Creating solutions for a NET ZERO world

Catalytic Non-Thermal Plasma Process for Hydrogen Production

Hydrogen Shot Summit
Thermal Conversion with Carbon Capture and Storage Panel

Plasma Technologies
August 31, 2021
Current Team and Technology Focus

RESEARCH & DEVELOPMENT TEAM

- Raghbir Gupta, President & Co-Founder
- S. James Zhou, Senior Director
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BUSINESS TEAM

- Shantanu Agarwal, President / Co-Founder
- Rich McGivney, Chief Financial Officer
- Sudarshan Gupta, Commercial Lead
- Brian Alexander, Director, Contracts & Legal Affairs
- Brittany Wood, Senior Administrator

Green / Blue Hydrogen Production

Natural Gas to H₂

Hydrogen production from natural gas with <3 kg CO₂ / kg H₂

Low Temperature Plasma Reforming with pure CO₂ production

Methane Pyrolysis
Hydrogen Production - Reforming of Natural Gas

Steam Methane Reforming

- Natural Gas
- Steam
- Supplemental Natural Gas
- Air

- Pre-Reformer
- Reformer
- WGS
- CO₂ Sep
- PSA

- CO₂ Sep
- CO₂ Compressor
- Stack
- CO₂ Product

- Stack Gas
- Fuel Gas

Green / Blue Hydrogen Production
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- Green / Blue Hydrogen Production
Low Temperature Plasma Reforming

- Simplified process for distributed hydrogen production
- Low temperature operation (<500°C)
- Integration of renewable electricity
Low Temperature Plasma Reforming

Jet Propulsion Laboratory (JPL) pioneered the development of a scaled-up dielectric barrier discharge (DBD) reactor to produce hydrogen from steam methane reforming (SMR)

- Scaled-up DBD reactor: 0.9 kg H₂/day.
- Conversion efficiency of the DBD reactor: 70–80% at 550°C and 500 W.
- Demonstrated continuous run of 8 hours
- Typical product gas: 69% H₂, 6% CO₂, 15% CO, 10% CH₄

Susteon formed a partnership with SoCalGas and JPL to further develop and commercialize this technology.
Low Temperature Plasma Reforming of Natural Gas

Technology

- Cold, non-thermal plasma driven-steam methane reformer reactor
  \[ \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2 \]
- Plasma selectively heats the catalyst → significantly lower bulk temperature
- Eliminates fossil fuel combustion to drive the endothermic SMR f reaction
- Modular integrated skid process unit to produce high purity H\(_2\)
Low Temperature Plasma Reforming of Natural Gas

Green / Blue Hydrogen Production

- **H₂ (74.3%)**
- **CH₄ (6.1%)**
- **CO₂ (14.5%)**
- **CO (5.1%)**

Diagram showing the process of plasma reforming with conversion rates and product concentrations.
Comparison of Hydrogen Production Routes

### Cost Distribution among various sections\(^1\) ($/kg \text{H}_2$

<table>
<thead>
<tr>
<th>Category</th>
<th>Electric SMR</th>
<th>PEM Electrolysis</th>
<th>Plasma Reformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital and Operating Cost</td>
<td>3.48</td>
<td>1.50(^*)</td>
<td>1.10</td>
</tr>
<tr>
<td>Feedstocks**</td>
<td>0.52</td>
<td>0</td>
<td>0.26</td>
</tr>
<tr>
<td>Electricity***</td>
<td>0.42</td>
<td>3.80</td>
<td>1.08</td>
</tr>
<tr>
<td>Unit Cost of Hydrogen</td>
<td>$4.42/kg</td>
<td>$5.30/kg</td>
<td>$2.44/kg</td>
</tr>
</tbody>
</table>

\(^1\)Estimations done using the H2A model
\(^*\)Electrolysis capital and other costs = $1500/kW
\(^\circ\)Feedstock is natural gas @ $3/MMBTU; water for electrolysis
\(^\circ\)Electricity price is $0.06/kWh

All the three technologies include CO\(_2\) capture and H\(_2\) product compression to 350 bar.
Comparison – Pathway to $1/kg

Green / Blue Hydrogen Production

Cost Distribution among various sections ($/kg H₂)

<table>
<thead>
<tr>
<th>Category</th>
<th>Current</th>
<th>Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital and Operating Cost</td>
<td>1.10</td>
<td>0.50</td>
</tr>
<tr>
<td>Feedstocks</td>
<td>0.26*</td>
<td>0.13</td>
</tr>
<tr>
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All the three technologies include CO₂ capture and H₂ product compression to 350 bar.

*Feedstock is natural gas @ $3/MMBTU; water for electrolysis
**Electricity price is $0.06/kWh

45% of current cost
Natural gas @ $1.5/MMBTU
Electricity @ $0.02/kWh
Conclusions

• **Plasma Reforming of natural gas** is an attractive route for distributed hydrogen production.

• Pioneered by JPL and SoCalGas, **Susteon developed this technology at bench-scale**.

• Results show that the plasma reformer manifests into significant process intensification to achieve **high natural gas conversions and H₂-rich product at <500°C and 1 atm.**

• This technology can also **produce a pure CO₂ stream**.

• Has the **potential to produce hydrogen at $1/kg** with further R&D.
Thermochemical Conversions:¹

Steam Reforming

\[ CH_4 + H_2O \rightarrow CO + 3H_2 \quad \Delta H = +206 \text{ kJ/mole} \]

Dry Reforming

\[ CH_4 + CO_2 \rightarrow 2CO + 2H_2 \quad \Delta H = +247 \text{ kJ/mole} \]

Partial Oxidation

\[ CH_4 + \frac{1}{2} O_2 \rightarrow CO + 2H_2 \quad \Delta H = -36 \text{ kJ/mole} \]

• DR/PO can be combined (Autothermal Reforming)
• require high temperature for good conversion
• catalysts allow operation at < 1200°C ensuring good yields
• water-gas shift (catalysts) is used to increase H\textsubscript{2} product in conjunction with CO\textsubscript{2} sequestration
• Costs\textsuperscript{2} range from $1.50 \rightarrow $2.50/kgH\textsubscript{2}
• Catalysts contribute >50% of the costs\textsuperscript{3}

Thermochemical Plasma Conversion

Enables access to higher temperatures circumventing catalysts

- plasma SMR too costly (even at wholesale pricing of electricity)
- combined with partial oxidation (Steam ATR)

\[ \text{CH}_4 + \frac{1}{2} \text{H}_2\text{O} + \frac{1}{4} \text{O}_2 \rightarrow \text{CO} + \frac{5}{2} \text{H}_2 \quad \Delta H = +85 \text{ kJ/mole} \]

- heat recovery necessary to hit $1/\text{kgH}_2$ boundary
- electricity pricing of $0.03/\text{kWhr} \rightarrow$ well in range
DOE-H$_2$ Earth-Shot Summit

Thermochemical Plasma Conversion

Precommercial/Commercial

- Electrodeless microwave thermal plasma
- Linearly scalable ~5 kW units/few processing steps
- Requires air separation
- Product separation
- WGS for higher H$_2$ yields and CC
- Specialized sector provides market entry at slightly above $1/kgH_2$

Technical Improvements

- Reduce waste heat (regeneratively heat reactants)
- Exceptional plasma arc stability
- Efficient reactant/plasma mixing to prevent blow-by (improve yields/conversion efficiency)

Expand to Larger Market Sectors (Biggest Barriers)

- Scaling plasma source to larger unit power units for MW-level processing
  - Reduce overall CAPEX/OPEX
  - Tens of 100 kW units (>1 tonneH$_2$/unit/day)
- Challenges include
  - Managing “hotter”, less stable and higher power plasmas (thermal plasmas constrict)
  - Reactor prone to increased radiation loss
  - Greater need for mixing and new strategies for heat recovery

Industry Sector

- Targeting landfill gas/bio-digestion gases
- Plasma ATR with CO$_2$ instead of steam
- Electrodeless microwave thermal plasma

10 x 5.5 x 9 (in)
### DOE-H₂ Earth-Shot Summit

#### Thermal Plasma Advantages

**Advantages of plasma-reforming technology?**
- **Less energy** requirement compared to electrolysis and SMR
- **Lower OPEX** leading to lower cost hydrogen production.
- Inherently modular design for easy **scalability**
- **Product steam/heat** that can be used for other processes

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#### R&D Requirements

**R&D required to scale technology up to industrial scale?**
- Impurity management (up and downstream)
- **Product gas thermal management** for optimal use of steam and heat generated for downstream syngas to hydrogen conversion
- **plasma stability** at 10x power
- Develop tools for simulating complex EM-plasma flow coupling

*These are needed now for achieving $1/kgH₂ at scale*

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#### Funding to Accelerate Progress

**Specific areas where government funding could accelerate progress for your approach?**
- Financing/Loan guarantees not dependent on hydrogen offtake agreements
- H₂ infrastructure specific funding, such as CAPEX grants
- Electricity subsidies for ALL hydrogen production technologies (not just for electrolysis)

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#### For Deployment at Scale

**Other immediate needs for deployment at scale:**
- Testing and development facilities capable of handling reactant and product volume for high power units
- Relatively **low-cost downstream equipment** for modular low-volume units