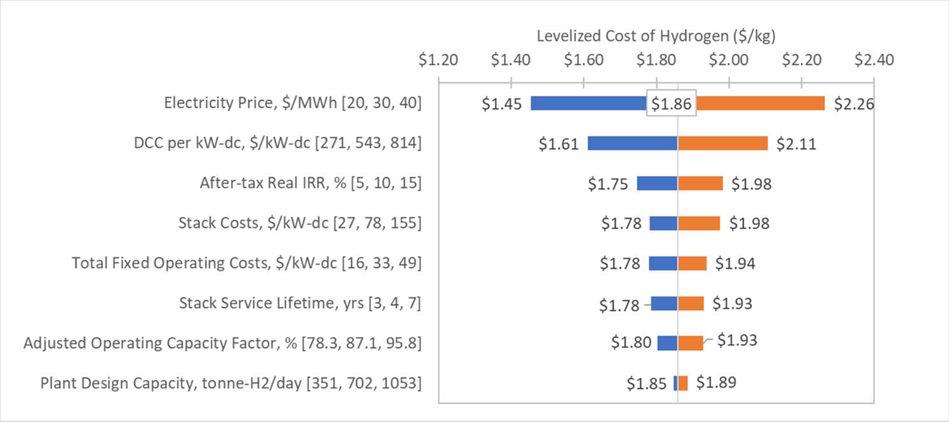


Figure 2. NPP-HTSE H_2 sensitivity analysis of the LCOH with respect to eight of the same parameters in Figure 1.

When performing the sensitivity analysis, there are two types of inputs: dependent and independent inputs. Dependent inputs are defined as inputs that are explicitly functions of other inputs, indicating that a change of one input can affect the other inputs. Independent inputs are defined as inputs that are independent with respect to other inputs, indicating that changing one input does not affect other inputs. Energy price, after-tax real IRR, and service lifetime of the stacks are independent inputs while direct capital cost (DCC), stack costs, total fixed operating costs, capacity factor, and plant design capacity are dependent inputs.

By comparing Figure 1 and Figure 2, the LCOH calculated based on varying the electricity price, after-tax real IRR, total fixed operating costs, stack service lifetime, adjusted operating capacity factor, and plant design capacity are either the same or negligible differences are observed. The baseline values are also the same in both plots. However, the sensitivity index for stack costs and DCC in Figure 1 and Figure 2 are somewhat different, leading to a different ranking of the parameters. The difference comes from the fact that the DCC was calculated based on a detailed quantification (i.e., to the level of the component cost in NPP-HTSE) in the INL NPP-HTSE study [8] whereas a correlation was used to estimate DCC as a function of total plant capacity (in the unit of MW-dc). While using a correlation for estimating DCC can simplify and expedite the simulation, the variation of the stack cost coming from the underlying component costs cannot be captured. In addition, when changing DCC, the percentage of stack costs with respect to the sum of stack and BOP cost does not change in INL NPP-HTSE study [8] while it changes as a function of DCC in the NPP-HTSE H_2 profitability tool. Therefore, the NPP-HTSE H_2 profitability tool is only applicable for the known stack costs and does not have the feature of the cost breakdown to the component level.

3.2 Code-to-code Comparison of LCOH Estimation with Varied Plant Capacities and Electricity Prices

Four case studies were completed to calculate LCOH to demonstrate the potential capabilities applicable for a large U.S. nuclear operating utility company as shown in the report INL/RPT-23-72743 [13]. Several updates were made from INL/RPT-22-66117 [8]:

- Adjusted plant capacity to 10 MW-dc, 20 MW-dc, 100 MW-dc, and 500 MW-dc sizes.
- Changed plant type to FOAK, indicating that the plant does not include cost reductions from learning effects.
- 10 and 20 MW-dc case stack costs adjusted to value computed for 100 MW/yr manufacturing capacity: $145/kW plus 10% contingency and 30% markup ($207/kW-dc total).

- 100 and 500 MW-dc case stack costs adjusted to value computed for 1000 MW/yr manufacturing capacity: $78/kW plus 10% contingency and 30% markup ($112/kW-dc total).
- Used regression analysis for developing correlation-based models of capital cost estimation.
- Adjusted the percentage of engineering and design from 2.3% to 10% without consideration of the learning effect.
- Adjusted the percentage of process contingency from 1.6 % to 7.1741% without consideration of the learning effect.

LCOH was calculated as a function of plant design capacities and varied electricity prices per MWh. Changing the plant design capacity affects several phenomena: the rate of hydrogen production (i.e., plant output per day), the power and thermal requirement for specific amounts of hydrogen production, the stack costs, the utility costs, the DCCs, and total capital investment. Yearly hydrogen production, power and thermal requirement for specific amounts of hydrogen production, and utility costs vary linearly with plant design capacities while stack costs, DCCs and total capital investment behave nonlinearly with the plant design capacities.

The following paragraphs document the results of code-to-code comparisons for LCOH estimations by using the NPP-HTSE H_2 profitability tool with a different method of calculating the DCCs as shown in Equation (4).

$$DCC\ (\$) = 10^{3.2999} * (Cap)^{-0.1620} * 1000 * Cap \qquad \text{Equation (4)}$$

Equation (4) is a correlation-based model developed by fitting the data points generated from the INL NPP-HTSE study [8]. In Equation (4), Cap represents the plant capacity in the unit of MW-dc. The calculated LCOH values based on Equation (4) are compared with those from a 2023 NPP-HTSE hydrogen market and production analysis report [13] in Table 2.

Table 2. Code-to-code comparisons of LCOH between NPP-HTSE H_2 profitability tool and a 2023 NPP-HTSE hydrogen market and production analysis report.

HTSE Plant Capacity	**Electricity Price**	**LCOH, $/kg (NPP-HTSE H_2 profitability tool)**	**LCOH, $/kg (2023 NPP-HTSE report)** [13]	**ΔLCOH, $/kg**	**% Error**
500 MW-dc	$70/MWh	$3.81	$3.77	$0.04	1.06%
	$50/MWh	$2.99	$2.95	$0.04	1.36%
	$30/MWh	$2.17	$2.13	$0.04	1.88%
	$20/MWh	$1.76	$1.73	$0.03	1.73%
100 MW-dc	$70/MWh	$4.07	$3.96	$0.11	2.78%
	$50/MWh	$3.25	$3.14	$0.11	3.50%
	$30/MWh	$2.43	$2.32	$0.11	4.74%
	$20/MWh	$2.02	$1.91	$0.11	5.76%
20 MW-dc	$70/MWh	$4.65	$4.63	$0.02	0.43%

HTSE Plant Capacity	**Electricity Price**	**LCOH, $/kg (NPP-HTSE H_2 profitability tool)**	**LCOH, $/kg (2023 NPP-HTSE report)** [13]	**ΔLCOH, $/kg**	**% Error**
	$50/MWh	$3.83	$3.81	$0.02	0.52%
	$30/MWh	$3.01	$3.00	$0.01	0.33%
	$20/MWh	$2.60	$2.59	$0.01	0.39%
10 MW-dc	$70/MWh	$4.94	$5.01	$0.07	1.40%
	$50/MWh	$4.12	$4.19	$0.07	1.67%
	$30/MWh	$3.30	$3.37	$0.07	2.08%
	$20/MWh	$2.89	$2.96	$0.07	2.36%

In Table 2, ΔLCOH ($/kg) is calculated as the difference between calculated LOCH using the NPP-HTSE H_2 profitability tool and LCOH from the 2023 hydrogen market report [13]. Percent error (% error) is calculated based on ΔLCOH and LCOH from the 2023 hydrogen market report. In Table 2, lower errors are observed when HTSE plant capacity is close to the lower and upper bound while a higher error is observed for the 100 MW-dc case. This is because the correlation-based model in Equation (4) can predict the DCC more accurately with a lower and higher HTSE plant capacity. However, the maximum error is no more than 6%, which is acceptable considering the insignificant impacts of plant design capability of the LCOH from Figure 1 and Figure 2. Therefore, the correlation-based model is recommended for use in analysis due to increased flexibility in choosing different values of plant capacity.

3.3 Code-to-code Validation with Industry Tools

Another code-to-code comparison was done by comparing the LCOH, IRR, and ΔNPV generated from the NPP-HTSE H_2 profitability tool and a financial analysis tool developed by a large U.S. nuclear operating utility company investigating the possibility of integrating hydrogen production with an existing LWR.

The results of the code-to-code comparisons indicate that the LCOH estimated from the NPP-HTSE H_2 profitability tool is around 4% lower than that from the utility company's tool. This is because additional costs of hydrogen compression and storage are considered in the utility company's tool. The IRR and ΔNPV from the NPP-HTSE H_2 profitability tool are higher than those from the utility company's tool since all the hydrogen produced in the NPP-HTSE H_2 profitability tool is assumed to be sold to the market with the given hydrogen market price versus being used for energy arbitrage as assumed by the utility company's tool. Based on this comparison, it shows that the NPP-HTSE H_2 profitability tool can be used to estimate the financial performance of NPP-HTSE hydrogen production with a simple user-friendly interface and the potential improvement of adding additional features such as equipping the costs of hydrogen compression and storage.

4 EXAMPLE CASES

In this section, four different example cases are illustrated to demonstrate the utility of the NPP-HTSE H_2 profitability tool:

- Case 1: Breakeven Case, where hydrogen market price is set to be the same as LCOH, resulting in zero NPV.
- Case 2: User-defined Hydrogen Market Price
- Case 3: NG-Correlated Hydrogen Price and the Electricity Price within Regulated Market

Case 4: Hydrogen Market Price correlated with Natural Gas Price and De-regulated Electricity Price

Table 3 summarizes the input specifications for the four cases.

Table 3. Input specifications for the four example use cases demonstrating the NPP-HTSE H_2 profitability tool.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Notes**
HTSE plant capacity (MW-dc)	500	500	500	500	500 MW-dc is a practical size based on the 2023 hydrogen market report [13].
Annual hydrogen production (ktonne/year)	111.5	111.5	111.5	111.5	Calculated based on 500 MW-dc HTSE electrolyzer.
Plant Life (years)	20	20	20	20	20 years of plant life is selected from INL NPP-HTSE study [8]..
Weighted Average of Capital Cost (%)	12.10%	12.10%	12.10%	12.10%	12.10% is the discount rate before inflation selected from INL NPP-HTSE study [8].
PTC (\$/kg-H_2)	0.02	3	3	3	A maximum \$3/kg of PTC is available based on IRA [2].
Hydrogen Market Price (\$2023/kg-H_2)	2.28	1.00	1.60	1.96	Case 1 sets LCOH equivalent to the hydrogen market price. Case 2 assumes \$1/kg-H_2 to meet 111 targets. The hydrogen market price for Cases 3 and 4 are calculated from NG price.
Electricity Price (\$2023/MWh)	30	28	66.35	78.30	\$30/MWh is selected from INL NPP-HTSE study [8]. \$28/MWh is selected for Case 2 so that ΔNPV is positive. The electricity price for Case 3 and 4 are calculated from NG price.
NG Price (\$2023/MMBtu)	4.22	4.22	4.22	6.27	\$4.22/MMBtu is selected for the industrial NG price in April 2023 [14]. \$6.27/MMBtu is the average NG price in 2023 from EIA AEO 2023 [10].

All four cases are analyzed for an NPP-HTSE plant with 500 MW-dc of HTSE plant capacity, 20 years of HTSE plant life, 12.10% of WACC, and with or without consideration of PTC. Changes in the hydrogen market price, electricity price, or NG price can affect the profitability of hydrogen production. Case 1 is a breakeven case, where the PTC is not included and the sale price of hydrogen is set equal to the production cost of hydrogen (the LCOH). Cases 2 through Case 4 include the PTC of \$3/kg-H_2. Case 2 uses a fixed user-defined hydrogen market selling price. Case 3 uses an NG-correlated hydrogen market price for estimating the hydrogen market selling price. The electricity price in Case 1, Case 2, and Case 3 are assumed to be a constant value (representing a regulated utility that could set a 'behind the meter' price to a constant low value) over the years of operation. Case 4 utilizes an electricity price that varies yearly (representing a deregulated utility that would take the grid market price of electricity).

Each case study with five primary outputs is reviewed to better understand the results. The five primary outputs covered include the following:

- Financial performance
- Parameter sensitivity
- Profitability sensitivity
- Electricity versus hydrogen production preference analysis
- Market competitiveness analysis.

For guidance on how to use the tool, please see Appendix A: User Guide. The following sections will cover each of the cases and key outputs detailed above. The user may refer to Appendix B: Screenshots for Example Cases for more details on setting up the cases.

4.1 Example Case 1: Breakeven

The objective of having a "breakeven case" is to find the condition where LCOH and the revenue of hydrogen are equivalent. It assumes that the hydrogen market price is equivalent to LCOH without consideration of a PTC and other parameters.

Table 3 and Table 4 show the outputs of the financial performance metrics for Case 1. The NG price in Case 1 is not correlated with electricity price or hydrogen market price. Therefore, the NG price is not required for Case 1. The BAU case assumed all the electricity generated from NPP is sold through the electricity grids.

Table 4. Case 1 financial performance metrics

Performance Metrics	**Value**
LCOH with PTC (\$/kg-H_2)	2.26
LCOH without PTC (\$/kg-H_2)	2.28
IRR (%)	12.10%
NPV_{H2} (\$ Million)	0
NPV_{BAU} (\$ Million)	808.7
ΔNPV (\$ Million)	-808.7

From Table 4, a zero NPV and the same IRR (12.10%) are obtained. This means that the calculated LCOH is a breakeven condition, where LCOH without consideration of PTC is the same as the revenue from hydrogen production. Table 4 also shows the LCOH with consideration of PTC, where PTC offsets the LCOH by approximately the amount of PTC incorporated. The breakdown chart of hydrogen cost and revenue is shown in Figure 3.

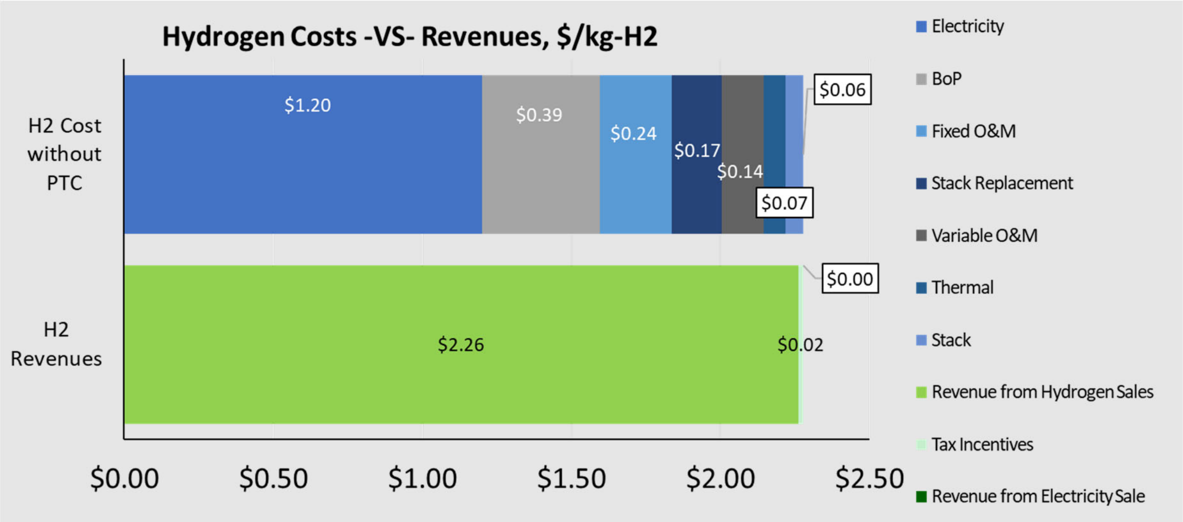


Figure 3. The hydrogen cost and revenue breakdown for Case 1 with 500 MW-dc of HTSE plant capacity, 20 years of plant life, 12.10% WACC, $30/MWh for the regulated and uncorrelated electricity price, and zero PTC.

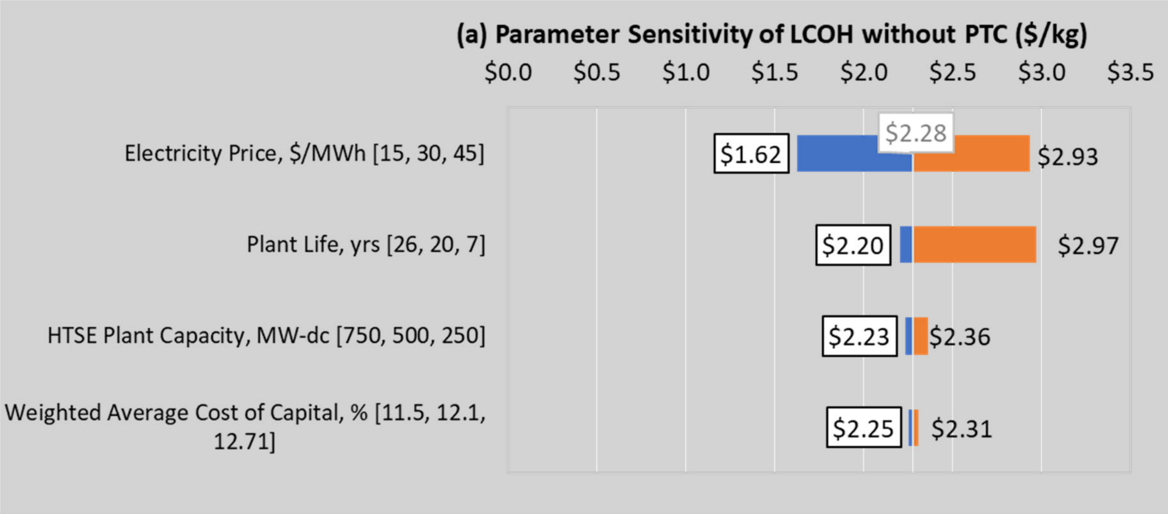
From Figure 3, 59% of the cost comes from electricity prices. The cost contributed by BOP (14%), fixed O&M (9%), stack replacements (6%), and variable O&M (6%) are less significant compared to the electricity price. The LCOH associated with thermal energy (4%) and stack costs (2%) are the least significant. All revenue is generated from selling hydrogen. Case 1 assumes no revenue is generated from the electricity sales and no PTC is implemented.

Sensitivity studies were performed and are shown in Figure 4. The sensitivity analysis ranks selected input parameters using the tornado charts, where the input parameters are ranked based on the sensitivity index of the model outputs (i.e., LCOH, NPV_{H2}, and NPV_{BAU}). The sensitivity index is defined as the difference between the maximum and minimum possible values of the model outputs by changing the inputs one at a time. The lower, nominal and upper bounds of each selected input are shown in Table 5.

Table 5. Lower, nominal, and upper bounds of the selected parameters for sensitivity study in Case 1.

Performance Metrics	**Lower Bound**	**Nominal Value**	**Upper Bound**	**Note**
HTSE plant capacity (MW-dc)	250	500	750	The upper bound and lower bounds are calculated by 50% of the nominal value from INL NPP-HTSE studies [8].
Plant Life (years)	7	20	26	7 years is selected as the lower bound based on the maximum stack service lifetime in INL NPP-HTSE studies [8]. 26 years is selected based on the constraint of the data from EIA AEO from 2022 to the year 2050 [10].
Electricity Price ($/MWh)	15	30	45	The upper bound and lower bounds are calculated by 50% of the nominal value from INL NPP-HTSE studies [8].

Performance Metrics	**Lower Bound**	**Nominal Value**	**Upper Bound**	**Note**
Weighted Average of Cost Capital (%)	11.50	12.10	12.71	A variation of 5% is assumed for WACC-based expert judgment
PTC ($/kg)	0	0.02	3	PTC is between -0.02 to $3 per kilogram of hydrogen production based on the IRA [2]


(a) Parameter Sensitivity of LCOH without PTC ($/kg)

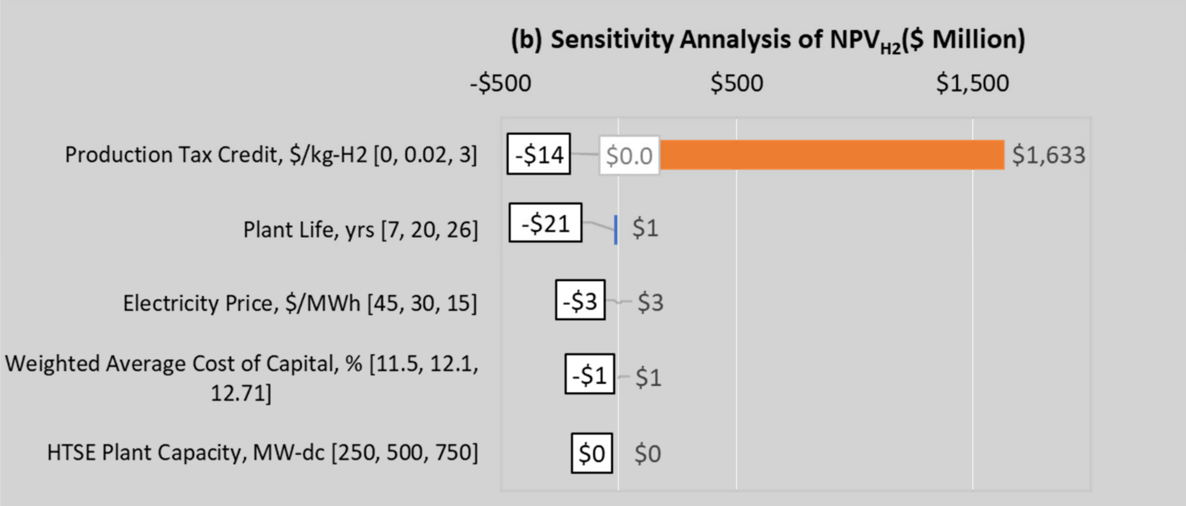
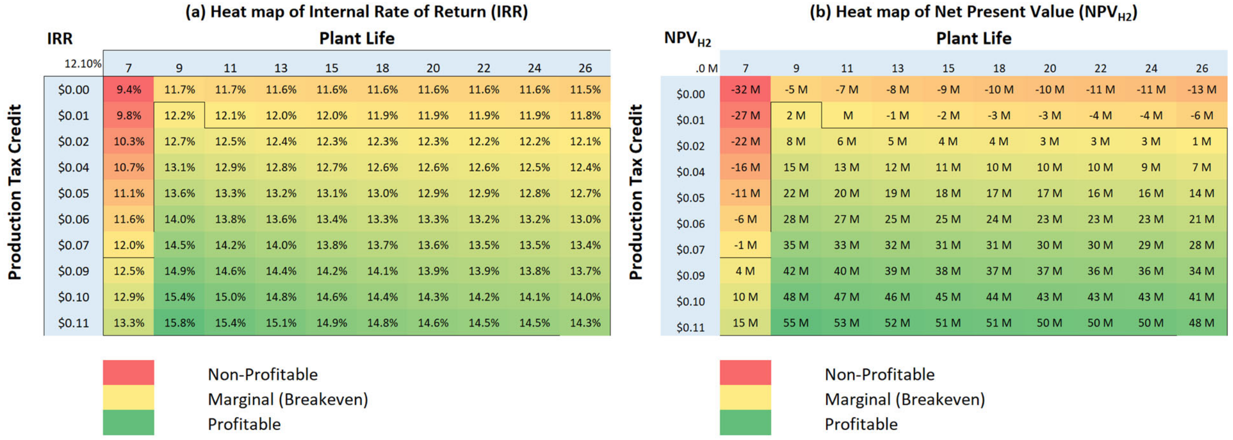

(b) Sensitivity Annalysis of NPV$_{H2}$($ Million)

Figure 4. Sensitivity analysis for Case 1 with respect to (a) LCOH, and (b) NPV$_{H2}$.

From Figure 4(a) and Figure 4(b), electricity price is the most sensitive parameter in LCOH estimation while PTC is the most sensitive parameter for estimating NPV$_{H2}$. In Figure 4(b), the PTC is the only parameter with significant impact to NPV estimation. The profitability analysis is performed by selecting the top two sensitive parameters (i.e., PTC and plant life from Figure 4(b)). The upper and lower bounds of PTC and plant life are specified so that adequate resolutions can demonstrate the breakeven point where NPV=0 and IRR is greater than WACC. The results of the profitability analysis represented as heat maps are shown in Figure 5.



(a) Heat map of Internal Rate of Return (IRR)

IRR 12.10%	7	9	11	13	15	18	20	22	24	26
$0.00	9.4%	11.7%	11.7%	11.6%	11.6%	11.6%	11.6%	11.6%	11.6%	11.5%
$0.01	9.8%	12.2%	12.1%	12.0%	12.0%	11.9%	11.9%	11.9%	11.9%	11.8%
$0.02	10.3%	12.7%	12.5%	12.4%	12.3%	12.3%	12.3%	12.2%	12.2%	12.1%
$0.04	10.7%	13.1%	12.9%	12.8%	12.7%	12.6%	12.6%	12.6%	12.5%	12.4%
$0.05	11.1%	13.6%	13.3%	13.2%	13.1%	13.0%	12.9%	12.9%	12.8%	12.7%
$0.06	11.6%	14.0%	13.8%	13.6%	13.4%	13.3%	13.3%	13.2%	13.2%	13.0%
$0.07	12.0%	14.5%	14.2%	14.0%	13.8%	13.7%	13.6%	13.5%	13.5%	13.4%
$0.09	12.5%	14.9%	14.6%	14.4%	14.2%	14.1%	13.9%	13.9%	13.8%	13.7%
$0.10	12.9%	15.4%	15.0%	14.8%	14.6%	14.4%	14.3%	14.2%	14.1%	14.0%
$0.11	13.3%	15.8%	15.4%	15.1%	14.9%	14.8%	14.6%	14.5%	14.5%	14.3%

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

(b) Heat map of Net Present Value (NPV_{H2})

NPV_{H2} .0 M	7	9	11	13	15	18	20	22	24	26
$0.00	-32 M	-5 M	-7 M	-8 M	-9 M	-10 M	-10 M	-11 M	-11 M	-13 M
$0.01	-27 M	2 M	M	-1 M	-2 M	-3 M	-3 M	-4 M	-4 M	-6 M
$0.02	-22 M	8 M	6 M	5 M	4 M	4 M	3 M	3 M	3 M	1 M
$0.04	-16 M	15 M	13 M	12 M	11 M	10 M	10 M	10 M	9 M	7 M
$0.05	-11 M	22 M	20 M	19 M	18 M	17 M	17 M	16 M	16 M	14 M
$0.06	-6 M	28 M	27 M	25 M	25 M	24 M	23 M	23 M	23 M	21 M
$0.07	-1 M	35 M	33 M	32 M	31 M	31 M	30 M	30 M	29 M	28 M
$0.09	4 M	42 M	40 M	39 M	38 M	37 M	37 M	36 M	36 M	34 M
$0.10	10 M	48 M	47 M	46 M	45 M	44 M	43 M	43 M	43 M	41 M
$0.11	15 M	55 M	53 M	52 M	51 M	51 M	50 M	50 M	50 M	48 M

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

Figure 5. Profitability analysis using heat maps for Case 1 with respect to (a) IRR, and (b) NPV_{H2},

From Figure 5, higher IRR and NPV are observed with higher PTC, which is consistent with the observation in Figure 4(b). The IRR and NPV variation with respect to plant life is limited but both IRR and NPV increase at the early plant life (i.e., before 18 years) but decrease after 18 years of plant life. Investment in hydrogen production is profitable in the region where the IRR is greater than the WACC and NPV is positive. Based on these criteria, the marginal (yellow area) and profitable conditions (green area) demonstrate the profitability conditions with PTC of more than $0.02/kg and the plant life higher than 9 years. . Figure 5 provides a reference for utilities to compare the profitability conditions quickly by adjusting PTC and plant life ranges of interest, replacing the need to iterate conditions manually. The profitability conditions have two meanings: (1) profits are sufficient to cover the cost and break even (i.e., yellow and green area in Figure 5) and (2) the profits from hydrogen production (NPV_{H2},) are more than the one selling electricity to the grid (NPV_{BAU}). The decision-makers may consider each element in Figure 5 as an independent investment. Investments with positive NPV and IRR greater than WACC would be a good investment. However, whether the utilities should produce hydrogen or sell electricity is made by comparing the NPV_{H2}, with the NPV_{BAU} at a specific electricity price as shown in Figure 6.

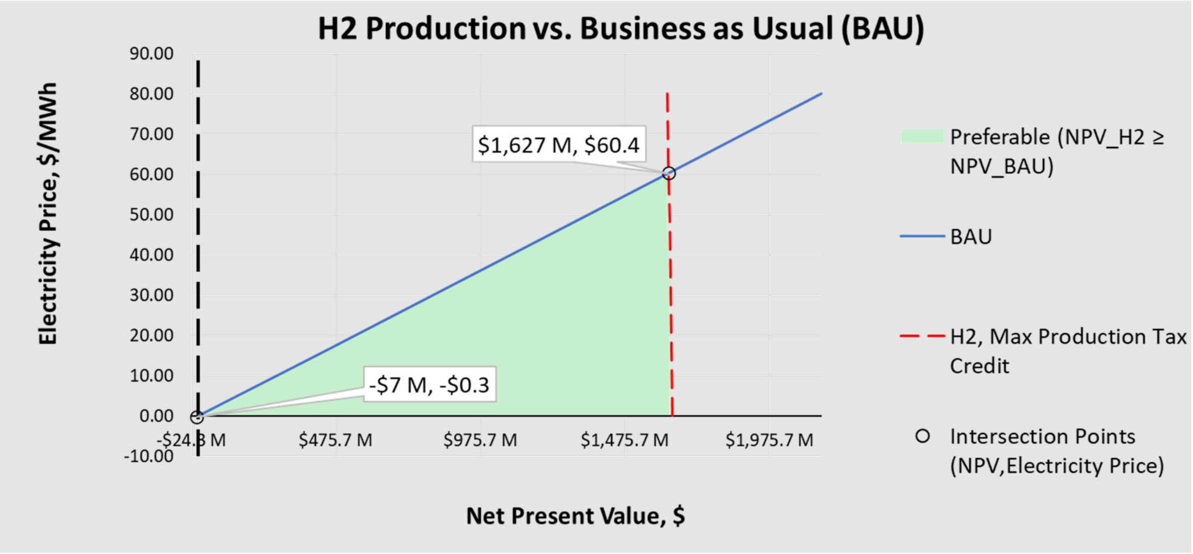


Figure 6. Electricity versus hydrogen production preference analysis for Case 1 with 500 MW-dc of HTSE plant capacity, 20 years of plant life, 12.10% of WACC, and regulated electricity price.

In Figure 6, both NPV_{BAU} and NPV_{H2}, are a function of electricity price. Electricity price is selected as the parameter in the Y-axis since it is a dependent variable of the BAU electricity price. Hydrogen production with and without PTC are selected for comparison since they are independent of BAU. From Figure 6, the preferable region is defined as the region where NPV_{H2}, is greater than the NPV_{BAU}, meaning that producing hydrogen with NPP-HTSE is more profitable than selling the electricity to the grid. Based on this definition, the green area represents the profitable conditions, where for each given electricity price, the ΔNPV is always positive. For Case 1, the preferable region is bounded by the maximum PTC, positive NPV_{BAU}, and positive electricity price. The decision maker should target the investment located in the preferable region (i.e., the green area in Figure 6), where the electricity price is between zero to \$62/MWh. In other words, the utilities should sell the electricity to the grid if the electricity price is above \$62/MWh.

As mentioned in Section 1, a vast majority of hydrogen is currently produced via SMR, where NG is the feedstock. Therefore, the existing hydrogen market price is almost entirely determined by this technology. Given the lack of hydrogen market price data, an H2A model developed by the National Energy Technology Laboratory (NETL) [15] is used for estimating the LCOH from SMR with or without CCS. The modeled levelized costs of SMR hydrogen can be used as a benchmark target that NPP-HTSE hydrogen must meet to be competitive. Figure 7 shows a comparison between the modeled levelized costs of SMR hydrogen and NPP-HTSE hydrogen.

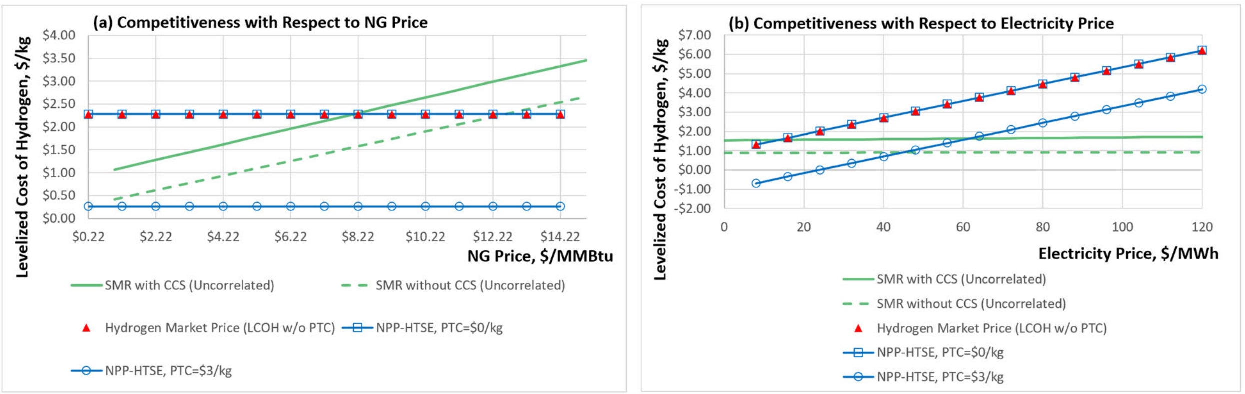


Figure 7. Competitive analysis for Case 1 with respect to (a) NG price and (b) electricity price.

From Figure 7(a) and (b), the red-triangled dots overlap with the blue-squared lines, which aligns with the assumption that the hydrogen market price is the same as LCOH from NPP-HTSE in Case 1. In other words, the blue-squared lines and red triangle dots represent Case 1. The blue-circle trendline shows the LCOH from NPP-HTSE with consideration of PTC. The two green lines represent the LCOH from SMR with and without CCS as a function of electricity and NG price. In Figure 7(a), the LCOH from NPP-HTSE is independent of NG price which is consistent with the assumption that electricity price and hydrogen market price are uncorrelated with NG price for Case 1. As shown in Figure 7(a) and (b), when the LCOH from NPP-HTSE is equal to or less than SMR, the hydrogen generated from NPP-HTSE can compete in the market. For example, Figure 7 (b) shows that Case 1 is competitive with the hydrogen produced from SMR without CCS if the electricity price is less than \$8/MWh. If the current SMR considers CCS, the electricity price can increase to the maximum of \$16/MWh for Case 1 to be competitive. If PTC is considered, an electricity price of \$64/MWh or greater can make the hydrogen from NPP-HTSE competitive with hydrogen produced from SMR with CCS.

4.2 Case 2: User-defined Hydrogen Market Price

In Case 1, the hydrogen market price is assumed to be the same as LCOH. However, this is not necessary the case in the real market. Case 2 assumes the hydrogen market price is known and independent of LCOH. Case 2 demonstrates the financial performance and hydrogen profitability conditions at the given user-defined hydrogen market price. Table 6 summarizes the financial performance results from inputting the parameters for case 2 provided in Table 3.

Table 6. Financial performance for Case 2 to demonstrate the NPP-HTSE H_2 profitability tool. The BAU case assumed all the electricity generated from NPP is sold through the electricity grids.

Performance Metrics	**Value**
LCOH with PTC ($/kg-$H_2$)	0.07
LCOH without PTC ($/kg-$H_2$)	2.09
IRR (%)	66.52%
NPV_{H2} ($ Million)	758.1
NPV_{BAU} ($ Million)	758.1
ΔNPV ($ Million)	3.4

From Table 6, both the LCOH with and without considering PTC is higher than the hydrogen market price. The NPV_{H2} is positive, and the IRR is greater than WACC in Table 3, indicating that Case 2 is a profitable investment. This is due to the significant contributions from the PTC, which is around 66% of the revenue of hydrogen production as shown in Figure 8. The positive ΔNPV relative to BAU confirms that Case 2 not only makes enough profits for hydrogen production but also assures that producing hydrogen is more profitable than solely selling the electricity to the grid.

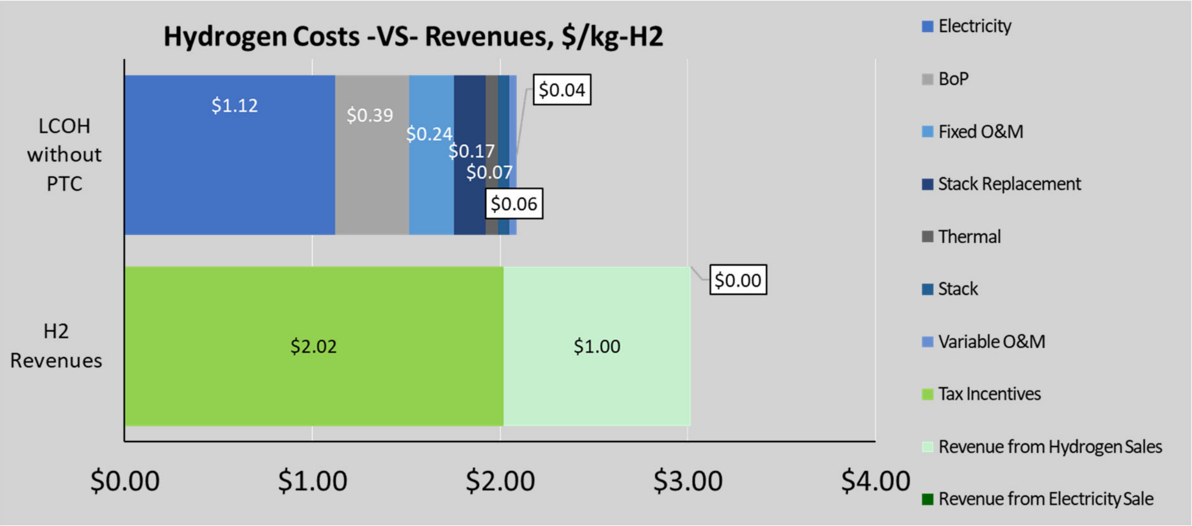


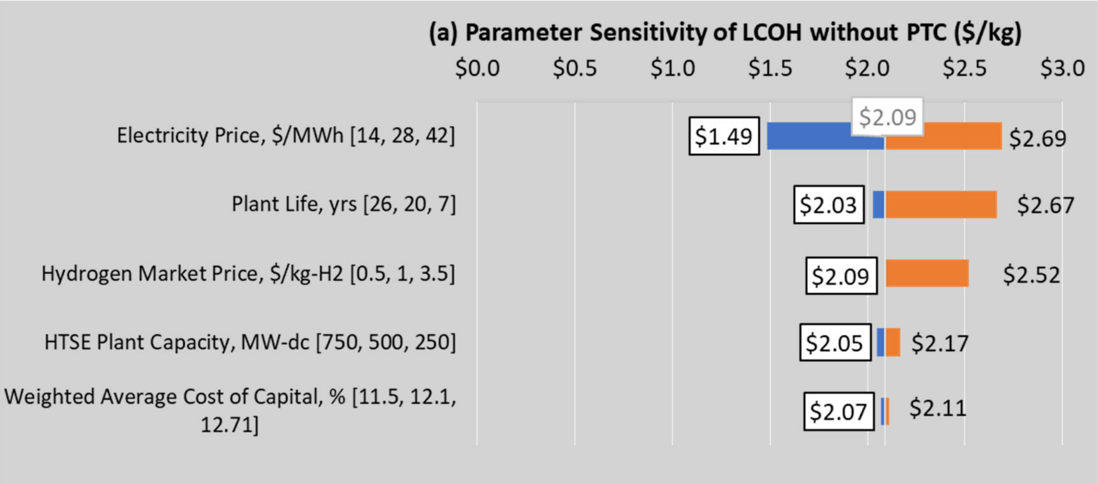
Figure 8. LCOH and revenue breakdown for Case 2 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, $3/kg PTC, hydrogen market price of $1.10/kg-$H_2$, and $30/MWh of regulated electricity price.

For sensitivity analysis of Case 2, the nominal, lower and upper bounds of the selected input parameters are shown in Table 7.

Table 7. Lower, nominal, and upper bounds of the selected parameters for sensitivity study in Case 2.

Performance Metrics	**Lower Bound**	**Nominal Value**	**Upper Bound**	**Note**
HTSE plant capacity (MW-dc)	250	500	750	The upper bound and lower bounds are calculated by 50% of the nominal value from INL NPP-HTSE studies [8].
Plant Life (years)	7	20	26	7 years is selected as the lower bound based on the maximum stack service lifetime in INL NPP-HTSE studies [8]. 26 years is selected based on the constraint of the data from EIA AEO from 2022 to the year 2050 [10].
Weighted Average of Cost Capital (%)	11.50	12.10	12.71	A variation of 5% is assumed for WACC-based expert judgment
PTC ($/kg)	0	3	3	PTC is between zero to $3 per kilogram of hydrogen production based on IRA [2]
Hydrogen market price	0.50	1.00	3.50	Nominal value from 111 targets. 50% lower for the lower bound while the upper bound is specified based on expert judgment.
Electricity Price ($/MWh)	14	28	42	The upper bound and lower bounds are calculated by 50% of the nominal value from INL NPP-HTSE studies [8].

Using Table 7, Figure 9(a), (b), and (c) show the sensitivity analyses with respect to LCOH, NPV_{H2}, and NPV_{BAU}.



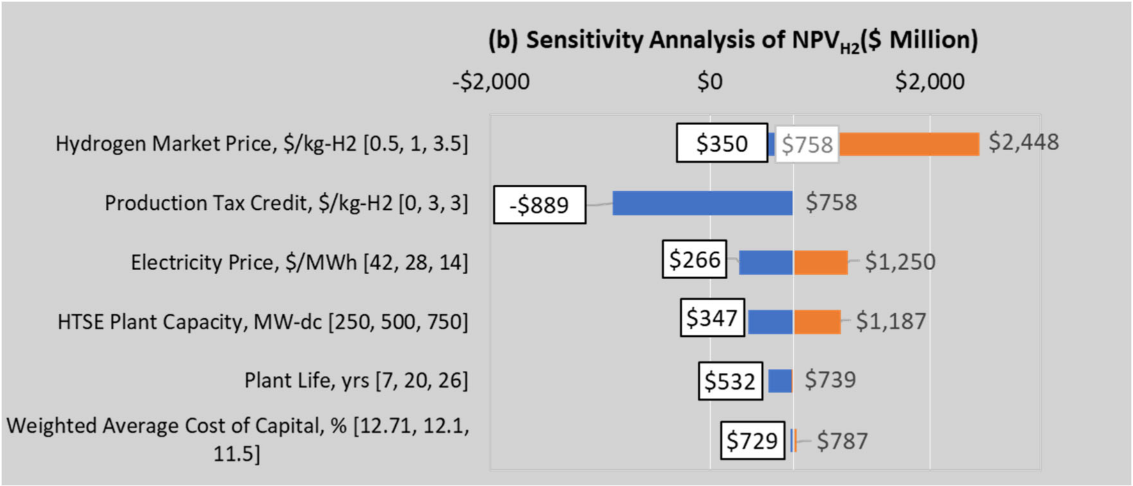
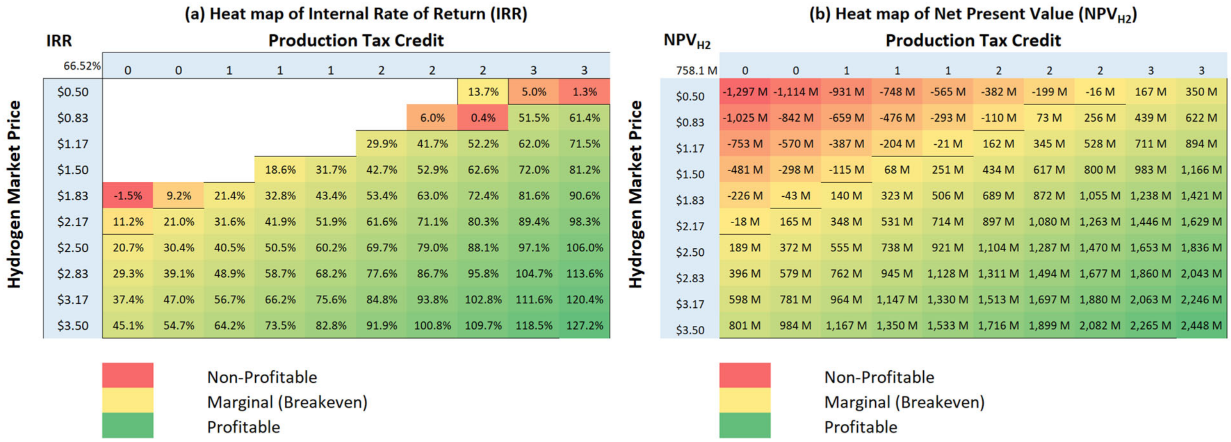


Figure 9. Sensitivity analysis for Case 2 with respect to (a) LCOH, and (b) NPV$_{H2}$.

From Figure 9 (a), the electricity price is the most sensitive parameter on the LCOH estimation consistent with the observation from Figure 8. For NPV$_{H2}$, hydrogen market price is the most important contributing factor, followed by PTC, electricity price, HTSE plant capacity, plant life, and WACC. The WACC is not sensitive to NPV$_{H2}$. For NPV$_{BAU}$, HTSE plant capacity and electricity price are equally significant to NPV estimation. The hydrogen market price and PTC are independent of NPV$_{BAU}$.

For profitability analysis using heat maps, hydrogen market price and PTC are selected since these two parameters are the top two sensitive parameters based on Figure 9 (b). The upper and lower bounds are defined as specified in Table 7.


(a) Heat map of Internal Rate of Return (IRR)

IRR — Production Tax Credit; Hydrogen Market Price

66.52%	0	0	1	1	1	2	2	2	3	3
$0.50								13.7%	5.0%	1.3%
$0.83							6.0%	0.4%	51.5%	61.4%
$1.17						29.9%	41.7%	52.2%	62.0%	71.5%
$1.50				18.6%	31.7%	42.7%	52.9%	62.6%	72.0%	81.2%
$1.83	-1.5%	9.2%	21.4%	32.8%	43.4%	53.4%	63.0%	72.4%	81.6%	90.6%
$2.17	11.2%	21.0%	31.6%	41.9%	51.9%	61.6%	71.1%	80.3%	89.4%	98.3%
$2.50	20.7%	30.4%	40.5%	50.5%	60.2%	69.7%	79.0%	88.1%	97.1%	106.0%
$2.83	29.3%	39.1%	48.9%	58.7%	68.2%	77.6%	86.7%	95.8%	104.7%	113.6%
$3.17	37.4%	47.0%	56.7%	66.2%	75.6%	84.8%	93.8%	102.8%	111.6%	120.4%
$3.50	45.1%	54.7%	64.2%	73.5%	82.8%	91.9%	100.8%	109.7%	118.5%	127.2%

(b) Heat map of Net Present Value (NPV$_{H2}$)

NPV$_{H2}$ — Production Tax Credit; Hydrogen Market Price

758.1 M	0	0	1	1	1	2	2	2	3	3
$0.50	-1,297 M	-1,114 M	-931 M	-748 M	-565 M	-382 M	-199 M	-16 M	167 M	350 M
$0.83	-1,025 M	-842 M	-659 M	-476 M	-293 M	-110 M	73 M	256 M	439 M	622 M
$1.17	-753 M	-570 M	-387 M	-204 M	-21 M	162 M	345 M	528 M	711 M	894 M
$1.50	-481 M	-298 M	-115 M	68 M	251 M	434 M	617 M	800 M	983 M	1,166 M
$1.83	-226 M	-43 M	140 M	323 M	506 M	689 M	872 M	1,055 M	1,238 M	1,421 M
$2.17	-18 M	165 M	348 M	531 M	714 M	897 M	1,080 M	1,263 M	1,446 M	1,629 M
$2.50	189 M	372 M	555 M	738 M	921 M	1,104 M	1,287 M	1,470 M	1,653 M	1,836 M
$2.83	396 M	579 M	762 M	945 M	1,128 M	1,311 M	1,494 M	1,677 M	1,860 M	2,043 M
$3.17	598 M	781 M	964 M	1,147 M	1,330 M	1,513 M	1,697 M	1,880 M	2,063 M	2,246 M
$3.50	801 M	984 M	1,167 M	1,350 M	1,533 M	1,716 M	1,899 M	2,082 M	2,265 M	2,448 M

Figure 10. Profitability analysis using heat maps for Case 2 with respect to (a) IRR, and (b) NPV$_{H2}$.

From Figure 10, the profitable region (i.e., the IRR is greater than WACC and NPV is positive) is located on the right and below the black boundaries. The higher the PTC and lower the hydrogen market price, the higher IRR and NPV. This trend can be verified by comparing Figures 10 (a) and 10 (b). A PTC of $3/kg and hydrogen market price of $1.0/kg results in a NPV of $758 million, which is between $ 662 M and $950 M in Figure 10 (b).

For electricity versus hydrogen production preference analysis, the electricity price is selected for the Y-axis since it is dependent on NPV$_{BAU}$ while PTC and hydrogen market prices are selected due to the independency of the NPV$_{BAU}$. The upper and lower bound of the electricity changes to $80/MWh and

$0/MWh without losing generality. The upper bounds and lower bounds of the PTC and hydrogen market price are the same as those specified in Table 7.

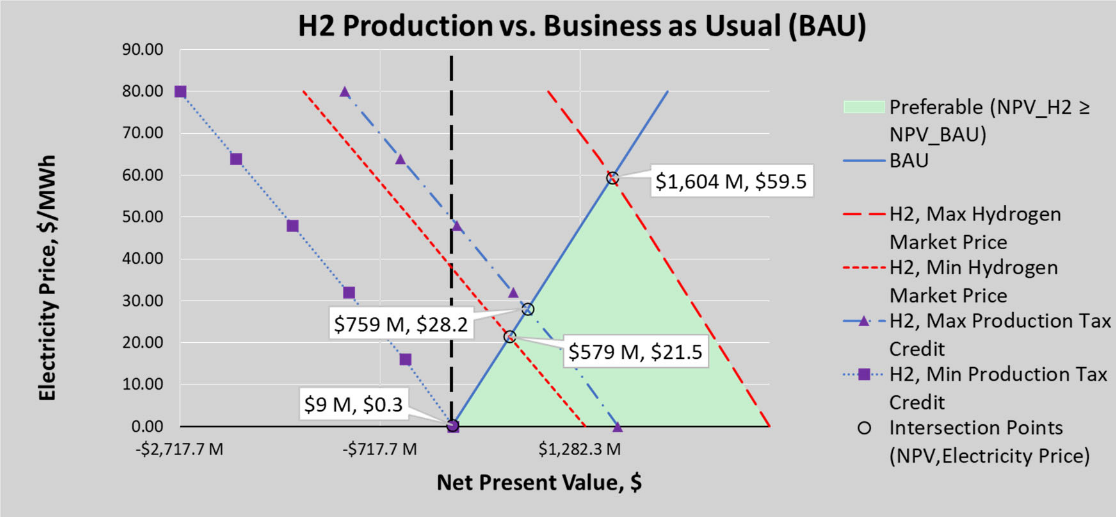


Figure 11. Hydrogen production profitability analysis for Case 2 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, and regulated electricity price.

From Figure 11, the dashed lines represent the calculated NPV_{H2} as a function of electricity price while the solid blue line represents the NPV_{BAU} given electricity price. The intersection points indicate that the NPV_{H2} is the same as NPV_{BAU}. The green area below the intersections, where ΔNPV is always positive, indicates the condition when producing hydrogen is preferred. In other words, the decision maker should consider the preferable conditions within the green area when integrating an HTSE plant with NPP for hydrogen production instead of purely selling the electricity to the grid. Otherwise, the NPP should sell the electricity to the grid.

For competitive analysis, the upper and lower bound of the electricity changes from $0/MWh to $120/MWh while the NG price is from $0 MMBtu to $15 MMBtu to cover all the possible ranges in Figure 12.

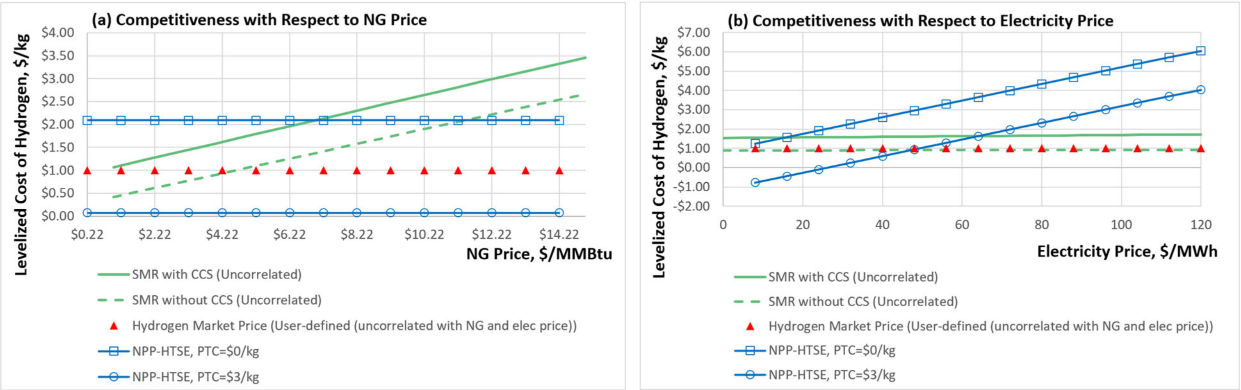


Figure 12. Competitive analysis for Case 2 with respect to (a) NG price, and (b) electricity price.

From Figure 12(a) and (b), the two green lines are generated from SMR as the same results in Figure 7(a) and (b), representing the existing hydrogen market price. The triangle trendline represents the constant user-defined hydrogen market price that is uncorrelated with the NG price, which is close to the LOCH from SMR without CCS in Figure 7(b). The squared and circled lines represent the LCOH from hydrogen production using NPP-HTSE with and without consideration of PTC, respectively. Case 2 corresponds to the circle dots and is competitive with the hydrogen generated from SMR without CCS if the electricity price is below \$48/MWh regardless of the NG price. Comparing the LOCHs between SMR with CCS and NPP-HTSE, Case 2 is competitive to hydrogen generated from SMR with electricity price below around \$64/MWh.

4.3 Case 3: NG-Correlated Hydrogen Price and the Electricity Price with Regulated Market

In Cases 1 and 2 the hydrogen market price is a fixed constant value that is uncorrelated with the NG price and the electricity price is uncorrelated with NG price. Case 3 demonstrates the condition where the hydrogen market price is estimated using a correlation between hydrogen and NG price while the electricity price is estimated through another correlation between electricity and NG price. The NG-Hydrogen market correlation was developed by performing linear regression using an arbitrary NG price and LCOH from H2A models for SMR [15]. The following correlations are obtained from the linear regression: (1) correlated with NG price with CCS, and (2) correlated with NG price without CCS. In the H2A model for SMR, both the electricity price and NG prices are the inputs for LCOH estimation. The correlation between electricity price and NG price is obtained by performing the linear regression using the Energy Information Administration (EIA) data [10] from 2022 to 2050. For Case 3, the NG price is assumed to be in a regulated market (i.e., no time-dependent variations for NG price). Other input parameters such as HTSE plant capacity, plant life, WACC, and PTC are found in Table 3. The financial performance results are shown in Table 8.

Table 8. Financial performance for the Case 3 to demonstrate the NPP-HTSE H_2 profitability tool. BAU case assumed all the electricity generated from NPP is sold through the electricity grids.

Performance Metrics	Value
Hydrogen Market Price (\$2023/kg-H_2)	1.60
Electricity Price (\$2023/MWh)	66.41
LCOH with PTC (\$2023/kg-H_2)	1.73
LCOH without PTC (\$2023/kg-H_2)	3.74
IRR (%)	13.68%
NPV_{H2} (\$ Million)	-23.8
NPV_{BAU} (\$ Million)	1790.2
ΔNPV (\$ Million)	-1814.0

In Table 8 the hydrogen market price of \$1.60/kg-H_2 is obtained by using the correlated hydrogen market price with CCS and the correlated electricity price of \$66.41/MWh based on a NG price of \$4.22/MMBtu.. The calculated hydrogen market price is lower than the LCOH with and without PTC, indicating that the PTC is not enough to make the hydrogen production competitive. Case 3 is not profitable because NPV_{H2} is negative. The IRR is slightly greater than WACC, which indicates that the revenue is not large enough to make profits even though PTC contributes 54% of the revenue as shown in Figure 13. The ΔNPV is negative, indicating that producing hydrogen from NPP-HTSE has limited benefits compared to selling electricity to the grid.

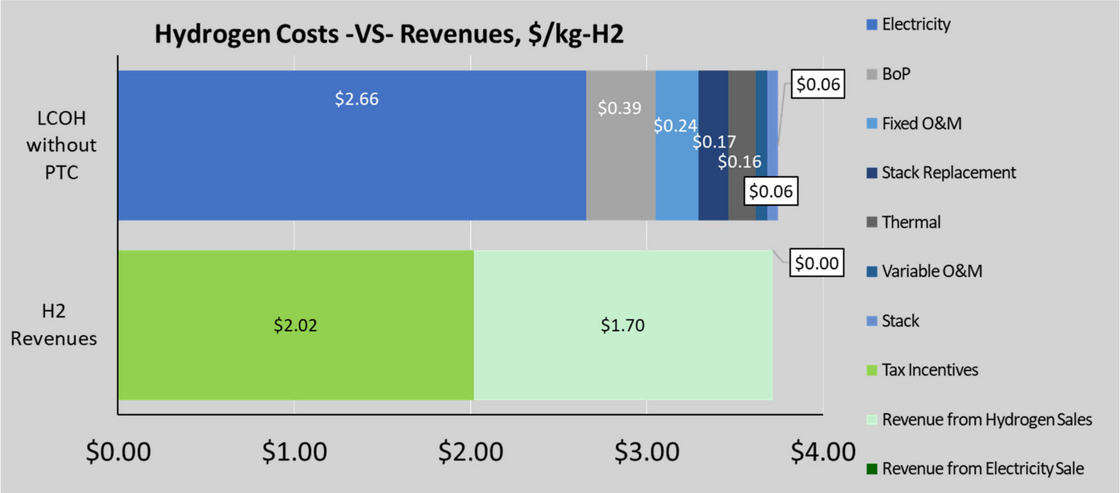


Figure 13. The input parameters and financial performance for Case 3 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, $3/kg PTC, NG-correlated hydrogen market price, and regulated NG-correlated electricity price.

The sensitivity analysis is performed based on the specified upper and lower bounds of the selected independent and uncorrelated inputs based on Table 9.

Table 9. Lower, nominal, and upper bounds of the selected parameters for sensitivity study in Case 3.

Performance Metrics	**Lower Bound**	**Nominal Value**	**Upper Bound**	**Note**
HTSE plant capacity (MW-dc)	250	500	750	The upper bound and lower bounds are calculated by the 50% of the nominal value from INL NPP-HTSE studies [8].
Plant Life (years)	7	20	26	7 years is selected as the lower bound based on the maximum stack service lifetime in INL NPP-HTSE studies [8]. 26 years is selected based on the constraint of the data from EIA AEO from 2022 to the year 2050 [10].
Weighted Average of Cost Capital (%)	11.50	12.10	12.71	A variation of 5% is assumed for WACC-based expert judgment
PTC ($/kg)	0	3	3	PTC is between zero to $3 per kilogram of hydrogen production based on IRA [2]
NG Price ($/MMBtu)	0	4.22	15.00	$4.22/MMBtu is selected for the industrial NG price on April 2023 while15 /MMBtu is the maximum industrial NG price in history [14]

Figure 14 (a) and (b) show the results of the sensitivity study for Case 3.

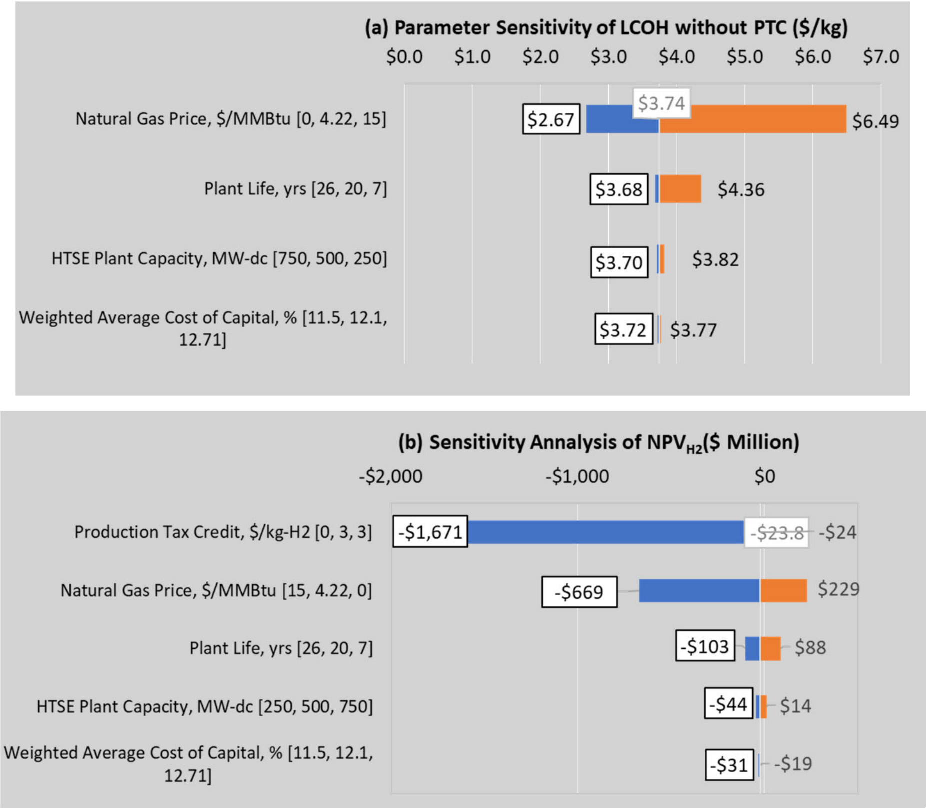
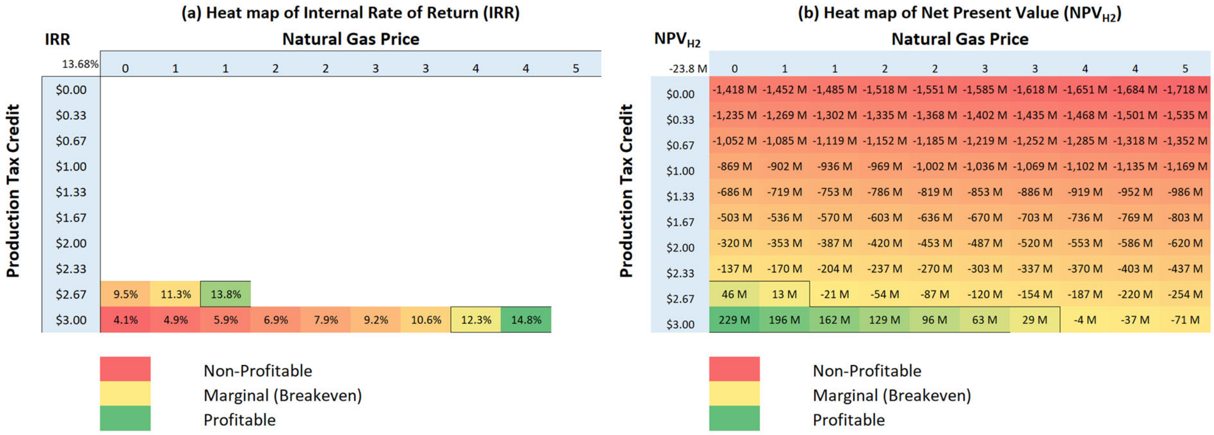


Figure 14. Sensitivity analysis for Case 3 with respect to (a) LCOH, and (b) NPV_{H2}.

From Figure 14 (a), and (b), both the hydrogen market price and electricity prices are excluded from the sensitivity analysis since they are correlated with NG price. NG price is added in the sensitivity analysis and the results show that the NG price is the most sensitive parameter for LCOH and NPV_{H2} estimation. The two highest sensitive parameters for contributing to NPV_{H2} are PTC and NG price, which are used for profitability analysis using heat maps as shown in Figure 15. The upper and lower bounds of the NG price are set to $5/MMBtu and $0/MMBtu, respectively to cover most possible ranges of NG prices



(a) Heat map of Internal Rate of Return (IRR)

IRR	Natural Gas Price									
13.68%	0	1	1	2	2	3	3	4	4	5
$0.00										
$0.33										
$0.67										
$1.00										
$1.33										
$1.67										
$2.00										
$2.33										
$2.67	9.5%	11.3%	13.8%							
$3.00	4.1%	4.9%	5.9%	6.9%	7.9%	9.2%	10.6%	12.3%	14.8%	

(b) Heat map of Net Present Value (NPV_{H2})

NPV_{H2}	Natural Gas Price									
-23.8 M	0	1	1	2	2	3	3	4	4	5
$0.00	-1,418 M	-1,452 M	-1,485 M	-1,518 M	-1,551 M	-1,585 M	-1,618 M	-1,651 M	-1,684 M	-1,718 M
$0.33	-1,235 M	-1,269 M	-1,302 M	-1,335 M	-1,368 M	-1,402 M	-1,435 M	-1,468 M	-1,501 M	-1,535 M
$0.67	-1,052 M	-1,085 M	-1,119 M	-1,152 M	-1,185 M	-1,219 M	-1,252 M	-1,285 M	-1,318 M	-1,352 M
$1.00	-869 M	-902 M	-936 M	-969 M	-1,002 M	-1,036 M	-1,069 M	-1,102 M	-1,135 M	-1,169 M
$1.33	-686 M	-719 M	-753 M	-786 M	-819 M	-853 M	-886 M	-919 M	-952 M	-986 M
$1.67	-503 M	-536 M	-570 M	-603 M	-636 M	-670 M	-703 M	-736 M	-769 M	-803 M
$2.00	-320 M	-353 M	-387 M	-420 M	-453 M	-487 M	-520 M	-553 M	-586 M	-620 M
$2.33	-137 M	-170 M	-204 M	-237 M	-270 M	-303 M	-337 M	-370 M	-403 M	-437 M
$2.67	46 M	13 M	-21 M	-54 M	-87 M	-120 M	-154 M	-187 M	-220 M	-254 M
$3.00	229 M	196 M	162 M	129 M	96 M	63 M	29 M	-4 M	-37 M	-71 M

Figure 15. Profitability analysis using heat maps for Case 3 with respect to (a) Internal Rate of Return, and (b) NPV_{H2}.

From Figure 15(a) and (b), the profitable conditions that have positive NPV are located at the left-bottom region with low NG price and high PTC. However, the IRR heat maps predict an opposite behavior, where the region with highest WACC is located at the right-bottom region. There is no region that satisfies the condition where NPV is positive and IRR is greater than WACC, indicating that Case 3 is not profitable.

For the hydrogen production profitability analysis, the NG price is selected instead of the electricity price since it depends on NPV_{BAU} while PTC is selected since it is not dependent on NPV_{BAU}. Figure 16 shows that there is no profitable region of producing hydrogen based on NPP-HTSE compared to the NPP-BAU.

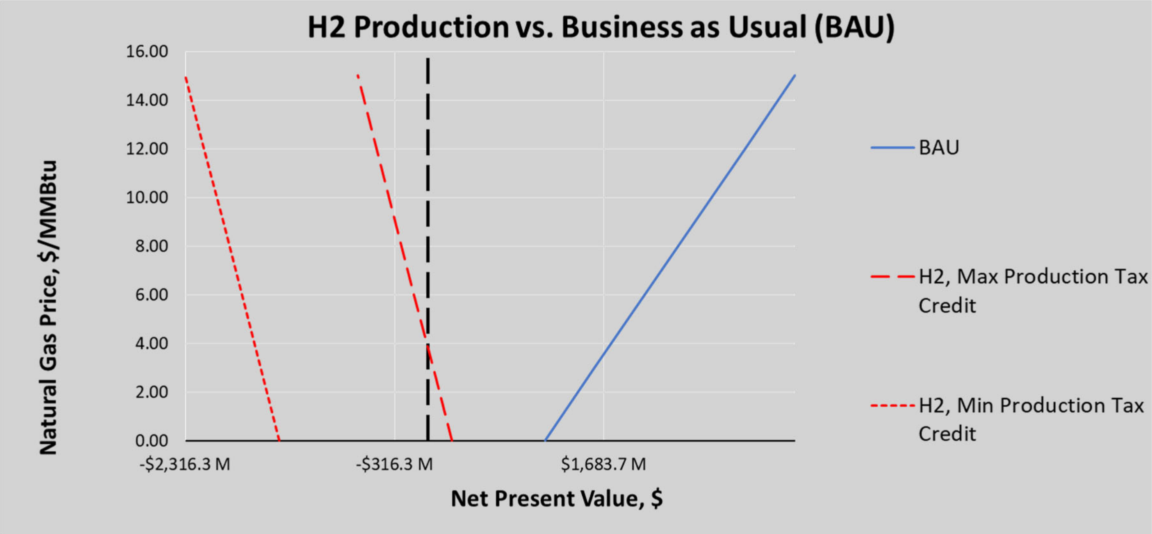


Figure 16. Electricity versus hydrogen production preference analysis for Case 3 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, NG-correlated hydrogen market price, and NG-correlated regulated electricity price.

From Figure 16, linear behavior is observed for both BAU and hydrogen production. However, there is no preferred region where NPV from hydrogen production is overlapped with NPV from BAU. Therefore, selling electricity to the grid is a better option. The main explanation for this result is that the electricity price data, used to correlate between electricity price and NG price, is relatively high considering all types of energy sources in U.S. The user may want to enter their data for both electricity and NG prices in the tool as an alternative.

To compare the LCOH from NPP-HTSE with SMR, Figure 17 shows the conditions when the hydrogen production from NPP-HTSE is competitive with the existing hydrogen market price.

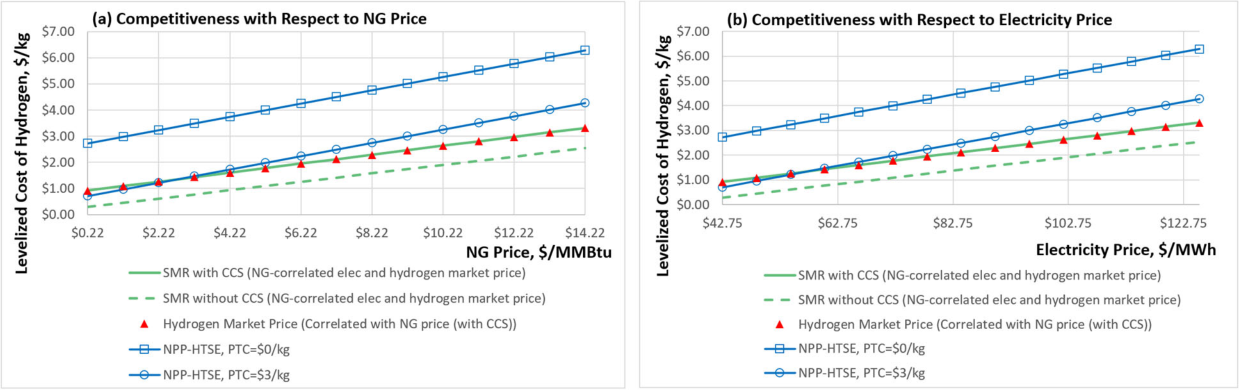


Figure 17. Competitive analysis for Case 3 with respect to (a) NG price and (b) electricity price.

From Figure 17, LCOH from SMR with CCS is overlapped with the hydrogen market price given the assumption that the hydrogen market price is dominated by hydrogen produced using SMR. Case 3 (i.e., LCOH from NPP-HTSE with PTC) is represented by the blue-circle lines and is competitive against the hydrogen market with NG price less than $2.22/MMBtu or the NG-correlated electricity price less than $55/MWh. For the case that does not consider PTC, NPP-HTSE is not competitive with SMR with CCS or without CCS for all ranges of the NG price and electricity price.

4.4 Case 4: NG-Correlated Hydrogen Market Price with Deregulated Market

For Case 1, Case 2, and Case 3, a regulated market is assumed, meaning the electricity price is constant throughout the plant life. For Case 4, a deregulated NG price is reflected by changing the NG price each year. Therefore, the electricity price and hydrogen market price become time-dependent values. The deregulated NG price is obtained from the EIA AEO 2023 database with industrial energy price at the price of 2023 [10]. Table 10 shows the calculated NG correlated hydrogen market price with CCS and electricity price as well as other performance metrics for the year 2023.

Table 10. Financial performance for the Case 4 to demonstrate the NPP-HTSE H_2 profitability tool. BAU case assumed all the electricity generated from NPP is sold through the electricity grids.

Performance Metrics	**Value**
Hydrogen Market Price ($2023/kg-$H_2$)	1.96
Electricity Price ($2023/MWh)	78.53
LCOH with PTC ($2023/kg-$H_2$)	1.74
LCOH without PTC ($2023/kg-$H_2$)	3.75
IRR (%)	13.91%
NPV_{H2} ($ Million)	-27.7
NPV_{BAU} ($ Million)	1795.3
ΔNPV ($ Million)	-1822.9

From Table 10, the NG-correlated hydrogen market price and the NG-correlated electricity price increases compared to those in Case 3. The IRR is slightly greater than the WACC but NPV_{H2} is negative. This means that Case 4 is not profitable. There is potential that the investment can lose profit in the coming years. Similar to Case 3,more than 54% of the revenue came from the PTC as shown in Figure 18. In Case 4, the majority of the cost comes from electricity generation.

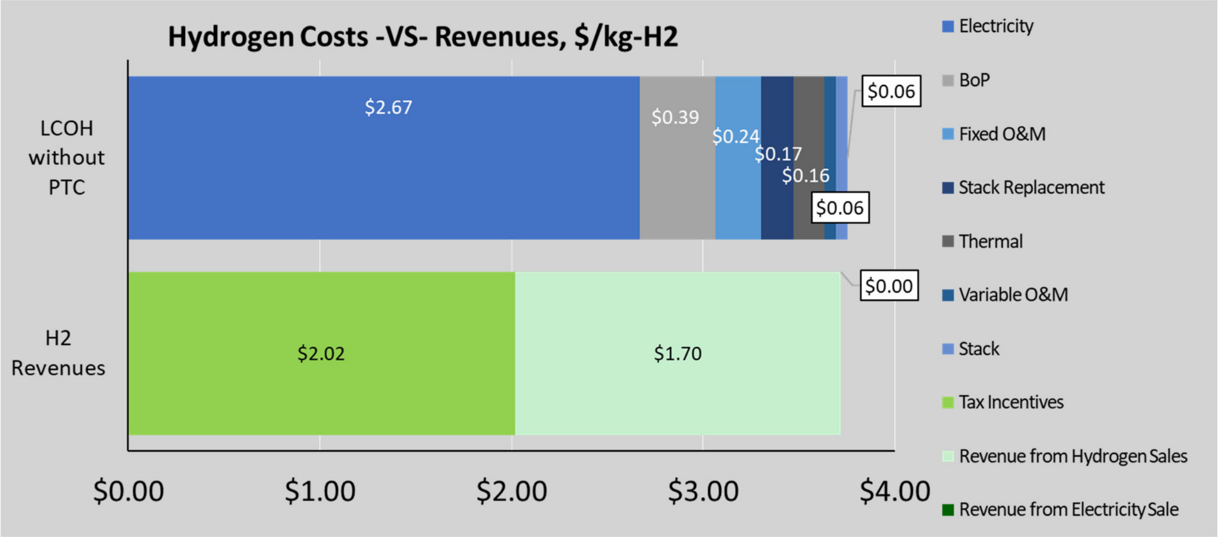


Figure 18. Financial performance for Case 4 with 500 MW-dc of HTSE design capacity, 20 years of plant life, 12.10% of WACC, $3/kg PTC, correlated hydrogen market price and electricity price, and deregulated NG price.

The sensitivity analysis for Case 4 is performed using the lower and upper bounds in Table 11.

Table 11. Lower, nominal, and upper bounds of the selected parameters for sensitivity study in Case 4.

Performance Metrics	**Lower Bound**	**Nominal Value**	**Upper Bound**	**Note**
HTSE plant capacity (MW-dc)	250	500	750	The upper bound and lower bounds are calculated by the 50% of the nominal value from INL NPP-HTSE studies [8].
Plant Life (years)	7	20	26	7 years is selected as the lower bound based on the maximum stack service lifetime in INL NPP-HTSE studies [8]. 26 years is selected based on the constraint of the data from EIA AEO from 2022 to the year 2050 [10].
Weighted Average of Cost Capital (%)	11.50	12.10	12.71	A variation of 5% is assumed for WACC-based expert judgment
PTC ($/kg)	0	3	3	PTC is between zero to $3 per kilogram of hydrogen production based on IRA [2]

Figure 19 shows the results of the sensitivity analysis, where hydrogen market price, electricity price, and NG price are excluded since they are time-dependent variables.

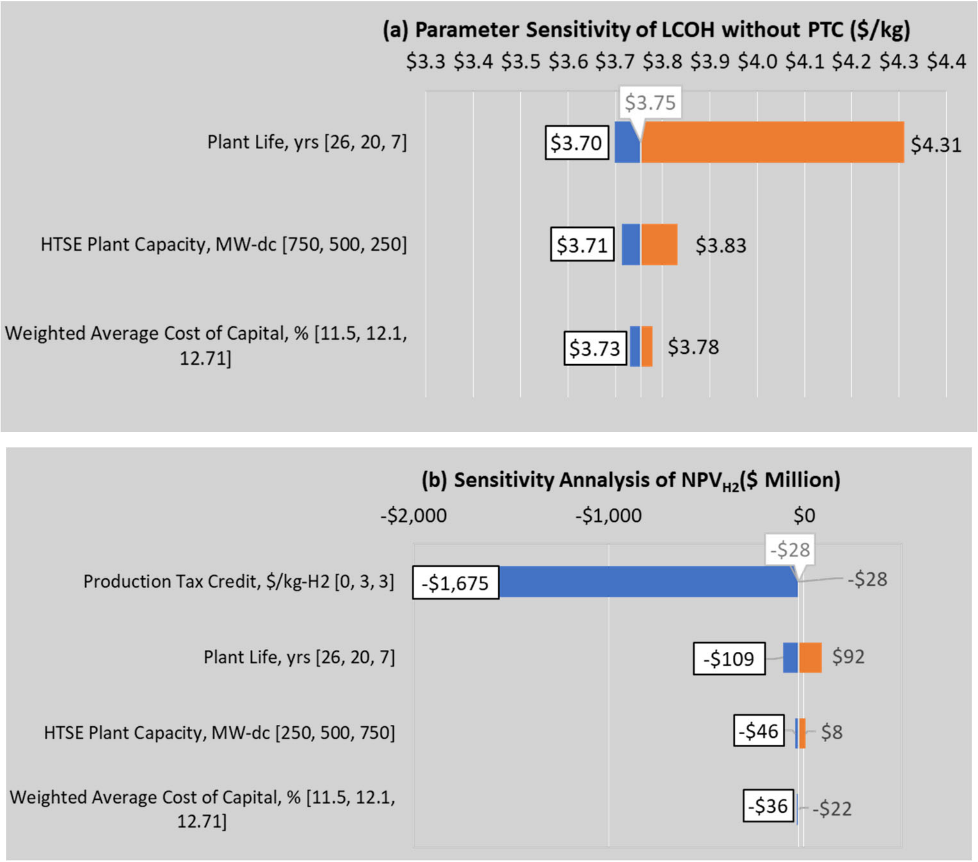
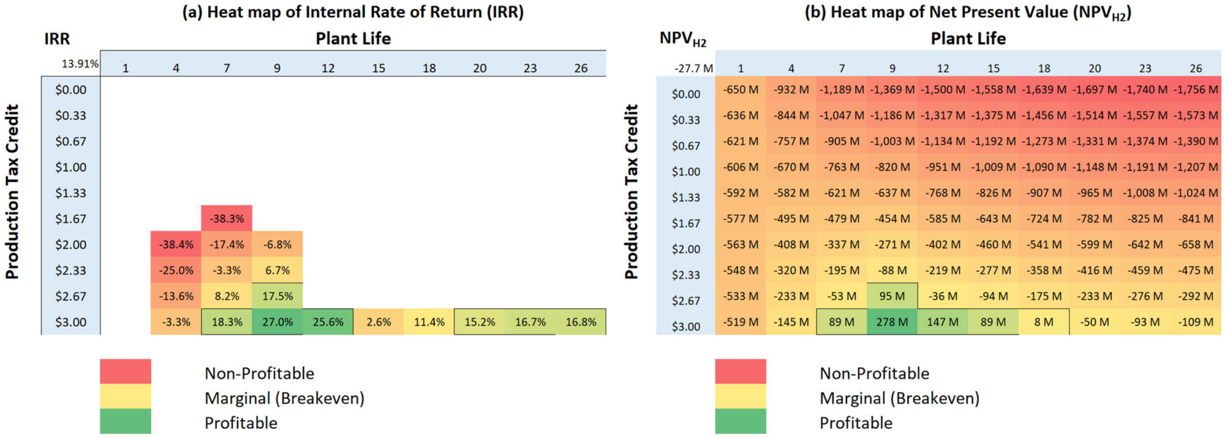


Figure 19. Sensitivity analysis for Case 4 with respect to (a)LCOH, and (b) NPV$_{H2}$.

From Figure 19(a) and Figure 19(b), plant life is the most sensitive parameter for LCOH estimation while PTC and plant life are the most sensitive parameters for NPV$_{H2}$. PTC and plant life are selected for the parameters in profitability analysis using heat maps as shown in Figure 20. The bounds of the PTC are adjusted to ensure the resolutions of the heat maps.



(a) Heat map of Internal Rate of Return (IRR)

IRR	Plant Life									
13.91%	1	4	7	9	12	15	18	20	23	26
$0.00										
$0.33										
$0.67										
$1.00										
$1.33										
$1.67			-38.3%							
$2.00		-38.4%	-17.4%	-6.8%						
$2.33		-25.0%	-3.3%	6.7%						
$2.67		-13.6%	8.2%	17.5%						
$3.00		-3.3%	18.3%	27.0%	25.6%	2.6%	11.4%	15.2%	16.7%	16.8%

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

(b) Heat map of Net Present Value (NPV$_{H2}$)

NPV$_{H2}$	Plant Life									
-27.7 M	1	4	7	9	12	15	18	20	23	26
$0.00	-650 M	-932 M	-1,189 M	-1,369 M	-1,500 M	-1,558 M	-1,639 M	-1,697 M	-1,740 M	-1,756 M
$0.33	-636 M	-844 M	-1,047 M	-1,186 M	-1,317 M	-1,375 M	-1,456 M	-1,514 M	-1,557 M	-1,573 M
$0.67	-621 M	-757 M	-905 M	-1,003 M	-1,134 M	-1,192 M	-1,273 M	-1,331 M	-1,374 M	-1,390 M
$1.00	-606 M	-670 M	-763 M	-820 M	-951 M	-1,009 M	-1,090 M	-1,148 M	-1,191 M	-1,207 M
$1.33	-592 M	-582 M	-621 M	-637 M	-768 M	-826 M	-907 M	-965 M	-1,008 M	-1,024 M
$1.67	-577 M	-495 M	-479 M	-454 M	-585 M	-643 M	-724 M	-782 M	-825 M	-841 M
$2.00	-563 M	-408 M	-337 M	-271 M	-402 M	-460 M	-541 M	-599 M	-642 M	-658 M
$2.33	-548 M	-320 M	-195 M	-88 M	-219 M	-277 M	-358 M	-416 M	-459 M	-475 M
$2.67	-533 M	-233 M	-53 M	95 M	-36 M	-94 M	-175 M	-233 M	-276 M	-292 M
$3.00	-519 M	-145 M	89 M	278 M	147 M	89 M	8 M	-50 M	-93 M	-109 M

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

Figure 20. Profitability analysis using heat maps for Case 4 with respect to (a) IRR, and (b) NPV$_{H2}$.

Figure 20 (a) identifies profitable conditions in a specific region where PTC is approximately \$3/kg and plant life ranges from 7 to 18 years. Under these conditions, utilities should target a short plant life (i.e., between 7 to 12 years) with maximum PTC.

For the hydrogen production profitability analysis, the plant life is selected for the Y-axis due to the significant impact on NPV_{BAU} and a continuous discussion following Figure 20. Similar to Case 3, PTC is selected as the parameter for comparison in Figure 21.

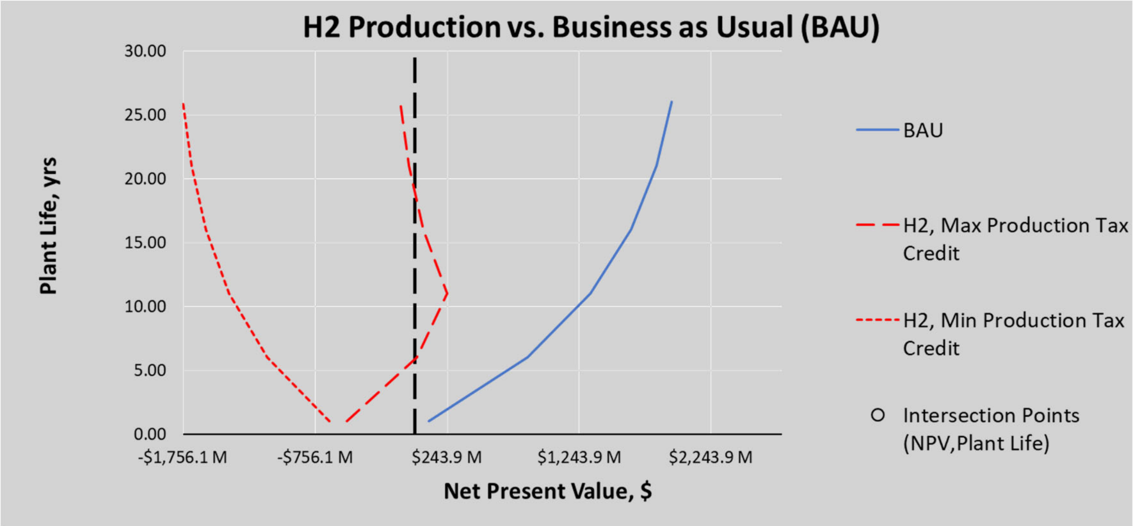


Figure 21. Hydrogen production profitability analysis for Case 4 with 20 years of plant life, 12.10% of WACC, correlated hydrogen market price and NG price, and deregulated electricity price.

From Figure 21, the NPV curves for BAU and hydrogen production are non-linear. When the HTSE plant life increase from 1 year to 11 years, NPV_{H2} increases accordingly due to the accumulated amount of hydrogen production and sales. However, there is a sharp change of the NPV_{H2} when after 11th year of the plant life, where NPV_{H2} decreases when plant life increases due to the increasing cost of the hydrogen production. This observation is consistent with the Figure 20, where a peak value is observed when a maximum PTC is considered. This indicates that there is an optimized point for operating a HTSE plant of 11 years for Case 4. Based on Figure 21, there is no profitable area where NPV_{H2} is greater than NPV_{BAU}. In other words, for Case 4, it is recommended to only produce electricity rather than producing hydrogen from NPP-HTSE.

Figure 22 shows the competitive analysis for Case 4. The deregulated NG price results in only a single value of LCOH, hydrogen market price, and electricity price in the current year (2023). The hydrogen market price is overlapped with the LOCH from SMR with CCS. Case 4 (LCOH from NPP-HTSE with PTC) is competitive with the hydrogen from SMR with CCS. However, Case 4 is not competitive with the hydrogen production from SMR without CCS.

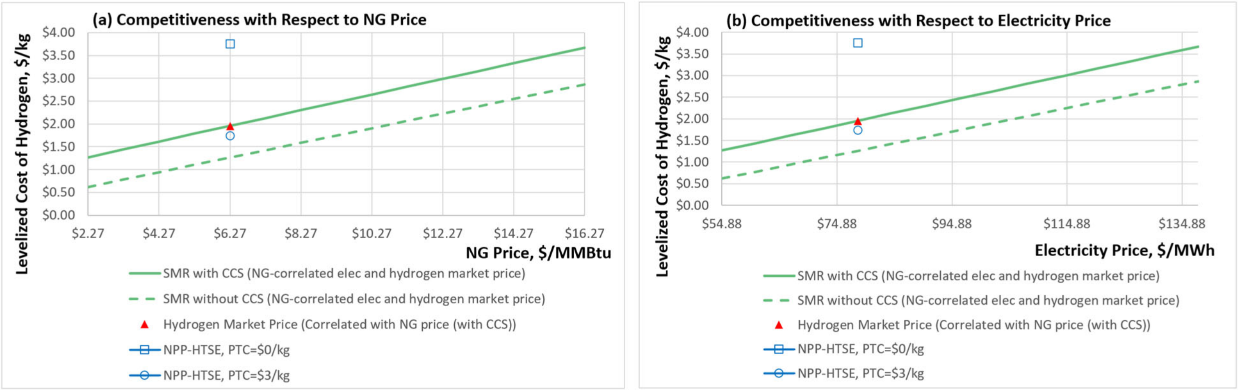


Figure 22. Competitive analysis for Case 4 with respect to (a) NG price, and (b) electricity price

5 CONCLUSION AND FUTURE WORK

5.1 Conclusions

A user-friendly NPP-HTSE H_2 profitability tool has been developed in Microsoft Excel to help nuclear operating utility companies evaluate the profitability of nuclear integrated hydrogen production. The tool has the features to perform the following analysis:

- Financial performance
- Sensitivity analysis
- Profitability analysis using heat maps
- Electricity versus hydrogen production preference analysis
- Competitiveness analysis.

The modeling methodologies and assumptions of the NPP-HTSE H_2 profitability tool are documented in this report with the user manual in the Appendix of this report. The user may change the utility and location-specific inputs by following the guidance in the tool.

The NPP-HTSE H_2 profitability tool has been verified with the existing models in the literature by performing code-to-code comparisons. Similar results are obtained and confirm the validity of the NPP-HTSE H_2 profitability tool.

A total of four cases are used to demonstrate the features and capability of the NPP-HTSE H_2 profitability tool. Case 1 is a breakeven case (without PTC included), where the hydrogen market selling price is set to the LCOH to estimate the NPV_{H2}. Case 2 uses a user-defined hydrogen market price. In both Case 1 and Case 2, the hydrogen market price and electricity price are uncorrelated with the NG price. For Case 3, both the hydrogen market price and electricity price are correlated with the NG price. For Case 1, Case 2, and Case 3, the hydrogen market price, electricity price, and NG price are fixed for the entire plant life (i.e., 20 years). That is, a regulated market is assumed for Case 1, Case 2, and Case 3. In Case 4, a deregulated market is implemented with hydrogen market price, electricity price, and NG price changing over the plant life. The input specification and financial performance for the four cases are summarized in Table 12.

Based on Table 12, conclusions for the four example cases are:

- Case 1 was used for validation and verification purposes.
- Case 2 is designed for users to provide the user-defined hydrogen market price and electricity price for the analysis. Based on the demonstration and the inputs considered, Case 2 is the only profitable, preferred, and potentially competitive case for producing hydrogen using the NPP-HTSE.
- Case 3 is not profitable but may competitive with SMR with CCS only when the NG price is low (e.g., below 2.22 MMBtu), which is not possible based on the historical data in the past two decades [14]. The user may enter their data for electricity price and NG price based on the most updated forecast data instead of relying on the EIA AEO 2023 [10].
- Case 4 is not profitable, however, the user may enter their data for electricity price and NG price to find profitable, preferred and competitive conditions for Case 4.

Table 12. Comparisons of four example use cases demonstrating the NPP-HTSE H_2 profitability tool. BAU case assumed all the electricity generated from NPP is sold through the electricity grids.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Notes**
HTSE plant capacity (MW-dc)	500	500	500	500	500 MW-dc is a practical size based on the 2023 hydrogen market report [13].
Annual hydrogen production (ktonne/year)	111.5	111.5	111.5	111.5	Calculated based on 500 MW-dc HTSE electrolyzer.
Plant Life (years)	20	20	20	20	20 years of plant life is selected from INL NPP-HTSE study [8].
Weighted Average of Capital Cost (%)	12.10%	12.10%	12.10%	12.10%	12.10% is the discount rate before inflation selected from INL NPP-HTSE study [8].
PTC (\$/kg-H_2)	0.02	3	3	3	A maximum of \$3/kg of PTC is available based on IRA [2]. \$0.02 is an adjustable credit to have breakeven conditions.
Hydrogen Market Price (\$2023/kg-H_2)	2.28	1.00	1.60	1.96	Case 1 sets LCOH equivalent to the hydrogen market price. Case 2 assumes \$1/kg-H_2 to meet 111 targets. The hydrogen market price for Cases 3 and 4 is calculated from NG price.
Electricity Price (\$2023/MWh)	30	28	66.68	78.53	\$30/MWh is selected from INL NPP-HTSE study [8]. 28/MWh is selected for Case 2 so that ΔNPV is positive. The electricity prices for Cases 3 and 4 are calculated from the NG price.
NG Price (\$2023/MMBtu)	4.22	4.22	4.22	6.27	\$4.22/MMBtu is selected for the industrial NG price on April 2023 [14]. \$6.27/MMBtu is the average NG price in 2023 from EIA AEO 2023 [10].
LCOH with PTC (\$2023/kg-H_2)	2.26	0.07	1.73	1.74	
LCOH without PTC (\$2023/kg-H_2)	2.28	2.09	3.74	3.75	
IRR (%)	12.10	66.52	13.68	13.91	
NPV_{H2} (\$ Million)	0	758	-24	-28	
NPV_{BAU} (\$ Million)	809	755	1790	1795	
ΔNPV (\$ Million)	-809	3	-1814	-1823	

Future Work

Future development of the tool can include the following:

- Identify and integrate functionality from other INL FORCE tools with into the NPP-HTSE H_2 profitability tool and provide specific outputs of the tool to the FORCE tools:

  Some of the intermediate outputs from NPP-HTSE H_2 profitability tool (e.g., DCC, fixed and varied O&M]cost) can be used as the inputs to the Holistic Energy Resource Optimization Network (HERON) for resources optimization [4]. One application is to find the optimized NPV or LCOH considering multiple variations of the inputs. In this case, there is a need to interface the NPP-HTSE H_2 profitability tool with HERON in a unified framework.

- Develop a web-based NPP-HTSE H_2 profitability tool:

  One of the objectives of developing the NPP-HTSE H_2 profitability tool is to simplify the accessibility and usage. A web-based version of the NPP-HTSE H_2 profitability tool would make the tool more accessible.

- Enhance the features of the NPP-HTSE H_2 profitability tool:

  The NPP-HTSE H_2 profitability tool predicts that an NPP-HTSE with 500 MW-dc can generate around one MMT per year of hydrogen. However, depending on the hydrogen demands on the market, there should be an option for hydrogen storage when needed. In this case, the cost of hydrogen storage can be added to the LCOH as a function of the annual hydrogen production. Considering the storage of hydrogen production, there is a possibility to optimize hydrogen storage and production by selling the hydrogen at a higher price while storing the hydrogen at a lower price.

- Expand the functionality of the tool beyond hydrogen:

  The NPP-HTSE H_2 profitability tool could be expanded to include analysis of advanced nuclear reactors such as High Temperature Gas Reactors (HTGR), Liquid Metal Cooled Fast Reactors (LMFR) such as sodium cooled fast reactors (SCFR), and advanced PWR LWRs integrated with industries that need heat, power, and hydrogen such as oil refineries, synthetic fuels (methanol as an example), and biomass / pulp and paper plants.

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7 Appendix A: User Guide

The NPP-HTSE H_2 profitability tool was developed in Microsoft Excel with multiple sheets that store inputs, outputs and background calculations (i.e., cash flow analysis, sensitivity studies, profitability analysis, electricity versus hydrogen production preference analysis, and competitive analysis). There are four visible sheets in the tool: “Tool Information”, “Dashboard”, “Proforma (Market), and Elec_NG_Price”.

The “Tool Information” sheet provides the status of the projects including the instructions, color codes, and version status. The “Dashboard” sheet of the hydrogen profitability tool is designed to include the critical inputs and outputs but hide the background calculations in other sheets or macros. There are six steps to follow when using this tool.

- Step-1: Input Specification

  There are a total of 61 input parameters in the NPP-HTSE H_2 profitability tool, where seven inputs are shown in the dashboard including HTSE plant capacity, plant life, WACC, PTC, hydrogen market price, electricity price, and NG price. These input parameters are selected based on the project interests, pre-sensitivity analysis and expert opinions. The user may click "Additional inputs information" on the dashboard to see the descriptions, assumptions, and data sources for the default values. The user can also provide the "user-defined inputs" to replace the default values in the orange cells. The user can click "clear all user-defined inputs" to reset all the values back to the default. Click "Go back to Dashboard" to return to the "Dashboard" Sheet.

- Step-2: Financial Performance

  To demonstrate hydrogen profitability, critical outputs such as LCOH with and without consideration of PTC, IRR, Net Present Value for producing hydrogen from NPP-HTSE (NPV_{H2}), Net Present Value for producing hydrogen from NPP-BAU (NPV_{BAU}), ΔNPV relative to BAU, and annual hydrogen production are shown as the output of financial performance. The breakdown contributions of LCOH without consideration of PTC and the revenues of hydrogen are available for comparison. Different color codes are implemented for IRR, NPV_{H2}, NPV_{BAU} and ΔNPV relative to BAU on the dashboard, where green color represents four different scenarios: (1) IRR is larger than WACC, (2) a positive value of NPV-HTSE, (3) a positive value of NPV_{BAU}, and (4) a positive ΔNPV relative to BAU. The case with IRR larger than WACC means that the utility has reached the goal of the profits. The positive value of NPV indicates that the utility that integrates the NPP-HTSE for hydrogen production is making money, but it is not guaranteed to earn enough profits to cover the WACC. A positive ΔNPV relative to BAU indicates that it is more profitable to generate hydrogen instead of purely selling the electricity to the grid. The user can click “Additional Outputs” to see other intermediate outputs (e.g., Daily HTSE Hydrogen Output). The users are not recommended to change the formula in the “Output (Formula)” sheet unless the user would like to ignore or change the dependency among the inputs with sufficient justifications. Click "Go back to Dashboard" to return to the "Dashboard" Sheet. The user can click “LCOH Breakdowns” to see how the LOCH is calculated or “NPV Breakdowns” to see the cash flow analysis in this tool. Click "Go back to Dashboard" on the “LCOH” or “NPV” sheet to return to the "Dashboard" Sheet. In “NPV” sheets, there are multiple macros to access other tables including (1) replacement cost table, (2) depreciation table, (3) tables for principal payment and debt interest. Click these icons to see detailed quantifications if necessary.

- Step-3: Sensitivity Analysis (Rank Input Parameters)

The tornado charts show the impacts of each selected input on LCOH and NPV_{H2}. The users should define the lower and upper bound by entering the percentage under "% Lower" and "% Upper" (highlighted in orange cells). The "%" means percent less or more with respect to the nominal value (e.g., 50% higher indicates 1.5 times the nominal value). If the percentage is hard to define, the user can select "N/A" for the "% Lower" or "% Upper" and define the exact values under "Exact low" and "Exact upper". The "Exact" means the real value at the upper and lower bound (e.g., \$3/kg is used as the upper bound of the PTC). The calculated lower and upper bounds highlighted in blue cells are demonstrated under "Cal. Lower" and "Cal. Upper", respectively. The blue cells are treated as a reference and the blue cell formulas should not be adjusted by the user. . The sensitivity index is defined as the difference between the maximum and minimum of the LOCH or NPV estimation. The highest sensitive input is ranked first (i.e., the first row of the chart) while the least sensitive input is ranked last (i.e., the last row of the chart). The tornado charts are obtained by using three different values (in the form of brackets) of selected input to construct the blue bar, center value, and orange bar for each parameter while using the nominal value for the other inputs. The blue bars represent the minimum values obtained by using the first value in the bracket. The center values represent the nominal LCOH, and NPVH2 using the second value in the bracket. The orange bars represent the maximum values obtained by using the third value in the bracket.

- Step-4: Profitability Analysis using Heat Maps

  For the heat maps of IRR and NPV, two input parameters are selected with specific lower and upper bounds. It is recommended to select the two top-ranked inputs from the sensitivity study of NPVH2. The user needs to define the exact lower and upper bounds of the select input variables highlighted in orange cells. Then, the user should click "Update Heat Maps" to update the results. For simplicity, the user can select the same values in Step-3. The white cells indicate the “N/A” value of IRR, indicating a negative cash flow. The red cell is the lowest IRR or NPV while the green cell is the highest IRR or NPV in the calculation. A solid black line shows the threshold of IRR and NPV. The user can check the IRR and NPV values for selecting the profitable areas. If necessary, the user may refine the bounds to enhance the resolutions of the heat maps.

- Step-5: Electricity versus Hydrogen Production Preferences Analysis

  For the BAU comparison, two independent input parameters can be selected in addition to the dependent variable such as electricity price. The users should provide the bounds of each input for calculating the NPV given each value of electricity price. After selecting the variables with the defined upper and lower bounds, the user can click "Update Plots for Comparisons". The user should be able to identify the “preferred region” (in green color) over selling the electricity to the grids. If no preferable area is shown, it indicates either generating hydrogen is not preferred or the user can draw the region of preferred conditions by identifying that NPV_{H2} is higher than NPV_{BAU}.

- Step-6: Competitiveness Analysis

  Perform the sensitivity analysis considering the interdependency of LCOH, electricity price, and NG price. Multiple runs of the original H2A model for SMR [2] are executed with the same reference year and start-up year in NPP-HTSE H_2 profitability tool to find the relationships among LCOH, electricity price, and NG price. The user just needs to click "Update plots". After the simulation is done, the user can check the results to determine under which condition it is more competitive to produce hydrogen based on NPP-HTSE instead of SMR. The hydrogen production from NPP-HTSE is more competitive when the LCOH from NPP-HTSE is smaller than the LCOH from SMR with or without CCS.

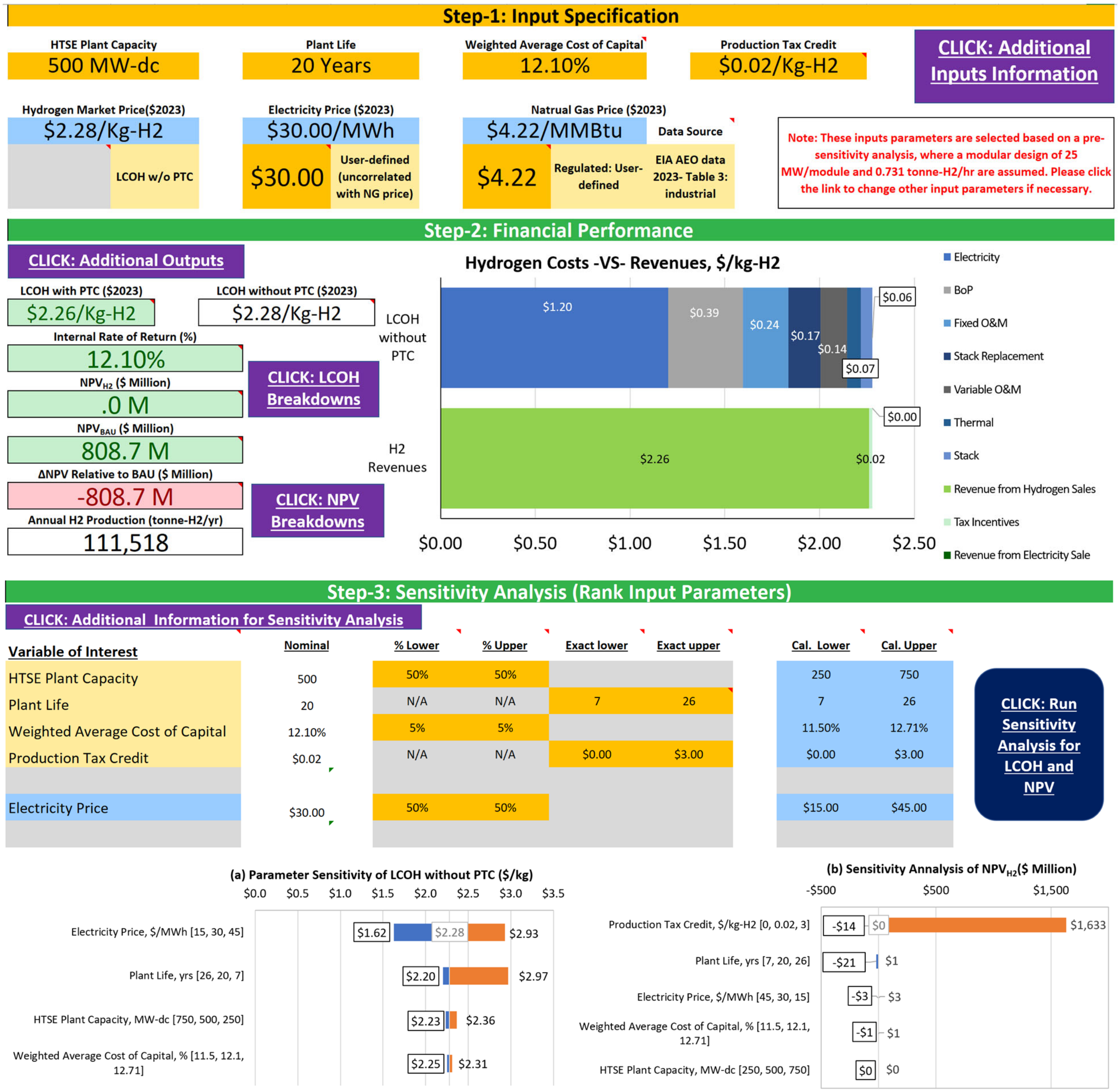
The “Proforma (Market)” sheet provides a summary of the detailed calculations of revenue, LCOH, gross profit, earnings before interest, tax, depreciation, and amortization, earnings before interest and tax, earnings before tax, and NPV. The “Proforma (Market)” sheet uses a different approach from the “NPV” sheets, which is hidden from the users. The user may compare the results of the NPV from the “Proforma (Market)” sheet with that on the “Dashboard” sheet, which is calculated from the hidden “NPV” sheets.

The” Elec_NG_Price” sheet is designed for the users who would like to enter the data for electricity price and NG price when selecting “User-defined” in Step-1 for the data sources of NG price. The default value uses a specific ratio to reduce the electricity price by a factor of 1.8 based on the costs of electricity from the average electricity costs of NPP in the U.S. Note that all the data from 2023 to 2050 should be filled to prevent an error message in the tool.

8 Appendix B: Screenshots for Example Cases

The screenshots of the dashboard for the four cases demonstrating the capabilities of the HTSE H_2 profitability tool are demonstrated here.

- Case 1: Breakeven



Step-1: Input Specification

HTSE Plant Capacity: 500 MW-dc

Plant Life: 20 Years

Weighted Average Cost of Capital: 12.10%

Production Tax Credit: $0.02/Kg-H2

Hydrogen Market Price($2023): $2.28/Kg-H2 — LCOH w/o PTC

Electricity Price ($2023): $30.00/MWh — $30.00 — User-defined (uncorrelated with NG price)

Natrual Gas Price ($2023): $4.22/MMBtu — $4.22 — Regulated: User-defined — Data Source: EIA AEO data 2023- Table 3: industrial

Note: These inputs parameters are selected based on a pre-sensitivity analysis, where a modular design of 25 MW/module and 0.731 tonne-H2/hr are assumed. Please click the link to change other input parameters if necessary.

Step-2: Financial Performance

LCOH with PTC ($2023): $2.26/Kg-H2

LCOH without PTC ($2023): $2.28/Kg-H2

Internal Rate of Return (%): 12.10%

NPV_{H2} ($ Million): .0 M

NPV_{BAU} ($ Million): 808.7 M

ΔNPV Relative to BAU ($ Million): -808.7 M

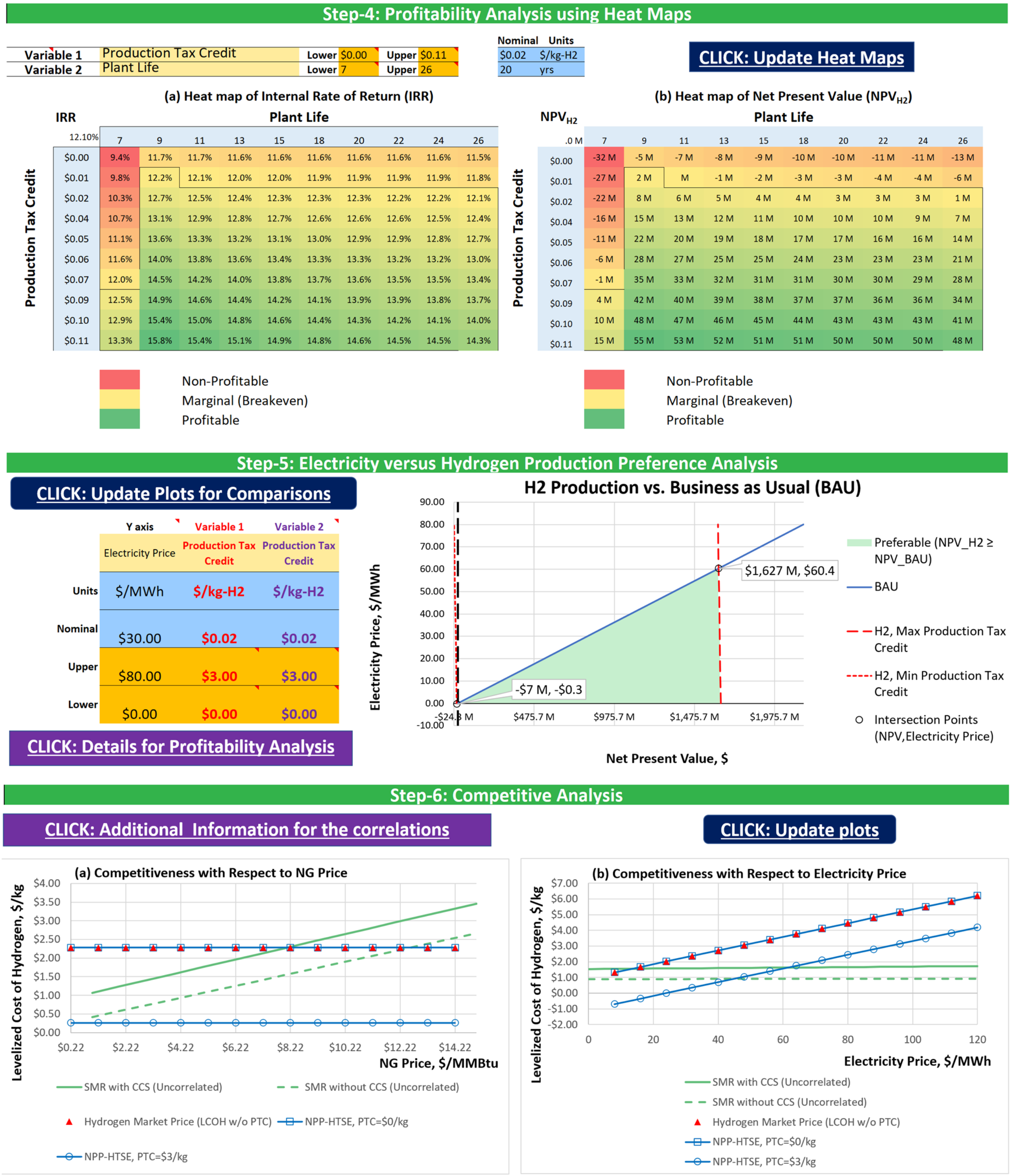
Annual H2 Production (tonne-H2/yr): 111,518

Step-3: Sensitivity Analysis (Rank Input Parameters)

Variable of Interest	Nominal	% Lower	% Upper	Exact lower	Exact upper	Cal. Lower	Cal. Upper
HTSE Plant Capacity	500	50%	50%			250	750
Plant Life	20	N/A	N/A	7	26	7	26
Weighted Average Cost of Capital	12.10%	5%	5%			11.50%	12.71%
Production Tax Credit	$0.02	N/A	N/A	$0.00	$3.00	$0.00	$3.00
Electricity Price	$30.00	50%	50%			$15.00	$45.00

(a) Parameter Sensitivity of LCOH without PTC ($/kg)

(b) Sensitivity Analysis of NPV_{H2}($ Million)



Step-4: Profitability Analysis using Heat Maps

						Nominal	Units
Variable 1	Production Tax Credit	**Lower**	$0.00	**Upper**	$0.11	$0.02	$/kg-H2
Variable 2	Plant Life	**Lower**	7	**Upper**	26	20	yrs

CLICK: Update Heat Maps

(a) Heat map of Internal Rate of Return (IRR)

IRR — **Plant Life** — **Production Tax Credit**

12.10%	7	9	11	13	15	18	20	22	24	26
$0.00	9.4%	11.7%	11.7%	11.6%	11.6%	11.6%	11.6%	11.6%	11.6%	11.5%
$0.01	9.8%	12.2%	12.1%	12.0%	12.0%	11.9%	11.9%	11.9%	11.9%	11.8%
$0.02	10.3%	12.7%	12.5%	12.4%	12.3%	12.3%	12.3%	12.2%	12.2%	12.1%
$0.04	10.7%	13.1%	12.9%	12.8%	12.7%	12.6%	12.6%	12.6%	12.5%	12.4%
$0.05	11.1%	13.6%	13.3%	13.2%	13.1%	13.0%	12.9%	12.9%	12.8%	12.7%
$0.06	11.6%	14.0%	13.8%	13.6%	13.4%	13.3%	13.3%	13.2%	13.2%	13.0%
$0.07	12.0%	14.5%	14.2%	14.0%	13.8%	13.7%	13.6%	13.5%	13.5%	13.4%
$0.09	12.5%	14.9%	14.6%	14.4%	14.2%	14.1%	13.9%	13.9%	13.8%	13.7%
$0.10	12.9%	15.4%	15.0%	14.8%	14.6%	14.4%	14.3%	14.2%	14.1%	14.0%
$0.11	13.3%	15.8%	15.4%	15.1%	14.9%	14.8%	14.6%	14.5%	14.5%	14.3%

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

(b) Heat map of Net Present Value (NPV_{H2})

NPV_{H2} — **Plant Life** — **Production Tax Credit**

.0 M	7	9	11	13	15	18	20	22	24	26
$0.00	-32 M	-5 M	-7 M	-8 M	-9 M	-10 M	-10 M	-11 M	-11 M	-13 M
$0.01	-27 M	2 M	M	-1 M	-2 M	-3 M	-3 M	-4 M	-4 M	-6 M
$0.02	-22 M	8 M	6 M	5 M	4 M	4 M	3 M	3 M	3 M	1 M
$0.04	-16 M	15 M	13 M	12 M	11 M	10 M	10 M	10 M	9 M	7 M
$0.05	-11 M	22 M	20 M	19 M	18 M	17 M	17 M	16 M	16 M	14 M
$0.06	-6 M	28 M	27 M	25 M	25 M	24 M	23 M	23 M	23 M	21 M
$0.07	-1 M	35 M	33 M	32 M	31 M	31 M	30 M	30 M	29 M	28 M
$0.09	4 M	42 M	40 M	39 M	38 M	37 M	37 M	36 M	36 M	34 M
$0.10	10 M	48 M	47 M	46 M	45 M	44 M	43 M	43 M	43 M	41 M
$0.11	15 M	55 M	53 M	52 M	51 M	51 M	50 M	50 M	50 M	48 M

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

Step-5: Electricity versus Hydrogen Production Preference Analysis

CLICK: Update Plots for Comparisons

	Y axis	Variable 1	Variable 2
	Electricity Price	Production Tax Credit	Production Tax Credit
Units	$/MWh	$/kg-H2	$/kg-H2
Nominal	$30.00	$0.02	$0.02
Upper	$80.00	$3.00	$3.00
Lower	$0.00	$0.00	$0.00

CLICK: Details for Profitability Analysis

H2 Production vs. Business as Usual (BAU)

Step-6: Competitive Analysis

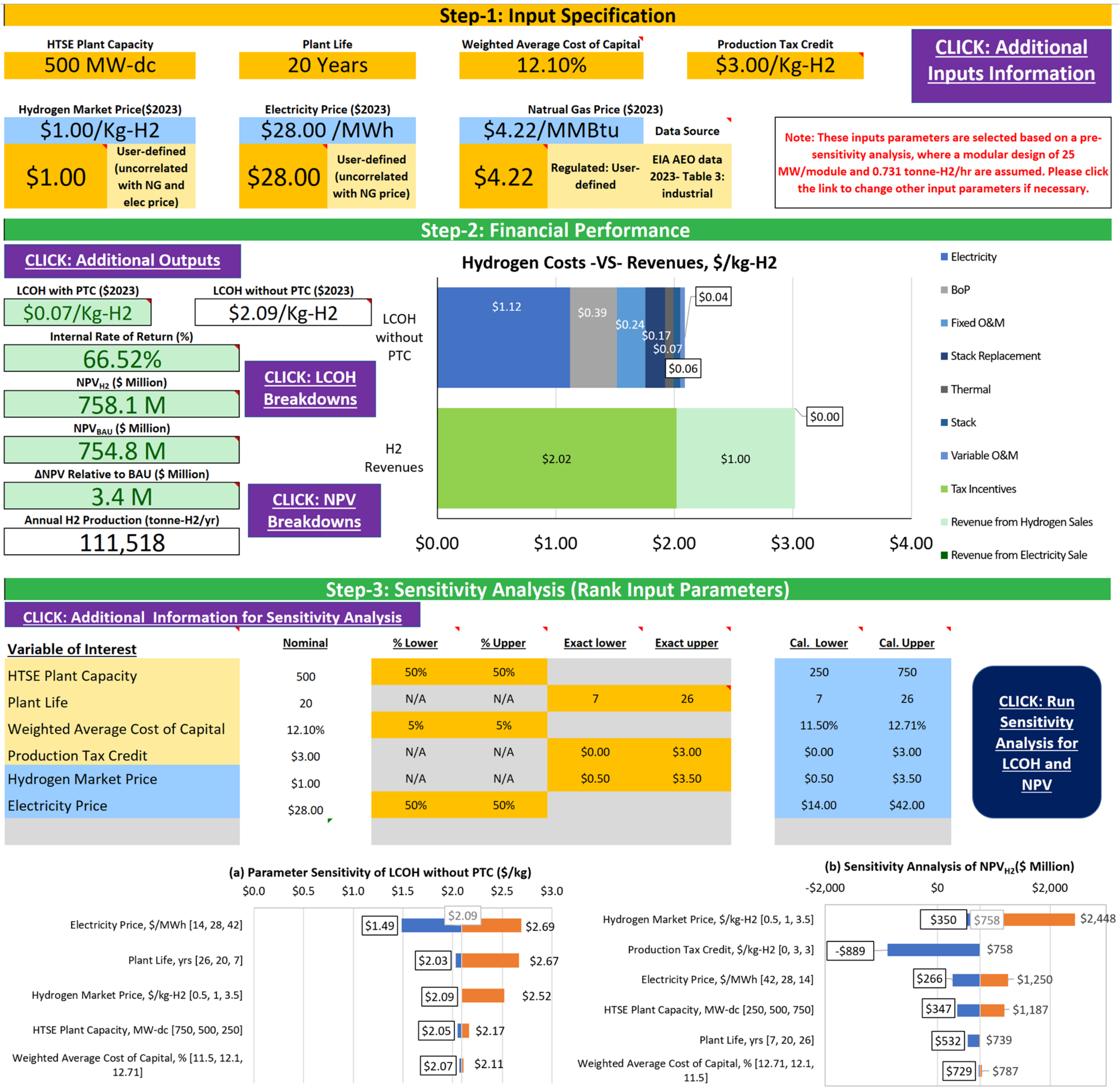
CLICK: Additional Information for the correlations

CLICK: Update plots

(a) Competitiveness with Respect to NG Price

(b) Competitiveness with Respect to Electricity Price

- Case 2: User-defined Hydrogen Market Price



Step-1: Input Specification

HTSE Plant Capacity: 500 MW-dc

Plant Life: 20 Years

Weighted Average Cost of Capital: 12.10%

Production Tax Credit: $3.00/Kg-H2

CLICK: Additional Inputs Information

Hydrogen Market Price($2023): $1.00/Kg-H2
$1.00 User-defined (uncorrelated with NG and elec price)

Electricity Price ($2023): $28.00 /MWh
$28.00 User-defined (uncorrelated with NG price)

Natrual Gas Price ($2023): $4.22/MMBtu
$4.22 Regulated: User-defined
Data Source: EIA AEO data 2023- Table 3: industrial

Note: These inputs parameters are selected based on a pre-sensitivity analysis, where a modular design of 25 MW/module and 0.731 tonne-H2/hr are assumed. Please click the link to change other input parameters if necessary.

Step-2: Financial Performance

CLICK: Additional Outputs

LCOH with PTC ($2023): $0.07/Kg-H2

LCOH without PTC ($2023): $2.09/Kg-H2

Internal Rate of Return (%): 66.52%

NPV_{H2} ($ Million): 758.1 M

NPV_{BAU} ($ Million): 754.8 M

ΔNPV Relative to BAU ($ Million): 3.4 M

Annual H2 Production (tonne-H2/yr): 111,518

CLICK: LCOH Breakdowns

CLICK: NPV Breakdowns

Step-3: Sensitivity Analysis (Rank Input Parameters)

CLICK: Additional Information for Sensitivity Analysis

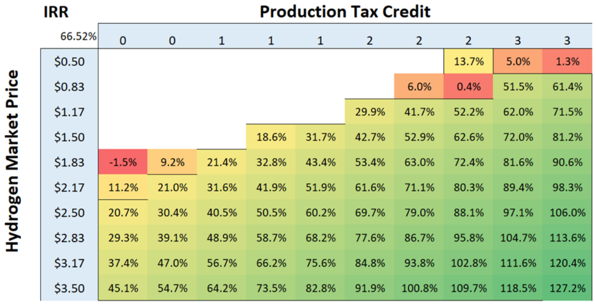
Variable of Interest	Nominal	% Lower	% Upper	Exact lower	Exact upper	Cal. Lower	Cal. Upper
HTSE Plant Capacity	500	50%	50%			250	750
Plant Life	20	N/A	N/A	7	26	7	26
Weighted Average Cost of Capital	12.10%	5%	5%			11.50%	12.71%
Production Tax Credit	$3.00	N/A	N/A	$0.00	$3.00	$0.00	$3.00
Hydrogen Market Price	$1.00	N/A	N/A	$0.50	$3.50	$0.50	$3.50
Electricity Price	$28.00	50%	50%			$14.00	$42.00

CLICK: Run Sensitivity Analysis for LCOH and NPV

Step-4: Profitability Analysis using Heat Maps

						Nominal	Units
Variable 1	Hydrogen Market Price	**Lower**	$0.50	**Upper**	$3.50	$1.00	$/kg-H2
Variable 2	Production Tax Credit	**Lower**	$0.00	**Upper**	$3.00	$3.00	$/kg-H2

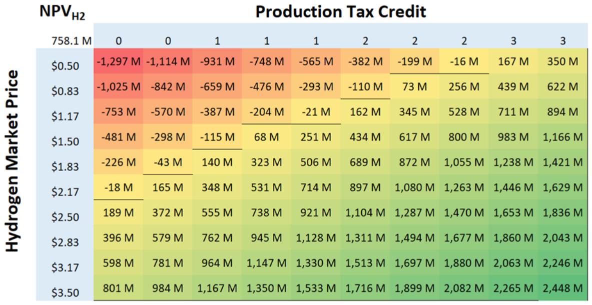
CLICK: Update Heat Maps



(a) Heat map of Internal Rate of Return (IRR)

IRR 66.52%	0	0	1	1	1	2	2	2	3	3
$0.50								13.7%	5.0%	1.3%
$0.83							6.0%	0.4%	51.5%	61.4%
$1.17						29.9%	41.7%	52.2%	62.0%	71.5%
$1.50				18.6%	31.7%	42.7%	52.9%	62.6%	72.0%	81.2%
$1.83	-1.5%	9.2%	21.4%	32.8%	43.4%	53.4%	63.0%	72.4%	81.6%	90.6%
$2.17	11.2%	21.0%	31.6%	41.9%	51.9%	61.6%	71.1%	80.3%	89.4%	98.3%
$2.50	20.7%	30.4%	40.5%	50.5%	60.2%	69.7%	79.0%	88.1%	97.1%	106.0%
$2.83	29.3%	39.1%	48.9%	58.7%	68.2%	77.6%	86.7%	95.8%	104.7%	113.6%
$3.17	37.4%	47.0%	56.7%	66.2%	75.6%	84.8%	93.8%	102.8%	111.6%	120.4%
$3.50	45.1%	54.7%	64.2%	73.5%	82.8%	91.9%	100.8%	109.7%	118.5%	127.2%

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable



(b) Heat map of Net Present Value (NPV_{H2})

NPV_{H2} 758.1 M	0	0	1	1	1	2	2	2	3	3
$0.50	-1,297 M	-1,114 M	-931 M	-748 M	-565 M	-382 M	-199 M	-16 M	167 M	350 M
$0.83	-1,025 M	-842 M	-659 M	-476 M	-293 M	-110 M	73 M	256 M	439 M	622 M
$1.17	-753 M	-570 M	-387 M	-204 M	-21 M	162 M	345 M	528 M	711 M	894 M
$1.50	-481 M	-298 M	-115 M	68 M	251 M	434 M	617 M	800 M	983 M	1,166 M
$1.83	-226 M	-43 M	140 M	323 M	506 M	689 M	872 M	1,055 M	1,238 M	1,421 M
$2.17	-18 M	165 M	348 M	531 M	714 M	897 M	1,080 M	1,263 M	1,446 M	1,629 M
$2.50	189 M	372 M	555 M	738 M	921 M	1,104 M	1,287 M	1,470 M	1,653 M	1,836 M
$2.83	396 M	579 M	762 M	945 M	1,128 M	1,311 M	1,494 M	1,677 M	1,860 M	2,043 M
$3.17	598 M	781 M	964 M	1,147 M	1,330 M	1,513 M	1,697 M	1,880 M	2,063 M	2,246 M
$3.50	801 M	984 M	1,167 M	1,350 M	1,533 M	1,716 M	1,899 M	2,082 M	2,265 M	2,448 M

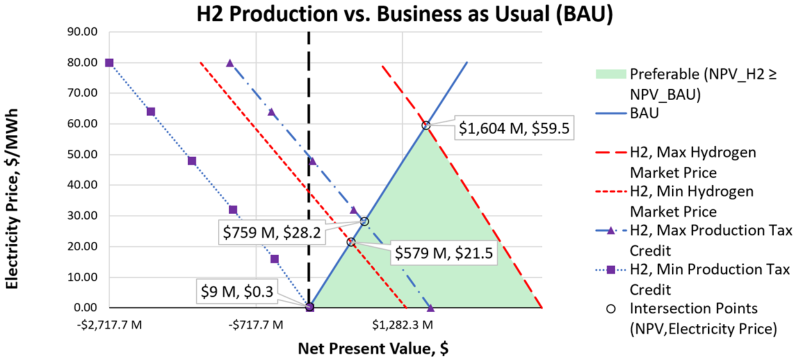
🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

Step-5: Electricity versus Hydrogen Production Preference Analysis

CLICK: Update Plots for Comparisons

	Y axis	Variable 1	Variable 2
	Electricity Price	Hydrogen Market Price	Production Tax Credit
Units	$/MWh	$/kg-H2	$/kg-H2
Nominal	$28.00	$1.00	$3.00
Upper	$80.00	$3.50	$3.00
Lower	$0.00	$0.50	$0.00

CLICK: Details for Profitability Analysis

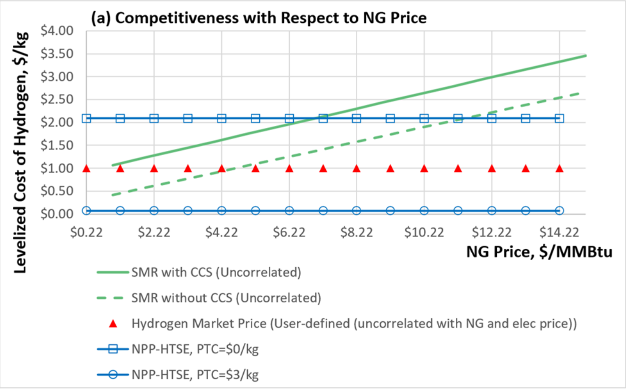


H2 Production vs. Business as Usual (BAU)

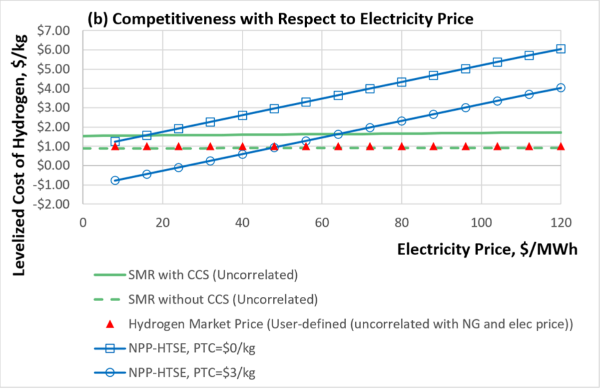
Step-6: Competitive Analysis

CLICK: Additional Information for the correlations

CLICK: Update plots

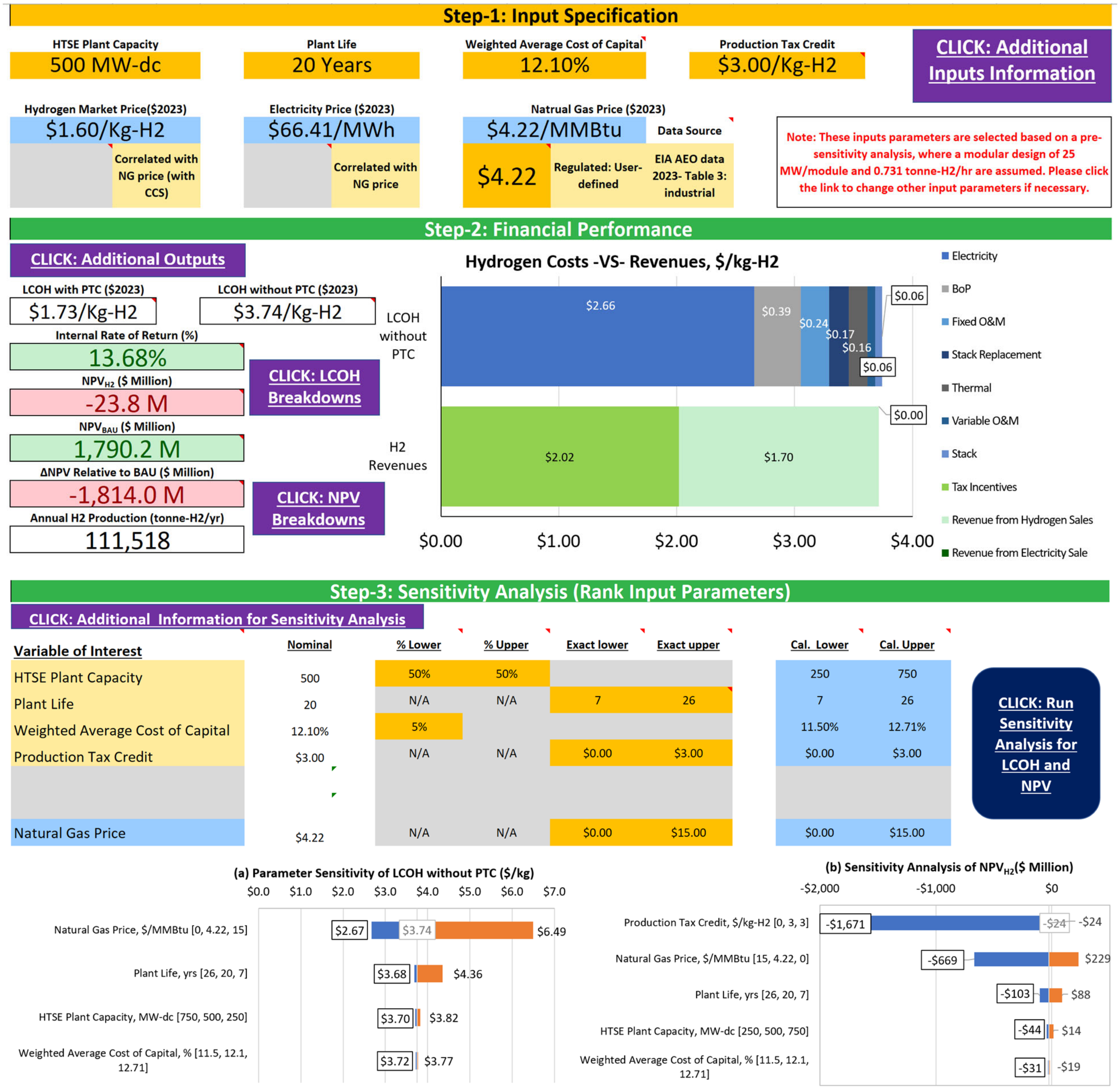


(a) Competitiveness with Respect to NG Price



(b) Competitiveness with Respect to Electricity Price

- Case 3: NG-Correlated Hydrogen Price and the Electricity Price with Regulated Market



Step-1: Input Specification

HTSE Plant Capacity	Plant Life	Weighted Average Cost of Capital	Production Tax Credit
500 MW-dc	20 Years	12.10%	$3.00/Kg-H2

CLICK: Additional Inputs Information

Hydrogen Market Price($2023)	Electricity Price ($2023)	Natrual Gas Price ($2023)
$1.60/Kg-H2	$66.41/MWh	$4.22/MMBtu
Correlated with NG price (with CCS)	Correlated with NG price	$4.22 Regulated: User-defined Data Source: EIA AEO data 2023- Table 3: industrial

Note: These inputs parameters are selected based on a pre-sensitivity analysis, where a modular design of 25 MW/module and 0.731 tonne-H2/hr are assumed. Please click the link to change other input parameters if necessary.

Step-2: Financial Performance

CLICK: Additional Outputs

LCOH with PTC ($2023): $1.73/Kg-H2

LCOH without PTC ($2023): $3.74/Kg-H2

Internal Rate of Return (%): 13.68%

NPV_{H2} ($ Million): -23.8 M

NPV_{BAU} ($ Million): 1,790.2 M

ΔNPV Relative to BAU ($ Million): -1,814.0 M

Annual H2 Production (tonne-H2/yr): 111,518

CLICK: LCOH Breakdowns

CLICK: NPV Breakdowns

Step-3: Sensitivity Analysis (Rank Input Parameters)

CLICK: Additional Information for Sensitivity Analysis

Variable of Interest	Nominal	% Lower	% Upper	Exact lower	Exact upper	Cal. Lower	Cal. Upper
HTSE Plant Capacity	500	50%	50%			250	750
Plant Life	20	N/A	N/A	7	26	7	26
Weighted Average Cost of Capital	12.10%	5%				11.50%	12.71%
Production Tax Credit	$3.00	N/A	N/A	$0.00	$3.00	$0.00	$3.00
Natural Gas Price	$4.22	N/A	N/A	$0.00	$15.00	$0.00	$15.00

CLICK: Run Sensitivity Analysis for LCOH and NPV

(a) Parameter Sensitivity of LCOH without PTC ($/kg)

(b) Sensitivity Annalysis of NPV_{H2}($ Million)

Step-4: Profitability Analysis using Heat Maps

						Nominal	Units
Variable 1	Production Tax Credit	**Lower**	$0.00	**Upper**	$3.00	$3.00	$/kg-H2
Variable 2	Natural Gas Price	**Lower**	$0.00	**Upper**	$5.00	$4.22	$/MMBtu

CLICK: Update Heat Maps

(a) Heat map of Internal Rate of Return (IRR)

Production Tax Credit (rows) / **Natural Gas Price** (columns)

IRR 13.68%	0	1	1	2	2	3	3	4	4	5
$0.00										
$0.33										
$0.67										
$1.00										
$1.33										
$1.67										
$2.00										
$2.33										
$2.67	9.5%	11.3%	13.8%							
$3.00	4.1%	4.9%	5.9%	6.9%	7.9%	9.2%	10.6%	12.3%	14.8%	

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

(b) Heat map of Net Present Value (NPV_{H2})

Production Tax Credit (rows) / **Natural Gas Price** (columns)

NPV_{H2} -23.8 M	0	1	1	2	2	3	3	4	4	5
$0.00	-1,418 M	-1,452 M	-1,485 M	-1,518 M	-1,551 M	-1,585 M	-1,618 M	-1,651 M	-1,684 M	-1,718 M
$0.33	-1,235 M	-1,269 M	-1,302 M	-1,335 M	-1,368 M	-1,402 M	-1,435 M	-1,468 M	-1,501 M	-1,535 M
$0.67	-1,052 M	-1,085 M	-1,119 M	-1,152 M	-1,185 M	-1,219 M	-1,252 M	-1,285 M	-1,318 M	-1,352 M
$1.00	-869 M	-902 M	-936 M	-969 M	-1,002 M	-1,036 M	-1,069 M	-1,102 M	-1,135 M	-1,169 M
$1.33	-686 M	-719 M	-753 M	-786 M	-819 M	-853 M	-886 M	-919 M	-952 M	-986 M
$1.67	-503 M	-536 M	-570 M	-603 M	-636 M	-670 M	-703 M	-736 M	-769 M	-803 M
$2.00	-320 M	-353 M	-387 M	-420 M	-453 M	-487 M	-520 M	-553 M	-586 M	-620 M
$2.33	-137 M	-170 M	-204 M	-237 M	-270 M	-303 M	-337 M	-370 M	-403 M	-437 M
$2.67	46 M	13 M	-21 M	-54 M	-87 M	-120 M	-154 M	-187 M	-220 M	-254 M
$3.00	229 M	196 M	162 M	129 M	96 M	63 M	29 M	-4 M	-37 M	-71 M

🟥 Non-Profitable
🟨 Marginal (Breakeven)
🟩 Profitable

Step-5: Electricity versus Hydrogen Production Preference Analysis

CLICK: Update Plots for Comparisons

	Y axis	Variable 1	Variable 2
	Natural Gas Price	Production Tax Credit	Production Tax Credit
Units	$/MMBtu	$/kg-H2	$/kg-H2
Nominal	$4.22	$3.00	$3.00
Upper	$15.00	$3.00	$3.00
Lower	$0.00	$0.00	$0.00

CLICK: Details for Profitability Analysis

H2 Production vs. Business as Usual (BAU)

Step-6: Competitive Analysis

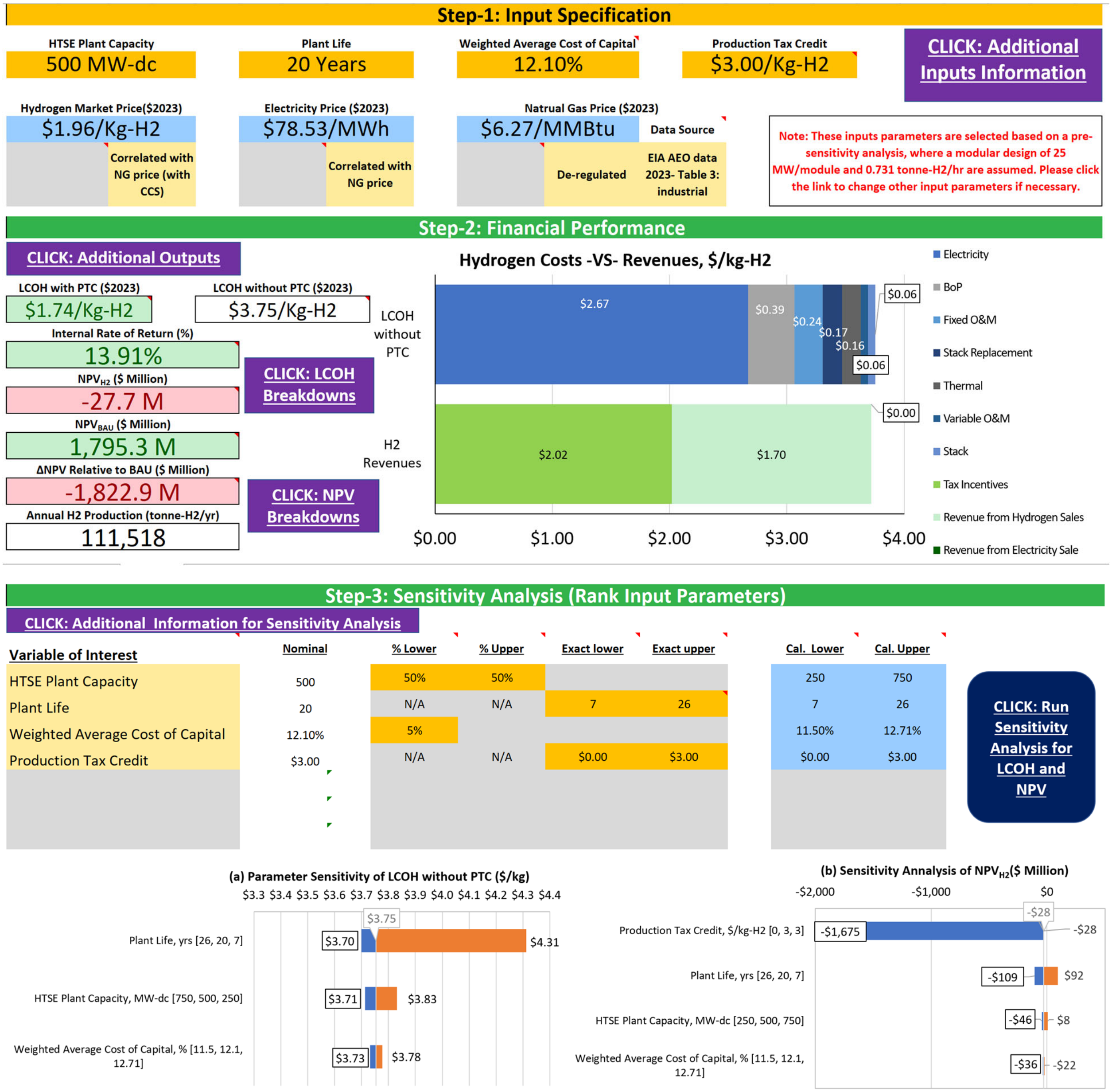
CLICK: Additional Information for the correlations

CLICK: Update plots

(a) Competitiveness with Respect to NG Price

(b) Competitiveness with Respect to Electricity Price

- Case 4: NG-Correlated Hydrogen Market Price with Deregulated Market



Step-1: Input Specification

HTSE Plant Capacity	Plant Life	Weighted Average Cost of Capital	Production Tax Credit
500 MW-dc	20 Years	12.10%	$3.00/Kg-H2

CLICK: Additional Inputs Information

Hydrogen Market Price($2023)	Electricity Price ($2023)	Natrual Gas Price ($2023)	Data Source
$1.96/Kg-H2	$78.53/MWh	$6.27/MMBtu	
Correlated with NG price (with CCS)	Correlated with NG price	De-regulated	EIA AEO data 2023- Table 3: industrial

Note: These inputs parameters are selected based on a pre-sensitivity analysis, where a modular design of 25 MW/module and 0.731 tonne-H2/hr are assumed. Please click the link to change other input parameters if necessary.

Step-2: Financial Performance

CLICK: Additional Outputs

LCOH with PTC ($2023)	LCOH without PTC ($2023)
$1.74/Kg-H2	$3.75/Kg-H2

Internal Rate of Return (%)
13.91%

NPV_{H2} ($ Million)
-27.7 M

NPV_{BAU} ($ Million)
1,795.3 M

ΔNPV Relative to BAU ($ Million)
-1,822.9 M

Annual H2 Production (tonne-H2/yr)
111,518

CLICK: LCOH Breakdowns

CLICK: NPV Breakdowns

Step-3: Sensitivity Analysis (Rank Input Parameters)

CLICK: Additional Information for Sensitivity Analysis

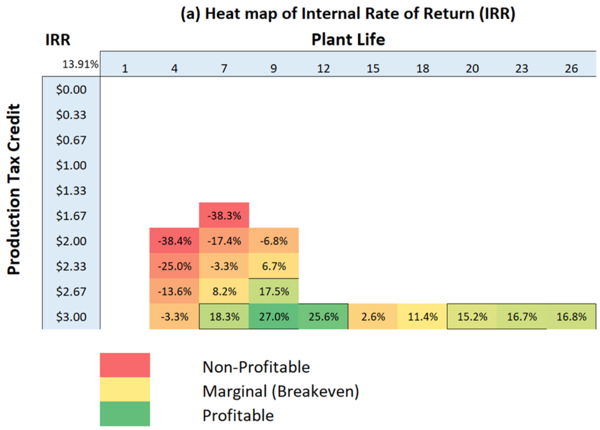
Variable of Interest	Nominal	% Lower	% Upper	Exact lower	Exact upper	Cal. Lower	Cal. Upper
HTSE Plant Capacity	500	50%	50%			250	750
Plant Life	20	N/A	N/A	7	26	7	26
Weighted Average Cost of Capital	12.10%	5%				11.50%	12.71%
Production Tax Credit	$3.00	N/A	N/A	$0.00	$3.00	$0.00	$3.00

CLICK: Run Sensitivity Analysis for LCOH and NPV

Step-4: Profitability Analysis using Heat Maps

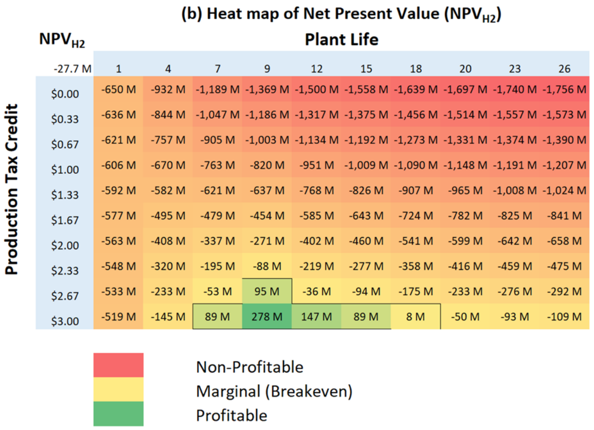
							Nominal	Units
Variable 1	Production Tax Credit	**Lower**	$0.00	**Upper**	$3.00		$3.00	$/kg-H2
Variable 2	Plant Life	**Lower**	1	**Upper**	26		20	yrs

CLICK: Update Heat Maps



(a) Heat map of Internal Rate of Return (IRR)

IRR 13.91%	1	4	7	9	12	15	18	20	23	26
$0.00										
$0.33										
$0.67										
$1.00										
$1.33										
$1.67			-38.3%							
$2.00		-38.4%	-17.4%	-6.8%						
$2.33		-25.0%	-3.3%	6.7%						
$2.67		-13.6%	8.2%	17.5%						
$3.00		-3.3%	18.3%	27.0%	25.6%	2.6%	11.4%	15.2%	16.7%	16.8%



(b) Heat map of Net Present Value (NPV_{H2})

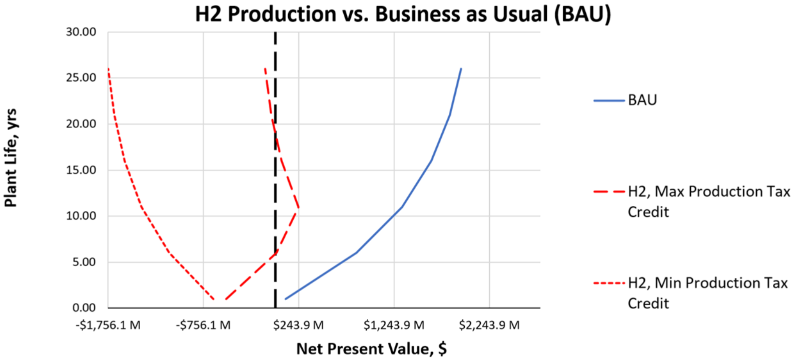
NPV_{H2} -27.7 M	1	4	7	9	12	15	18	20	23	26
$0.00	-650 M	-932 M	-1,189 M	-1,369 M	-1,500 M	-1,558 M	-1,639 M	-1,697 M	-1,740 M	-1,756 M
$0.33	-636 M	-844 M	-1,047 M	-1,186 M	-1,317 M	-1,375 M	-1,456 M	-1,514 M	-1,557 M	-1,573 M
$0.67	-621 M	-757 M	-905 M	-1,003 M	-1,134 M	-1,192 M	-1,273 M	-1,331 M	-1,374 M	-1,390 M
$1.00	-606 M	-670 M	-763 M	-820 M	-951 M	-1,009 M	-1,090 M	-1,148 M	-1,191 M	-1,207 M
$1.33	-592 M	-582 M	-621 M	-637 M	-768 M	-826 M	-907 M	-965 M	-1,008 M	-1,024 M
$1.67	-577 M	-495 M	-479 M	-454 M	-585 M	-643 M	-724 M	-782 M	-825 M	-841 M
$2.00	-563 M	-408 M	-337 M	-271 M	-402 M	-460 M	-541 M	-599 M	-642 M	-658 M
$2.33	-548 M	-320 M	-195 M	-88 M	-219 M	-277 M	-358 M	-416 M	-459 M	-475 M
$2.67	-533 M	-233 M	-53 M	95 M	-36 M	-94 M	-175 M	-233 M	-276 M	-292 M
$3.00	-519 M	-145 M	89 M	278 M	147 M	89 M	8 M	-50 M	-93 M	-109 M

Step-5: Electricity versus Hydrogen Production Preference Analysis

CLICK: Update Plots for Comparisons

	Y axis	Variable 1	Variable 2
	Plant Life	Production Tax Credit	Production Tax Credit
Units	yrs	$/kg-H2	$/kg-H2
Nominal	20	$3.00	$3.00
Upper	26	$3.00	$3.00
Lower	1	$0.00	$0.00

CLICK: Details for Profitability Analysis

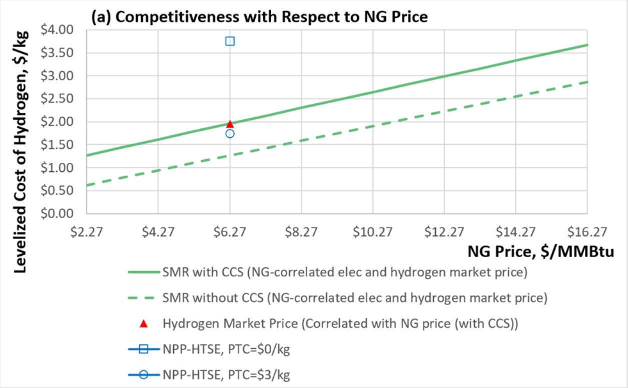


H2 Production vs. Business as Usual (BAU)

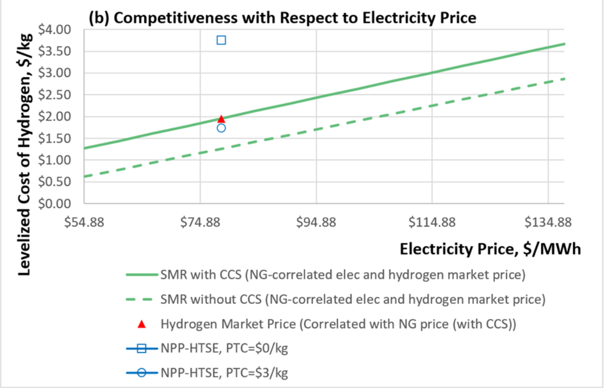
Step-6: Competitive Analysis

CLICK: Additional Information for the correlations

CLICK: Update plots



(a) Competitiveness with Respect to NG Price



(b) Competitiveness with Respect to Electricity Price