Technoeconomic Analysis (TEA) and Life Cycle Analysis (LCA) on the In-situ Hydrogen Production with Electro-magnetic Heating

Pingping Sun (PI), Vincenzo Cappello, Kwang Hoon Baek

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Energy Systems and Infrastructure Analysis (ESIA) Division
Argonne National Laboratory

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1. Introduction

This research aims to evaluate a new idea on the in-situ hydrogen production process which induces an in-situ methane pyrolysis in a gas reservoir. The scheme of the proposed process is illustrated in **Figure 1**. The heating source is an electro-magnetic (EM) assisted catalytic heating along with a horizontal well. The target reservoir is a shale gas reservoir in West Texas where inexpensive off-peak electricity from wind/solar energy can be a clean electricity source. The hydrogen after methane pyrolysis in the reservoir is produced through an only-hydrogen-permeable membrane which is set inside the horizontal well.

The scope of this research is the technoeconomic analysis (TEA) and life cycle analysis (LCA) for the in-situ hydrogen production by electro-magnetic heating in the gas reservoir. Argonne National Laboratory (ANL) developed the methane pyrolysis process at the reservoir conditions including methane conversion rate, energy consumption for EM heating, and energy consumptions for cooling and compression of hydrogen. The H2A Lite model[1] was applied to perform the TEA on the in-situ hydrogen production cost. The GHGs emission of in-situ hydrogen production was evaluated by the LCA with the GREET 2022 model[2].

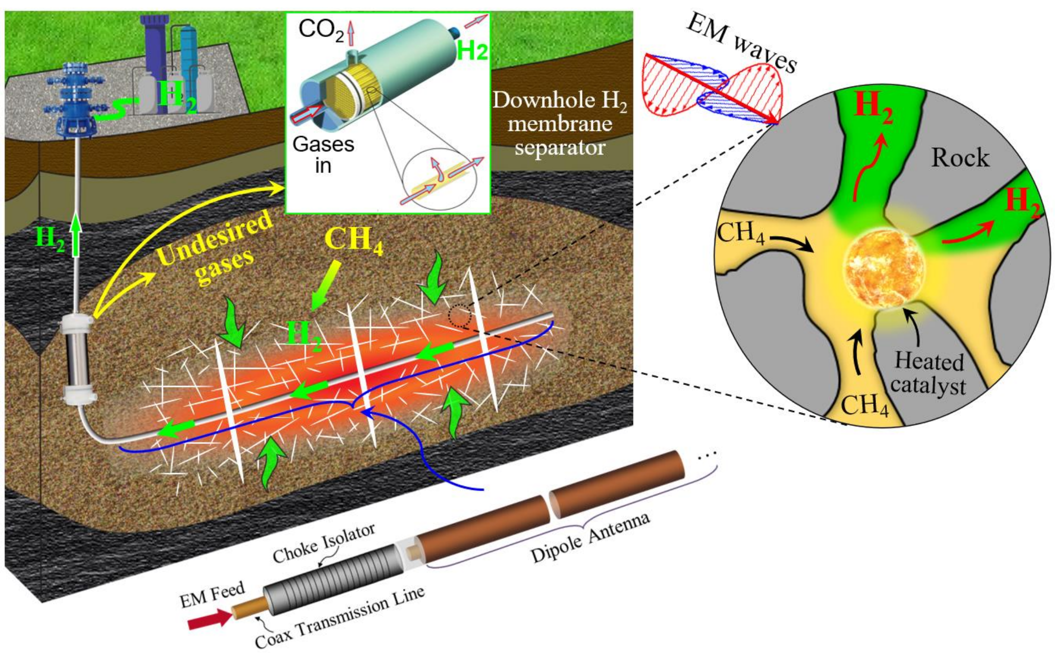

Figure 1. Schematic for in-situ hydrogen production from gas reservoirs

2. Process Description

A simplified process scheme is illustrated in **Figure 2**. The assumed reservoir conditions are 1,000°C and 150 bar. At this condition, the methane conversion rate is 50%. The conversion rate became lower than

[1] H2A-Lite: Hydrogen Analysis Lite Production Model, National Renewable Energy Laboratory (NREL), https://www.nrel.gov/hydrogen/h2a-lite.html

[2] GREET model, version 2022. Argonne National Laboratory, https://greet.es.anl.gov/

the lab-scale experimental results provided from the Hope Group at Texas Tech University (Dr. Qingwang Yuan) due to the high pressure used to model the reservoir. The 99.9% high purity hydrogen is produced to the surface through a palladium-based (Pd) membrane that only permits hydrogen with 90% recovery. The surface facilities include the cooling of hydrogen to 40°C and the compression of hydrogen to 20 bar. The electricity source can be either the Texas grid or renewables (wind/solar). ANL developed the ASPEN model based on this process scheme. The energy requirements for heating, cooling, and compression are summarized **Table 1**.

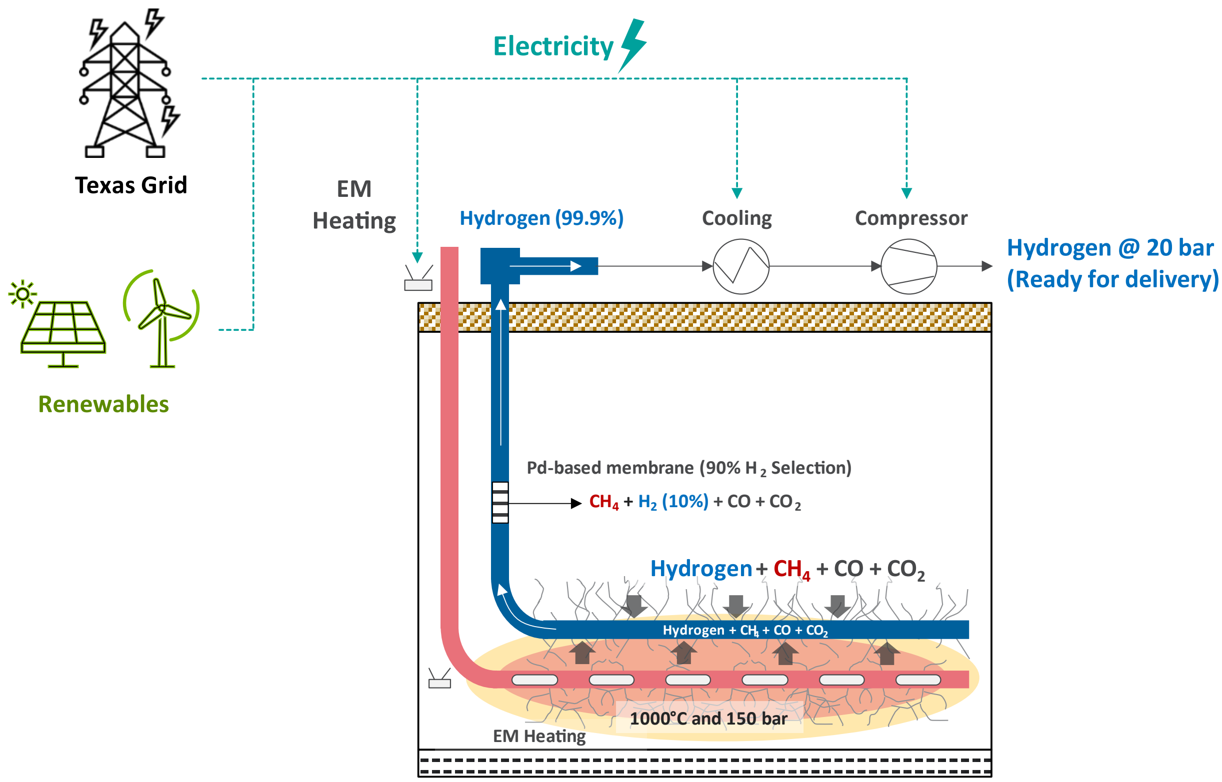

Figure 2. Process Scheme

Table 1. Energy Input Data from ASPEN

Process	Energy Input	Description
Heating	10.33 kWh/kg H_2	In-situ electro-magnetic heating (73% EM efficiency)
Cooling	0.016 kWh/kg H_2	Cooling of hydrogen before compression
Compression	1.53 kWh/kg H_2	Hydrogen compression for delivery

At certain temperature and pressure, the hydrogen production rate is proportional to the amount of natural gas in the reservoir. It is important to find a gas reservoir with a high natural gas expected production rate. Although natural gas production declines with time, the annual production rate could be controlled by fracking frequency, fracking pressure, or other operation conditions. Hence, a steady hydrogen production rate was assumed to avoid the excessive capital investment for the Pd membrane which can become the main cost driver when sized based on the max production rate.

Two shale gas fields were selected to compare low and high hydrogen production rates: Bone Spring Avalon (NM) and Haynesville (LA). The natural gas production data from two fields were obtained from data provided by collaborators and the EIA database[3], respectively. Based on the ASPEN model developed in this study, the calculated hydrogen production rates are 2,282 kg/day in Bone Spring Avalon and 35,124 kg/day in Haynesville (**Table 2**).

Table 2. Hydrogen Production Rates in Two Shale Gas Fields

Field	Location (State)	Expected Hydrogen Production Rate (for 10 years)
Bone Spring Avalon	New Mexico	2,282 kg/day
Haynesville	Louisiana	35,124 kg/day

3. Technoeconomic Analysis (TEA)

Approach and Economic Assumptions

The cost analysis was developed using the H2A-lite model[4]. The tool provides the levelized cost of hydrogen (i.e. the minimum selling price to have a net present value of zero) and the investor cash flow of the project.

Costs for the above-ground equipment were obtained from Aspen Plus Economic Analyzer, while the costs associated with the well (construction, completion, closing) were obtained from the FECM/NETL Unconventional Shale Well Economic Model. The assumptions used in the TEA are listed in **Table 3**.

To highlight the main cost drivers and their relationship with the production rate, four case studies were considered.

- Case #1: Bone Spring Avalon (NM), high membrane cost ($7,500/m^2)
- Case #2: Haynesville (LA), high-range membrane cost ($7,500/m^2)
- Case #3: Haynesville (LA), mid-range membrane cost ($3,500/m^2)
- Case #4: Haynesville (LA), low-range membrane cost ($2,000/m^2)

The levelized cost of hydrogen for each case is reported in the following section.

Table 3. Economic Assumptions for Technoeconomic Analysis

Item	Value
Construction time	12 months
Project time	10 years
Depreciation	7 years

[3] U.S. Energy Information Administration (EIA) Natural Gas Data. https://www.eia.gov/naturalgas/

[4] H2A-Lite: Hydrogen Analysis Lite Production Model, National Renewable Energy Laboratory (NREL), https://www.nrel.gov/hydrogen/h2a-lite.html

Item	Value
Well construction, completion, and closing costs	$5.5MM and $7MM (from shale well TEA tool[5])
Electro-magnetic (EM) System	$8MM
Membrane cost	$2,000/m^2, $3,750/m^2, and $7,500/m^2 [6]
Costs of other equipment	from Aspen Plus Economic Analyzer
Labor	2 Operators / 5 shifts
Electricity Price	$0.03/kWh

TEA Results

The results for Case #1 are shown in **Figure 3**. With the production data for the Bone Spring Avalon play, the levelized cost of hydrogen was about $5/kg, with the main contribution coming from the capital expenditures (62% of the production cost). At a low hydrogen production rate, the membrane area needed was small enough that its installed costs were below the costs for both the EM heating system and the well operations.

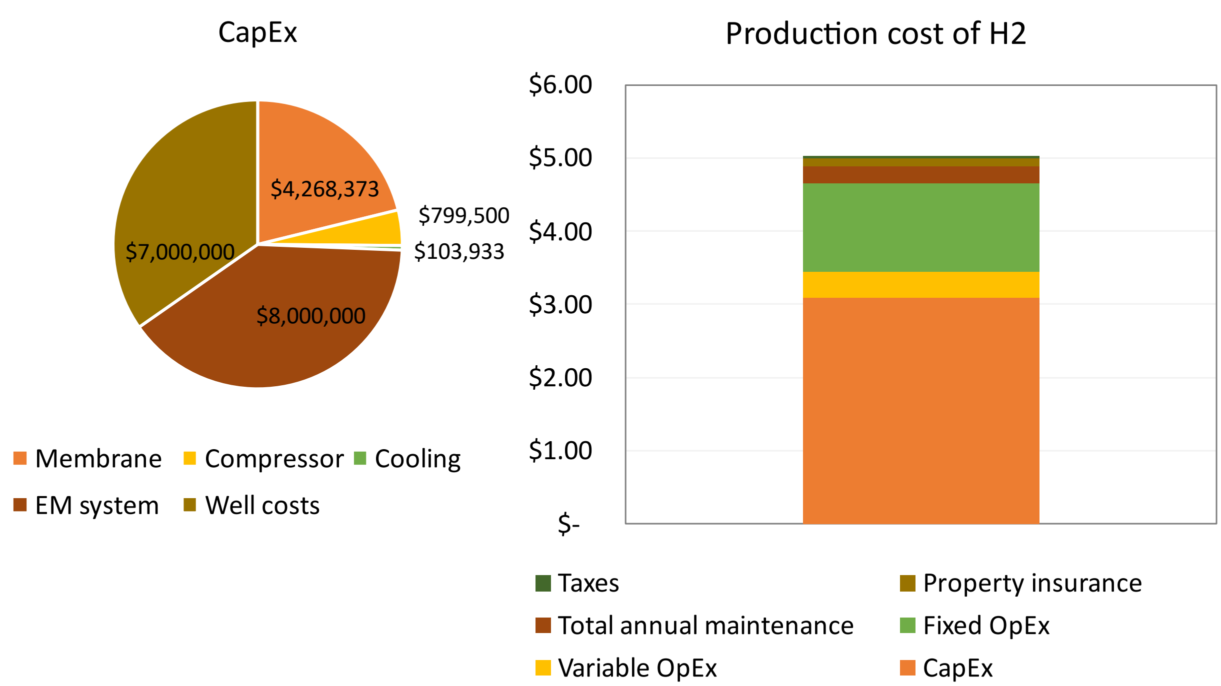

Figure 3. Breakdown of CapEx and levelized cost for Case #1.

In **Figure 4**, the impact of the IRA 45V tax credits is shown. For a project based on Case #1 that is eligible to the highest credit (i.e., $3/kg) and for the maximum duration of the incentive (i.e. ten years), the levelized cost of hydrogen would decrease by 81%, reaching a value of $0.96/kg.

[5] FECM/NETL Unconventional Shale Well Economic Model
[6] Salahshoor, Shadi, and Shaik Afzal. 2022. International Journal of Hydrogen Energy.

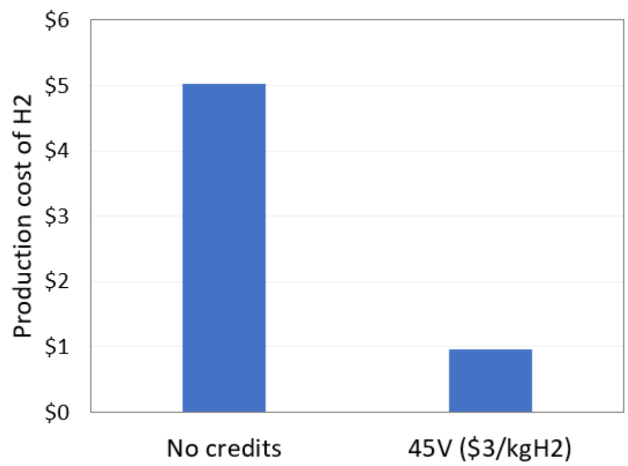

Figure 4. Hydrogen production cost for Case #1 with and without the IRA 45V tax credits.

A threefold increase in the CapEx was found when the hydrogen production rate increased to about 35,000 kg/day (Case #2). In this case, the membrane would require the highest capital investment, representing about 80% of the total CapEx (see **Figure 5**). However, given the higher hydrogen production rate, the levelized cost to produce a kg of hydrogen was $1.47. The fixed costs saw a significant reduction for the same reason, accounting for only 6% of the total production cost.

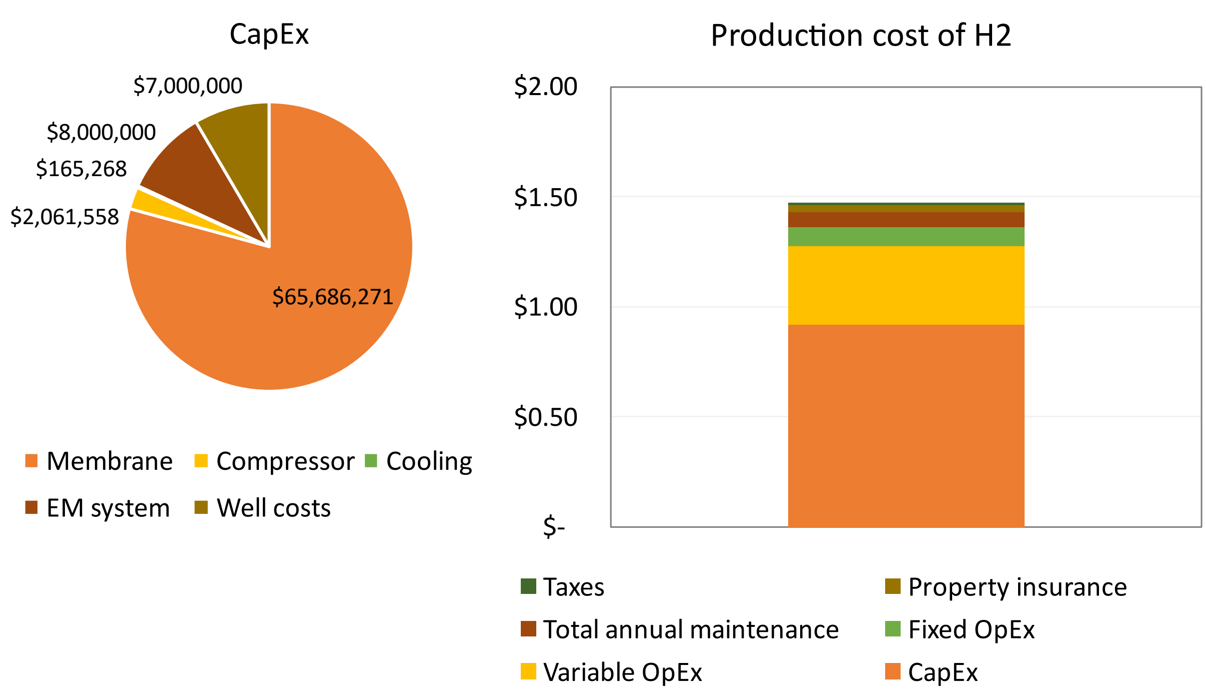

Figure 5. Breakdown of CapEx and levelized cost for Case #2.

In **Figure 6**, the impact of some operating and cost parameters is shown for Case #2.

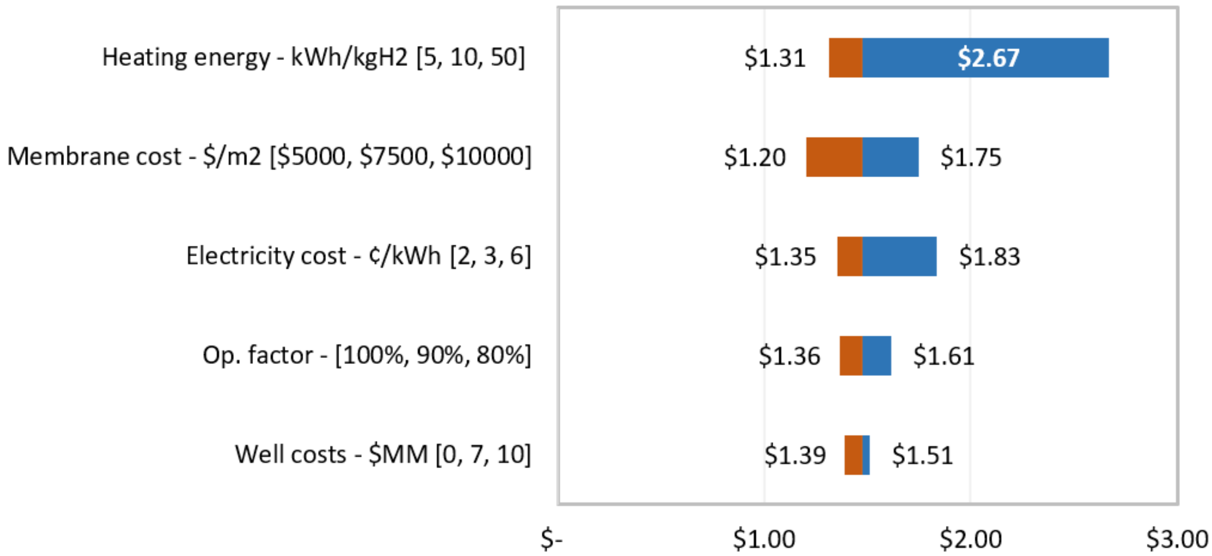

Figure 6. Sensitivity analysis for Case #2.

In **Figure 7**, the results for Case #3 are shown. By reducing the specific membrane cost to $3,500/m^2, the levelized cost of hydrogen was reduced by 27%, reaching $1.07/kg.

The lowest hydrogen production cost was found for Case #4 when considering $2,000/m^2 for the membrane cost and $5.5MM for the well-related costs (data provided by collaborators). The production cost of hydrogen was estimated at $0.86/kg (see **Figure 8**).

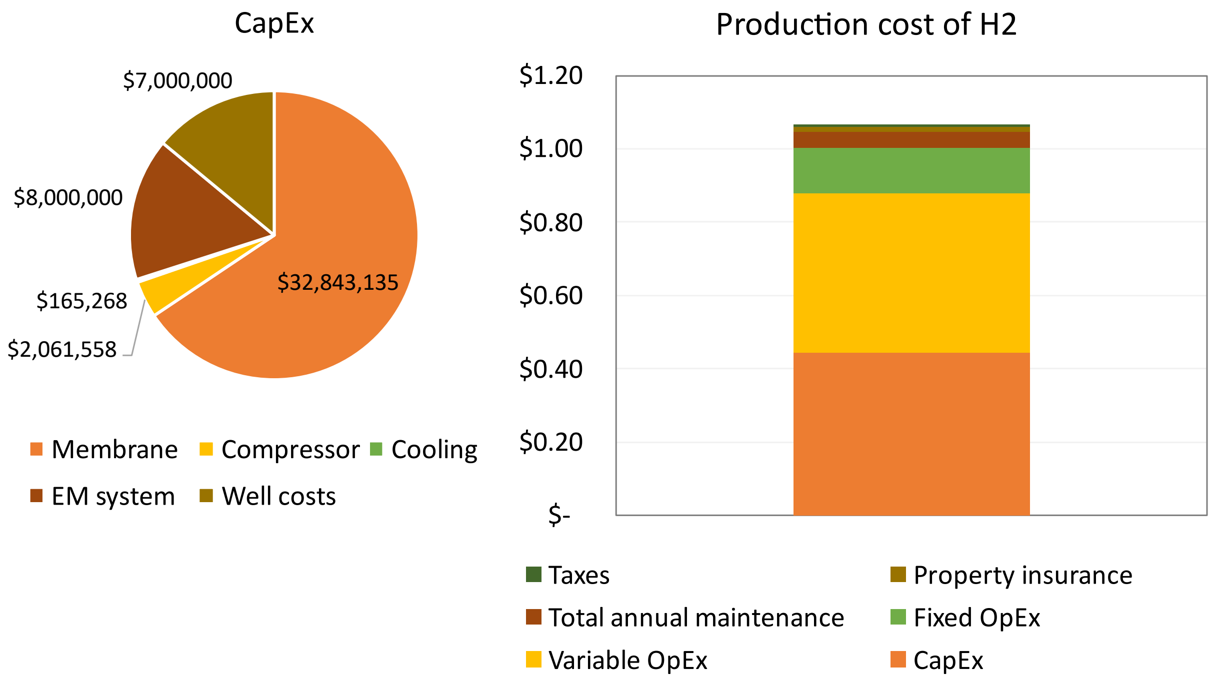

Figure 7. Breakdown of CapEx and levelized cost for Case #3.

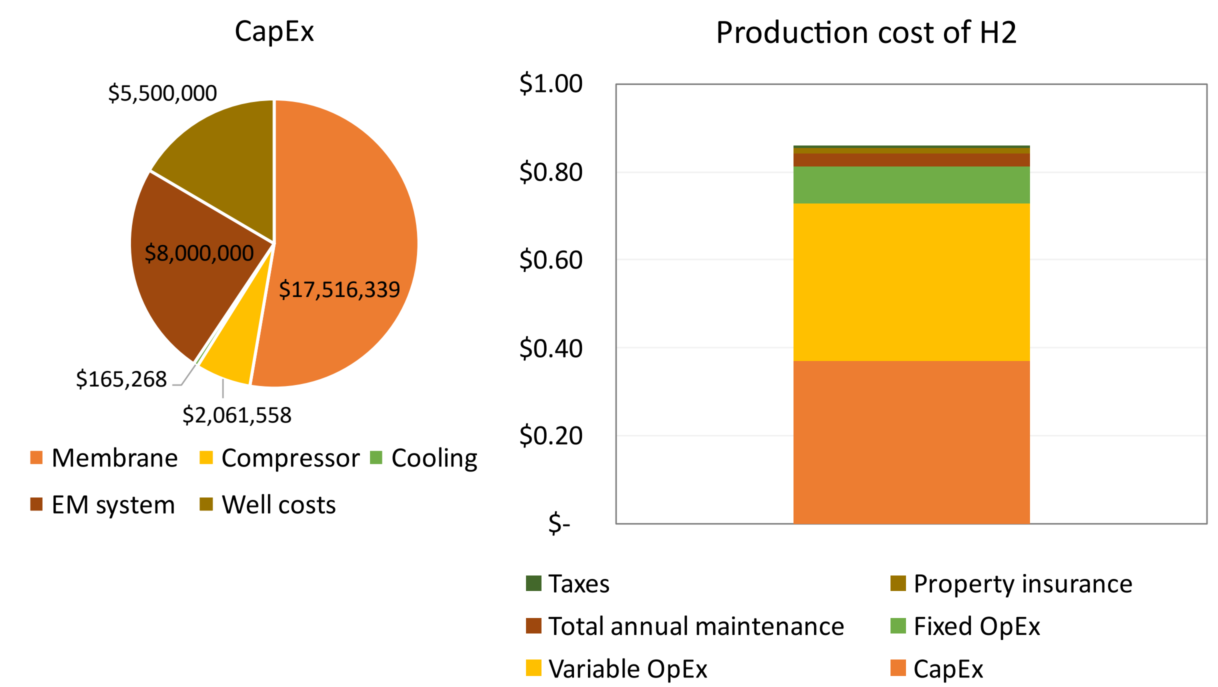

Figure 8. Breakdown of CapEx and levelized cost for Case #4.

4. Life Cycle Analysis (LCA)

GHGs Emission of in-situ Hydrogen Production by EM Heating

There is no direct GHGs emission in the process as the hydrogen production and separation occurs in-situ (assuming no leakage from underground). However, indirect emissions by electricity consumption should be counted in the life cycle analysis of this process. The major electricity consumptions are for the electro-magnetic heating, cooling, and compression (**Table 1**). The GHGs emission by grid electricity is calculated based on the GREET 2022[7] with two electricity sources: U.S grid mix and renewables. The Texas grid 2021 GHGs emission data was applied for the U.S grid mix case[8]. If the electricity source is renewables (i.e., wind/solar), there will be zero GHGs emission. Note that the embodied carbon emission of renewable electricity is not considered in this research.

The GHGs emission of the in-situ hydrogen production in this study is shown in **Figure 9**. If the process electricity is supplied by Texas grid mix, the GHGs emission is 4.6 kg/kg[9]. Compared to other hydrogen production, the in-situ hydrogen production with Texas grid mix emitted less GHGs than the conventional SMR[10] process (11.6 kg/kg), and similar GHGs to the conventional SMR process with CCS[11] (3.4 kg/kg). The in-situ hydrogen production using renewable electricity shows zero emission which is comparable to the hydrogen production by electrolysis with low carbon electricity sources like PEM (polymer electrolyte membrane) electrolysis with renewables and SOEC (solid oxide electrolyzer cell) with nuclear power plants.

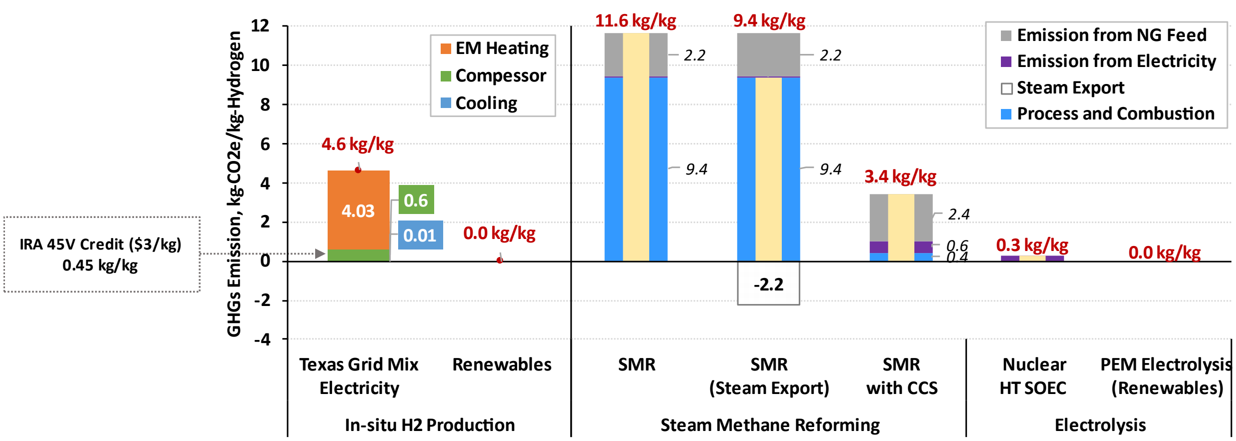

Figure 9. GHGs Emission Comparison among Different Hydrogen Production Process

GHGs Emission Reduction to be Qualified for the IRA 45V Credit

With the Inflation Reduction Act of 2022 (IRA), there will be a 10-year tax credit for the zero (or low) carbon intensity hydrogen (IRA 45V)[12]. The clean hydrogen credit can be eligible for the max. $3 per kg of hydrogen

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[7] GREET model, version 2022. Argonne National Laboratory, https://greet.es.anl.gov/

[8] EPA Emissions & Generation Resource Integrated Database (eGRID), https://www.epa.gov/egrid

[9] kg/kg = kg of GHGs emission per kg of hydrogen production

[10] SMR = Steam Methane Reforming

[11] CCS = Carbon Capture and Sequestration

[12] DOE - Financial Incentives for Hydrogen and Fuel Cell Projects, https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects

with the less than 0.45 kg/kg of the GHGs emission and the min. $0.6 per kg of hydrogen with the less than 4 kg/kg of the GHGs emission (**Table 4**). The GHGs emission of the in-situ hydrogen production (4.6 kg/kg) with the Texas grid mix would be above the IRA 45V criteria as shown in **Figure 9**. Therefore, to be qualified for the IRA 45V, either renewables should be applied as an electricity source, or the process electricity consumption should be reduced.

Table 4. Inflation Reduction Act 45V Hydrogen Tax Credit

Carbon Intensity (kg CO2e/kg H_2)	Max. Credit ($/kg H_2)
0 – 0.45	$ 3.00
0.45 – 1.5	$ 1.00
1.5 – 2.5	$ 1.75
2.5 – 4	$ 0.60

Renewable electricity is intermittent by nature. When renewables are not available, the Texas grid should be used for the in-situ hydrogen production. The effect of the renewable mix to the Texas grid on the GHGs emission is illustrated in **Figure 10**. It shows that the renewable electricity should be more than 90% to be qualified for the max IRA 45V credit ($3/kg H_2). When the 50% of renewable is mixed, $0.75/kg credit is qualified. When the renewable mix is less than 14%, there will be no credit.

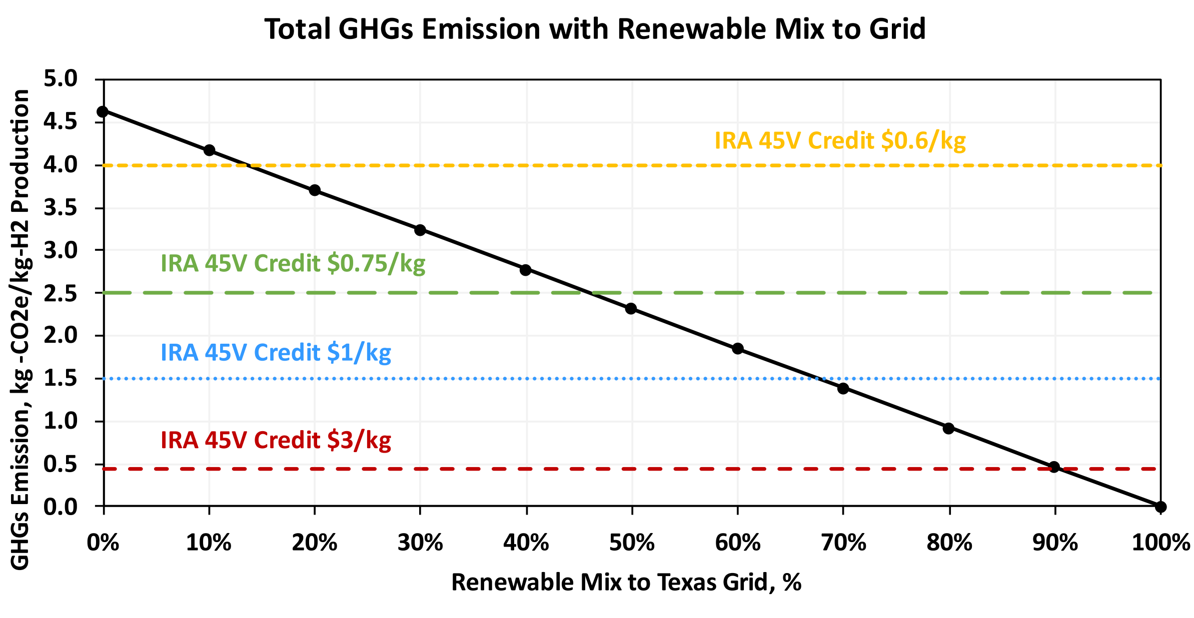

Figure 10. GHGs Emission by Renewable Mix to Texas Grid

Another way to reduce the GHGs emission is to improve the heating efficiency. **Figure 11** shows the different GHGs emission by different heating energy with the Texas grid. The current electro-magnetic heating energy is 10.3 kWh/kg. The in-situ hydrogen production with 100% Texas grid is not qualified for the IRA 45V credit. The heating efficiency should be improved to 8.7 kWh/kg to get $0.6/kg, 4.9 kWh/kg to get $0.75/kg, and 2.3 kWh/kg to get $1/kg. Because the GHGs emission by cooling and compression has already exceeded 0.45 kg/kg, the process cannot be qualified for the max. IRA 45V credit by improving heating efficiency only. Therefore, the in-situ hydrogen production system should be optimized with both renewable mix and heating efficiency.

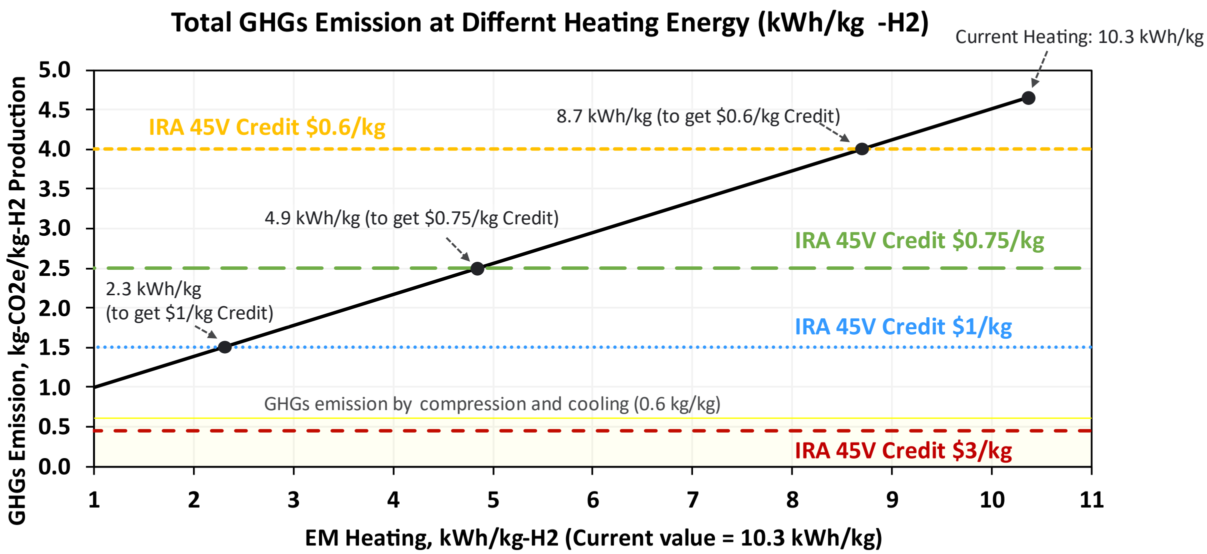

Figure 11. GHGs Emission by Electro-magnetic Heating Energy (100% Texas Grid)

5. Conclusions

The in-situ hydrogen production process with EM heating has potential to produce a low-carbon clean hydrogen. According to ANL's analysis, the production cost ranges between $1 to $5 per kg of hydrogen, and it could be as low as $0.86/kg. Then, the hydrogen production cost can be competitive with the conventional SMR (steam methane reforming) hydrogen process. Two key factors to reducing hydrogen production cost are 1) membrane cost (e.g., $2,000/m^2), and 2) the large gas reserves for high hydrogen production rate. Also, it is important to keep a steady hydrogen production rate to avoid the excess capital cost expense on the membrane as the membrane size should be matched with the maximum hydrogen production rate.

The LCA results show that the proposed process can be qualified for the IRA 45V clean hydrogen credit with certain conditions. Despite no emission by methane pyrolysis induced in the gas reservoirs, the GHGs emission from electricity consumption needs to be accounted for. The electro-magnetic heating is the major electricity demand (87%) for this process followed by the compression and cooling of produced hydrogen. If the entire process uses the U.S grid mix (Texas grid), the in-situ hydrogen production will not be qualified for the IRA credit. The potential electricity source for this process is off-peak electricity from wind/solar, but the renewables are intermittent by nature. When the Texas grid and renewables are mixed, renewables should be more than 90% to get the full IRA credit ($3/kg hydrogen). Also, the GHGs emission can be further reduced by improving heating efficiency.