

# Green Hydrogen Produced by Solar Thermal Separation Has Technical, Economic, and Environmental Aspirations

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**Abstract.** In this paper, the generation of green hydrogen utilizing the sun powered warm partition strategy is analyzed from a financial and natural point of view, and the arrangements of researchers and analysts to create this innovation and decrease its costs are considered, and insights are displayed for the generation of green hydrogen by this strategy. This paper analyzes the generation of green hydrogen utilizing sun oriented warm partition from a financial and natural point of view. It investigates the endeavors of researchers and analysts to create this innovation and decrease costs. The paper too presents insights on the generation of green hydrogen through this strategy.

## 1 Introduction

The move towards a maintainable and low-carbon vitality future has started significant intrigued within the progression of green hydrogen as a versatile and eco-friendly vitality carrier. Utilizing renewable vitality sources to deliver green hydrogen offers a promising arrangement for decreasing nursery gas outflows and decarbonizing different segments. The joining of renewable vitality sources, such as solar and wind control, within the generation of green hydrogen is basic for driving the change of the vitality division. This integration handle envelops innovative advance, deterrents, and openings that contribute to the natural and financial points of interest of green hydrogen. As a zero-emission fuel, green hydrogen holds potential for assorted applications over transportation, industry, and control era.

The objectives of this archive are to emphasize the importance of green hydrogen as a urgent arrangement in accomplishing a feasible vitality future, analyze the integration of renewable vitality sources in green hydrogen generation, evaluate the natural and financial benefits of green hydrogen, examine its applications over different divisions, and pinpoint approach suggestions for its far reaching appropriation. By tending to these destinations, this paper points to offer substantial proposals for overcoming boundaries to the appropriation of

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green hydrogen innovations and emphasize the significance of investigate and improvement in moving nonstop advancement in this division. See references: [5, 9].

## 2 Green hydrogen production methods

Interest in green hydrogen production has increased, with a focus on enhancing efficiency and reducing costs. The Solar Thermal Separation Method is a primary method that uses renewable solar energy and offers advantages such as zero net greenhouse gas emissions, but it lacks infrastructure and has higher production costs compared to gray hydrogen. Other methods include Electrolysis, which produces pure hydrogen from water using electricity, and Biomass Gasification, which utilizes renewable biomass feedstock. Traditional methods like Steam Methane Reforming and Coal Gasification have high yields but are associated with carbon emissions and environmental concerns. It is crucial to carefully consider the benefits and drawbacks of each method to make informed decisions about green hydrogen production and work towards achieving sustainability goals through technology development and cost reduction. See references: [2, 3, 5].

When comparing the methods of hydrogen production, we show the following There are four main methods of hydrogen production: steam methane reforming, coal gasification, biomass gasification, and water electrolysis.

Steam methane reforming is a well-established and cost-effective method that yields a high amount of hydrogen. However, it produces carbon emissions and relies on fossil fuels.

Coal gasification utilizes abundant coal resources and also yields a high amount of hydrogen. However, it has similar drawbacks to steam methane reforming, including carbon emissions, environmental concerns, and a complex gasification process.

Biomass gasification is an alternative method that uses renewable biomass feedstock, offering the potential for carbon-neutral hydrogen production. However, it has a lower hydrogen yield, faces challenges with feedstock availability, and requires optimization of the gasification process.

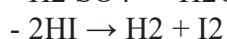
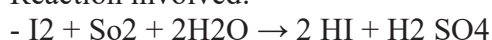
Water electrolysis directly produces pure hydrogen without generating carbon emissions. However, it requires a high energy input, is cost-intensive, and relies on electricity generation methods.

When considering which method to use, factors such as cost, resource availability, environmental impact, and technological maturity should be taken into account. (source: reference [2])

Below are examples of important data for TWSCs:

### 1. Cycle: Sulphur-Iodine

Reaction involved:



T max (°C): 850

Efficiency (LHV H<sub>2</sub> /heat duty): 52

Cost (€/kg H<sub>2</sub>): 5.5

### 2. Cycle: Westinghouse

Reaction involved:



T max (°C): 850

Efficiency (LHV H<sub>2</sub> /heat duty): 51

Cost (€/kg H<sub>2</sub>): 4.75

### 3. Cycle: Zinc Oxide

Reaction involved:

- $\text{ZnO} \rightarrow \text{Zn} + \text{O}_2$
  - $\text{ZnO} + \text{H}_2\text{O} \rightarrow \text{ZnO} + \text{H}_2$
- T max (°C):  $\approx 2000$   
Efficiency (LHV H<sub>2</sub> /heat duty): 20.8  
Cost (€/kg H<sub>2</sub>): 6.4

#### **4. Cycle: UT-3**

Reaction involved:

- $\text{CaBr}_2 + \text{H}_2\text{O} \rightarrow \text{CaO} + \text{HBr}$
- $\text{FeBr}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + \text{HBr} + \text{H}_2$
- $\text{Fe}_3\text{O}_4 + \text{HBr} \rightarrow 3\text{FeBr}_2 + 2\text{H}_2\text{O} + \text{Br}_2$
- $\text{CaO} + \text{Br}_2 \rightarrow \text{CaBr}_2 + \text{O}_2$

T max (°C): 760  
Efficiency (LHV H<sub>2</sub> /heat duty): 49.5  
Cost (€/kg H<sub>2</sub>): 4.0

#### **5. Cycle: Hybrid Copper chloride**

Reaction involved:

- $2\text{Cu}^{2+} + 2\text{HCl} \rightarrow 2\text{CuCl} + \text{H}_2$
- $4\text{CuCl} \rightarrow 2\text{Cu} + 2\text{CuCl}_2$
- $2\text{CuCl}_2 + \text{H}_2\text{O} \rightarrow \text{Cu}_2\text{OCl}_2 + 2\text{HCl}$
- $\text{Cu}_2\text{OCl}_2 \rightarrow 2\text{CuCl} + 0.5 \text{O}_2$

T max (°C): 550  
Efficiency (LHV H<sub>2</sub> /heat duty): 49  
Cost (€/kg H<sub>2</sub>): 4.7

#### **6. Cycle: Mixed ferrites**

Reaction involved:

- $2\text{MnFe}_2\text{O}_4 + 3\text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \rightarrow 6\text{Na}(\text{Mn}_{1/3}\text{Fe}_{2/3})\text{O}_2 + 3\text{CO}_2 + \text{H}_2$
- $6\text{Na}(\text{Mn}_{1/3}\text{Fe}_{2/3})\text{O}_2 + 3\text{CO}_2 \rightarrow 2\text{MnFe}_2\text{O}_4 + 3\text{Na}_2\text{CO}_3 + 0.5\text{O}_2$

T max (°C): 800  
Cost (€/kg H<sub>2</sub>): 7

#### **7. Cycle: Sulphur-Iodine modified**

Reaction involved:

- $\text{I}_2 + \text{SO}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{HI} + \text{H}_2\text{SO}_4$
- $\text{H}_2\text{SO}_4 + \text{Ni} \rightarrow \text{NiSO}_4 + \text{H}_2$
- $\text{NiSO}_4 \rightarrow \text{NiO} + \text{SO}_2 + 0.5 \text{O}_2$
- $\text{NiO} + 2\text{HI} \rightarrow \text{H}_2\text{O} + \text{NiI}_2$
- $\text{NiI}_2 \rightarrow \text{Ni} + \text{I}_2$

T max (°C): 900  
Efficiency (LHV H<sub>2</sub> /heat duty): 20  
(source: reference [14])

Here's a brief comparison between the different shades of hydrogen, without relying heavily on quotations:

Dim Hydrogen:

- Color: Dim
- Generation Handle: SMR or gasification utilizing methane or coal as the source
- CO<sub>2</sub> Emanations: 9-20 kg of CO<sub>2</sub> produced per kg of item
- Benefits: Moo generation taken a toll
- Drawbacks: Tall CO<sub>2</sub> outflows, not reasonable for a maintainable pathway

Blue Hydrogen:

- Color: Blue
- Generation Prepare: SMR or gasification with carbon capture (85-95% capture) utilizing methane or coal as the source

- CO2 Emanations: 1.5-4.5 kg of CO2 produced per kg of item
  - Benefits: Utilize of existing resources by means of carbon capture and capacity, lower nursery gas outflows compared to dark hydrogen
  - Drawbacks: Carbon capture can never be 100% proficient, subject to fossil fuel accessibility and cost changes
  - Turquoise Hydrogen:
    - Color: Turquoise
    - Generation Prepare: Pyrolysis utilizing methane as the source
    - CO2 Emanations: kg of CO2 produced per kg of item
    - Benefits: No CO2 created
    - Impediments: Still at the pilot organize, no mechanical applications, carbon within the methane turns into strong carbon dark fabric
  - Green Hydrogen:
    - Color: Green
    - Generation Prepare: Electrolysis utilizing renewable power as the source
    - CO2 Outflows: kg of CO2 created per kg of item
    - Benefits: Reliable with net zero CO2 outflows, ecologically neighborly
    - Impediments: Foundation, arrangements, and esteem acknowledgment as of now missing, generation fetched is 2-3 times higher than dark hydrogen
  - Evaluated % of regard for the environment:
    - Dim Hydrogen: 0%
    - Blue Hydrogen: 33%
    - Turquoise Hydrogen: 66%
    - Green Hydrogen: 100%
- (source: reference [3])

### 3 Economic analysis of green hydrogen production

Green hydrogen production through solar thermal separation is economically feasible, but initial investment and production costs are major factors influencing its viability. In Chile, the manufacturing cost of green hydrogen is USD 3.53/kg, indicating potential for viable production in the country. Off-grid green hydrogen plant capital investment was estimated at \$48,391,848. Lowering costs associated with renewable electricity generation is crucial for improving green hydrogen's economic competitiveness. Grid-connected facilities may have lower production costs, but cannot guarantee carbon-free hydrogen. Storing hydrogen in tanks is more cost-effective than storing renewable electrons in batteries. Green hydrogen currently has higher production costs compared to grey and blue hydrogen, but is expected to become more competitive as technology evolves and costs decrease. Water electrolysis has lower operational costs compared to solar thermal separation, but requires significantly lower electricity prices to be economically viable. Despite current cost disparities and high initial investment costs, there are promising prospects for improved economic viability as technology advances and costs decrease. See references: [1, 4, 6, 8, 18, 19].

**Table 1.** Production costs for different types of hydrogen (source: reference [6])

	Black Hydrogen	Gray Hydrogen	Blue Hydrogen	Green Hydrogen
Production price (\$/kg)	0.95 – 1.90 (2020) [1]	1.27 – 2.37 (2020) [1]	4 – 5 (2022) [2]	5.5 – 9.5 (2022) [3]

The total capital expenditures for hydrogen production with solar energy, based on the provided information, amount to USD 48,391,848. This total includes three main components:

1. Capex Electrolysis System (I): The total fixed-capital investment for the electrolysis system is USD 25,703,611 (A1 + A2). This includes two sub-categories:

a. Total Direct Plant Cost (A1): This accounts for USD 18,171,856 and covers various expenses such as purchased equipment, instrumentation and controls, piping, electrical systems, buildings, yard improvements, services facilities, and estimated land cost.

b. Total Indirect Plant Cost (A2): This amounts to USD 7,531,756 and covers expenses related to engineering and supervision, construction expenses, legal expenses, contractor's fee, and contingency.

2. Capex Renewable Energy System (II): This represents a separate capital expenditure for the renewable energy system and totals USD 19,283,243.

3. Capex Reverse Osmosis System (III): This represents another separate capital expenditure for the reverse osmosis system and amounts to USD 549,037.

It's important to note that a working capital of 10% of the total capital investment, which is USD 2,855,957, is also included in the calculations.

To summarize, the total capital expenditures for hydrogen production with solar energy are as follows:

- Capex Electrolysis System (I): USD 25,703,611
- Capex Renewable Energy System (II): USD 19,283,243
- Capex Reverse Osmosis System (III): USD 549,037

Therefore, the overall total capital expenditure amounts to USD 48,391,848.

(source: reference [1])

## **4 Environmental analysis of green hydrogen production**

Green hydrogen production, derived from sustainable energy sources, has the potential to significantly reduce greenhouse gas emissions compared to traditional methods. Research shows that using offshore wind or solar PV for hydrogen production can lead to substantial decreases in GHG footprint, especially in hard-to-decarbonize sectors like refineries and steel industries. Additionally, green hydrogen production using solar thermal separation can reduce overall water usage compared to traditional methods, addressing concerns about water scarcity. The decrease in carbon footprint is another crucial benefit of green hydrogen production, with potential to reduce CO<sub>2</sub> emissions in the hydrogen sector by up to 75% when powered by renewable sources. Overall, an environmental assessment illustrates the significant potential of green hydrogen for reducing emissions, minimizing water usage, and lowering the carbon footprint, highlighting its promise as a clean and sustainable energy source. See references: [3, 6, 12].

## **5 Preparations for technology development and cost reduction**

Solar thermal separation technology has advanced in green hydrogen production, attracting increased investments and government funding. The process requires high solar radiation, making it suitable for regions with abundant renewable energy. Reducing production costs is a primary challenge, but efforts are being made to develop new materials for more efficient and cost-effective hydrogen production. Concentrating solar power infrastructure and solar heat show promise for large-scale green hydrogen production, with significant projects receiving funding. Green hydrogen has potential for decarbonization in various sectors, but technological constraints, infrastructure development, costs, regulations, and public acceptance need addressing. Research focusing on efficiency and economic viability offers a positive outlook for the future of green hydrogen production using solar thermal separation technology. See references: [7, 8, 10].

## **6 Statistics on green hydrogen production by solar thermal separation method**

A recent analysis on the potential for green hydrogen production in Canada through the use of solar energy revealed that the country has a total capacity for generating 205.69 Mt, 201.12

Mt, and 211.17 Mt of green hydrogen using various types of electrolyzes powered by both onshore and offshore solar energy sources. The study examined the solar intensity of each of Canada's 13 provinces and found that the production potentials varied across the provinces, with Prince Edward Island having the lowest potential at 0.34 Mt and Quebec having the highest potential at 39.54 Mt.

Furthermore, it was noted that electrolyzes producing green hydrogen could lead to significant reductions in greenhouse gas emissions, with up to a 97% reduction compared to grey hydrogen when powered by offshore wind. Additionally, utilizing solar PV for hydrogen production could result in an 85% reduction compared to grey hydrogen.

These findings underscore the substantial potential for green hydrogen production using solar thermal separation methods, particularly in countries with abundant solar energy resources like Canada. See references: [4, 12].



Fig. 1. Hydrogen cost for the analyzed cities. (source: reference [15])

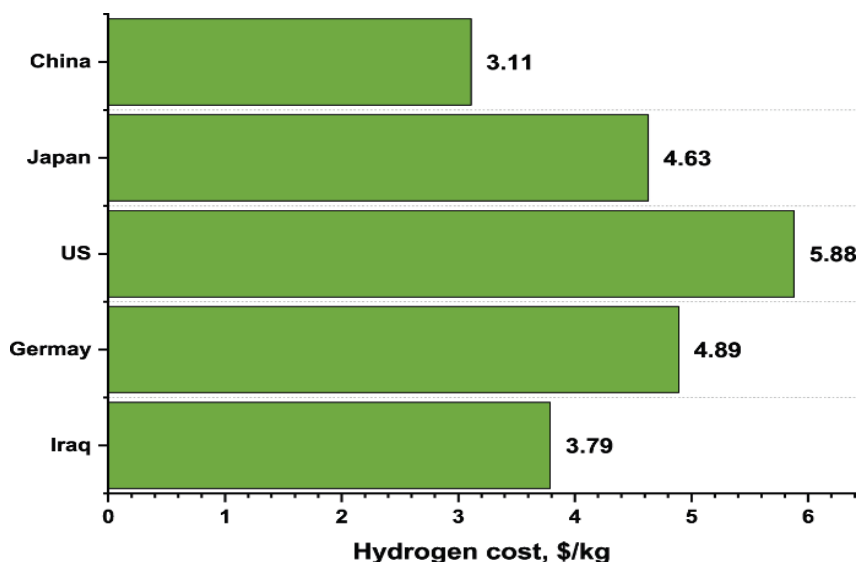


Fig. 2. Obtained hydrogen cost compared with other countries. (source: reference [15])

The aesthetic operating expenses for the basic condition of the wind energy can be summarized as follows:

1. *Fabricating Taken a toll (C1 + C2 + C3): \$3,531,944*
  - C1: Coordinate Generation Costs - \$1,439,878
  - Crude Materials: Not pertinent
  - Working labor (calculated): \$237,250
  - Coordinate supervisory and clerical labor (17.5% of 2): \$41,519
  - Utilities: Not pertinent

- Upkeep and repairs (6% of fixed-capital speculation): \$978,714
- Working supplies (15% of 5): \$146,807
- Research facility charges (15% of 2): \$35,588
- C2: Roundabout Generation Costs - \$1,337,576
- Devaluation (straight line devaluation): Not pertinent
- Neighborhood charges (2.5% of fixed-capital speculation): \$407,798
- Protections (0.7% of fixed-capital speculation): \$114,183
- C3: Plant-Overhead Costs (60% of 2 + 3 + 5): \$754,490
- 2. Common Costs (11 + 12 + 13): \$897,302**
- Authoritative costs (15% of 2 + 3 + 5): \$188,622
- Dispersion and offering costs (11% of III): \$487,217
- Investigate and improvement costs (5% of III): \$221,462
- 3. OPEX Electrolysis Framework (C + D): \$4,429,246**
- 4. OPEX Renewable Vitality Framework: \$355,743**
- 5. OPEX Switch Osmosis Framework: \$10,453**
- Add up to OPEX (I + II + III): \$4,795,442
- (source: reference [1])

Here is a summary of the different methods of producing hydrogen with various energy sources, their technological readiness levels (TRL), energy efficiency percentages, and references:

**1. Water Electrolysis (alkaline electrolysis):**

- Feedstock: Water
- Energy Efficiency: 61-82%
- TRL: 9-10
- Reference: Parra et al.

**2. Electrophotolysis (photo-electrochemical):**

- Feedstock: Water
- Energy Efficiency: 0.5-12%
- TRL: 1-2
- Reference: El-Emam and Özcan

**3. Photolysis (photosynthesis):**

- Feedstock: Water
- Energy Efficiency: < 5%
- TRL: 1-3
- Reference: Alanne and Cao

**4. Thermolysis (water thermolysis):**

- Feedstock: Water
- Energy Efficiency: 20-55%
- TRL: 1-3
- Reference: El-Shafie et al.

**5. Chemical (redox reaction):**

- Feedstock: Water
- Energy Efficiency: 3-5 wt%
- TRL: 4-6
- Reference: Alanne and Cao

**6. Biolysis (aqueous phase reforming):**

- Feedstock: Water + Biomass
- Energy Efficiency: 35-55%
- TRL: 5-7
- Reference: El-Shafie et al.

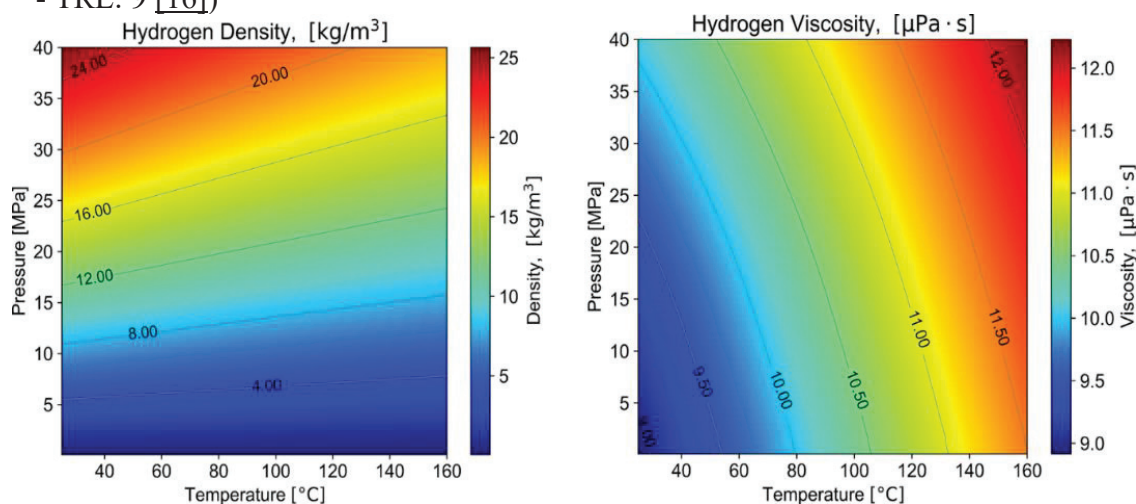
**7. Proton exchange membrane:**

- Feedstock: Brine
- Energy Efficiency: 67-84%
- TRL: 7-9
- Reference: Dawood et al.
- 8. Bioelectrolysis (microbial electrolysis):**
- Feedstock: Biomass
- Energy Efficiency: 70-80%
- TRL: 1-3
- Reference: El-Shafie et al.
- 9. Biothermolysis (co-fermentation hydrolysis):**
- Feedstock: Biomass
- Energy Efficiency: 35-45%
- TRL: 1-3
- Reference: Cheng et al.
- 10. Thermolysis (pyrolysis):**
- Feedstock: Biomass
- Energy Efficiency: 35-50%
- TRL: 8-10
- Reference: Dawood et al.
- 11. Thermolysis (gasification):**
- Feedstock: Biomass
- Energy Efficiency: 35-50%
- TRL: 10
- Reference: El-Emam and Özcan
- 12. Thermolysis (partial oxidation):**
- Feedstock: Biomass
- Energy Efficiency: 60-75%
- TRL: 7-9
- Reference: El-Shafie et al.
- 13. Biophotolysis (photofermentation):**
- Feedstock: Biomass
- Energy Efficiency: < 1%
- TRL: 1-3
- Reference: Dawood et al.
- 14. Thermolysis (gasification) of Coal:**
- Feedstock: Coal
- Energy Efficiency: 74-85%
- TRL: 10
- Reference: Mah et al.
- 15. Biolysis (dark fermentation) of Microorganisms:**
- Feedstock: Microorganism
- Energy Efficiency: 60-80%
- TRL: 3-5
- Reference: Mah et al.
- 16. Biophotolysis (photofermentation) of Microalgae:**
- Feedstock: Microalgae
- Energy Efficiency: < 1%
- TRL: 1-3
- Reference: El-Shafie et al.
- 17. Partial oxidation process of Hydrocarbons (fossil fuels):**
- Feedstock: Hydrocarbons

- Energy Efficiency: 60-75%
- TRL: 9
- Reference: Pinsky et al.

**18. Steam methane reforming of Natural Gas:**

- Feedstock: Natural gas
- Energy Efficiency: 74-85%
- TRL: 9 [16])



**Fig. 3.** Hydrogen production, storage, utilisation and environmental impacts [16]

The provided information discusses three different cases for storing hydrogen: (1) liquid storage, (2) cryogenic compressed gas storage, and (3) compressed gas storage. Each case is characterized by different pressure, temperature, and density conditions.

In Case I, which is liquid storage, the hydrogen is stored at a pressure of 0.1 MPa and at temperatures below -253°C. The density of the hydrogen in this case ranges from 60 to 70 kg/m<sup>3</sup>.

In Case II, which is cryogenic compressed gas storage, the hydrogen is stored at pressures ranging from 25 to 35 MPa and at temperatures below -253°C. The density of the hydrogen in this case is greater than 70 kg/m<sup>3</sup>.

In Case III, which is compressed gas storage, the hydrogen is stored at pressures ranging from 5 to 30 MPa and at temperatures ranging from 25 to 130°C. The density of the hydrogen in this case ranges from 10 to 40 kg/m<sup>3</sup>.

These three storage methods have different characteristics and are suitable for different applications. Liquid storage (Case I) allows for higher density but requires very low temperatures. Cryogenic compressed gas storage (Case II) combines high pressure and low temperatures to achieve higher density than compressed gas storage (Case III). Compressed gas storage (Case III) is less dense but can be stored at higher temperatures.

It is important to consider these storage methods in the context of hydrogen production, storage, use, and environmental impacts, as they have different implications for efficiency, safety, and sustainability. [16])

Table 2. The chemical exergy of pure compounds. (source: reference [17])

Compounds	Standard Mole Chemical Exergy (kJ/mol)
O <sub>2</sub>	3.87
H <sub>2</sub> O	9.50
CO <sub>2</sub>	19.87
H <sub>2</sub>	236.10

Compounds	Standard Mole Chemical Exergy (kJ/mol)
CO	275.10
C (s)	410.00
CH <sub>4</sub>	831.65

## 7 Conclusion

The prospect of integrating green hydrogen production using solar thermal separation holds great potential for transitioning to a sustainable and low-carbon energy system. Green hydrogen presents itself as a versatile and environmentally friendly energy carrier that can be generated through the use of renewable electricity, like solar power. By harnessing renewable energy sources, green hydrogen has the capacity to significantly diminish greenhouse gas emissions, air pollution, and reliance on finite fossil fuel resources. Ongoing research and development endeavors are concentrated on enhancing the effectiveness and cost-efficiency of green hydrogen production, storage, and utilization technologies by means of advancements in electrolysis technology, catalysts, and infrastructure development. It is imperative for stakeholders to collaborate in order to successfully integrate green hydrogen into the energy landscape. Establishing an all-encompassing hydrogen infrastructure involves constructing storage facilities, transport networks, and refuelling stations for transportation applications. Continuing investments in innovation, materials science, and process optimization have the potential to drive technological breakthroughs that will make green hydrogen more economically feasible and expedite its adoption across various industries. As nations such as Zambia explore the potential of green hydrogen production through solar thermal separation, they must tackle challenges such as production costs, storage, transportation, policy frameworks, environmental impact assessment, and workforce transition in order to fully realize the advantages of this sustainable energy solution. See references: [5, 11, 13].

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