Catalytic Non-Thermal Plasma Process for Hydrogen Production

Hydrogen Shot Summit

Thermal Conversion with Carbon Capture and Storage Panel

Plasma Technologies

August 31, 2021

Creating solutions for a NET ZERO world

Raghubir Gupta, President / Co-Founder

Susteon

Current Team and Technology Focus

Susteon

RESEARCH & DEVELOPMENT TEAM

Raghubir Gupta
President & Co-Founder

S. James Zhou
Senior Director

Cory Sanderson
Process Technologist

Vasudev Haribal
Research Engineer

Arnold Toppo
Research Engineer

Tyson Lanigan-Atkins
Materials Scientist

Jian Zheng
Sr. Research Engineer

Andrew Tong
Sr. Research Engineer

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 H_2

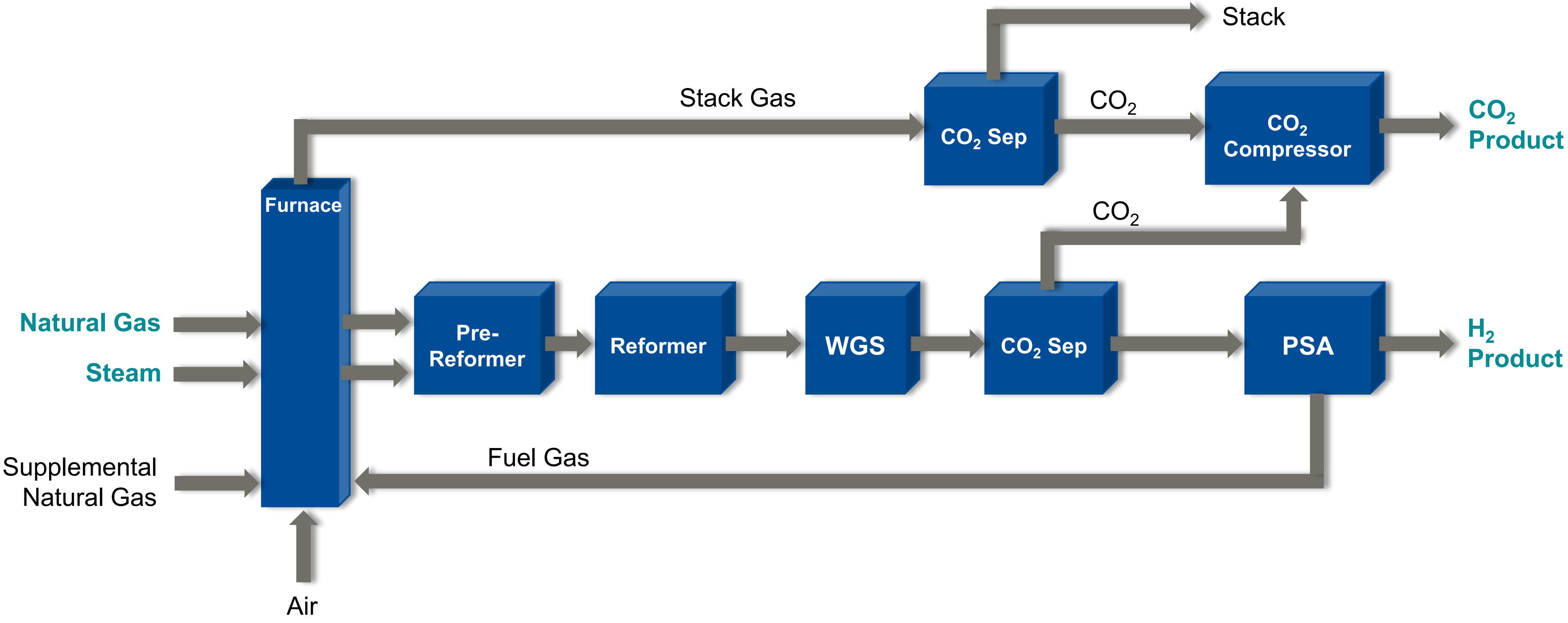
Hydrogen production from natural gas with <3 kg CO_2 / kg H_2

Low Temperature **Plasma Reforming** with pure CO_2 production

Methane Pyrolysis

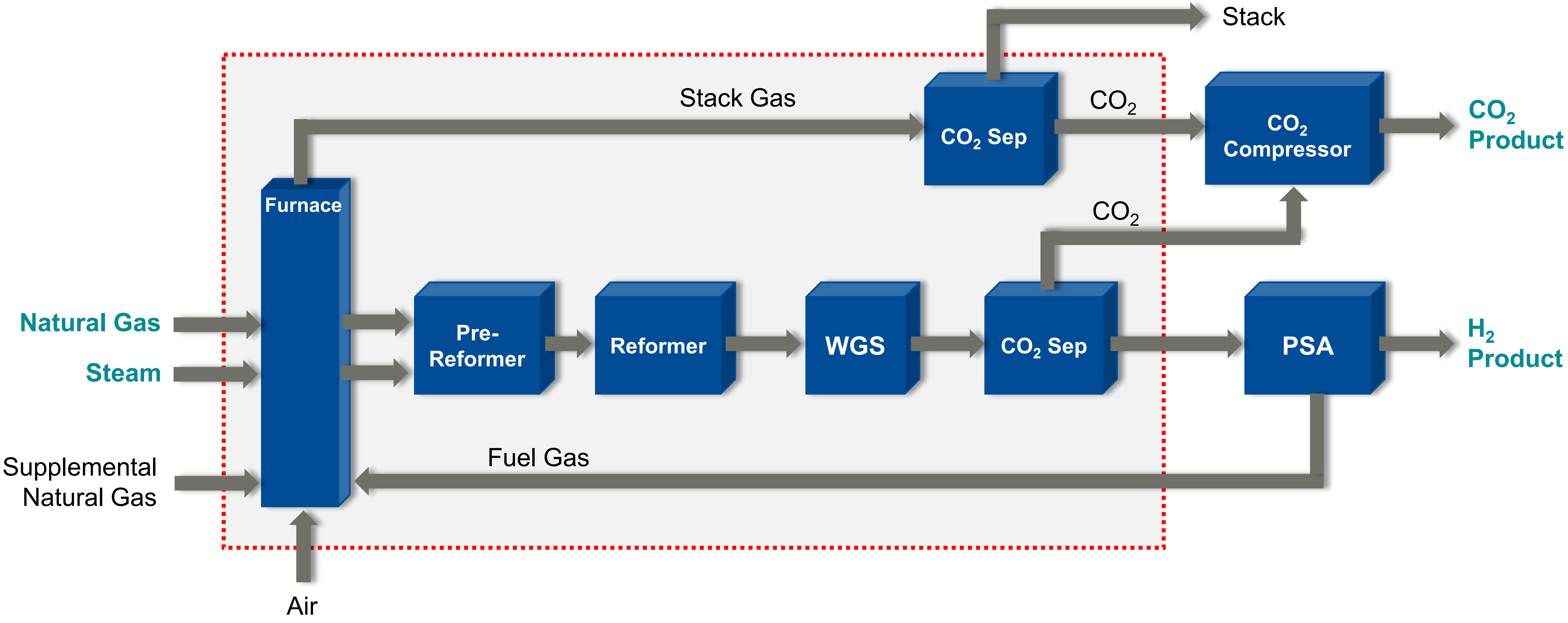
Hydrogen Production - Reforming of Natural Gas

Steam Methane Reforming



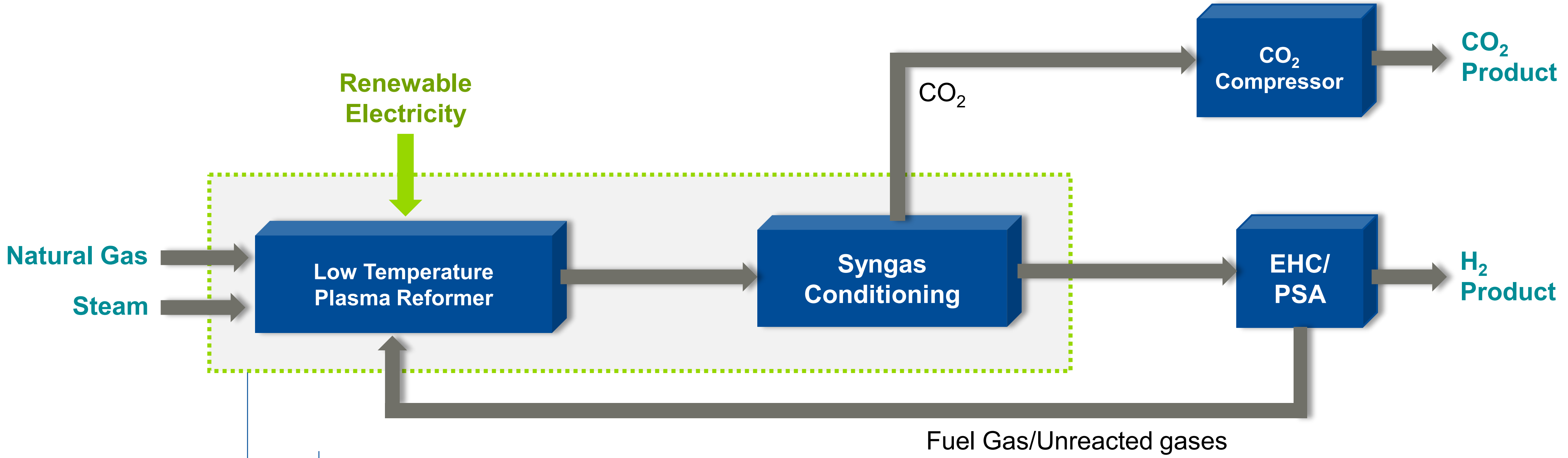
Hydrogen Production - Reforming of Natural Gas

Steam Methane Reforming



Hydrogen Production - Reforming of Natural Gas

Low Temperature Plasma Reforming



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

Low Temperature Plasma Reforming

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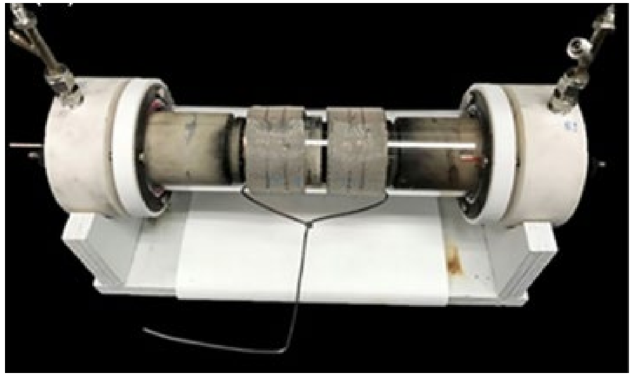
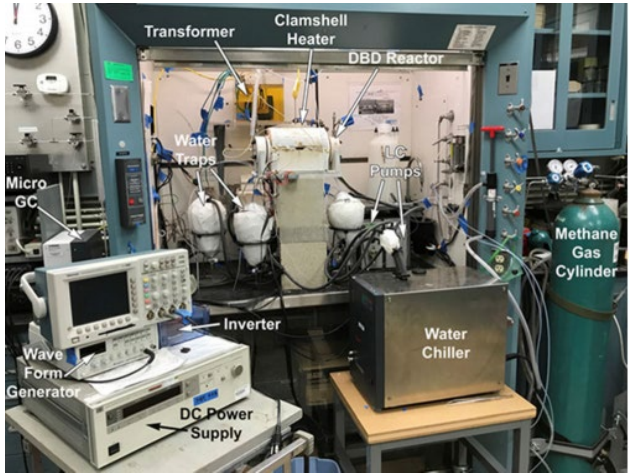
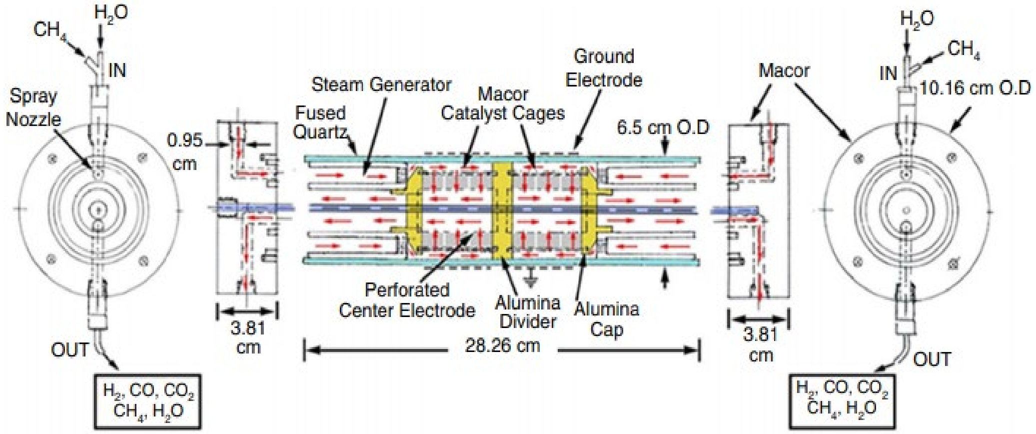
Jet Propulsion Laboratory (JPL) pioneered the development of a scaled-up dielectric barrier discharge (DBD) reactor to produce hydrogen from steam methane reforming (SMR)

- Scaled-up DBD reactor: 0.9 kg H_2/day.
- Conversion efficiency of the DBD reactor: **70–80%** at 550^{o}C and 500 W.
- Demonstrated continuous run of 8 hours
- Typical product gas: **69% H_2**, 6% CO_2, 15% CO, 10% CH_4







Susteon formed a partnership with SoCalGas and JPL to further develop and commercialize this technology.

U.S. Patent No. 10,898,875. 26 Jan. 2021. *AIChE Journal* 66.4 (2020): e16880.

JPL SoCalGas

Low Temperature Plasma Reforming of Natural Gas

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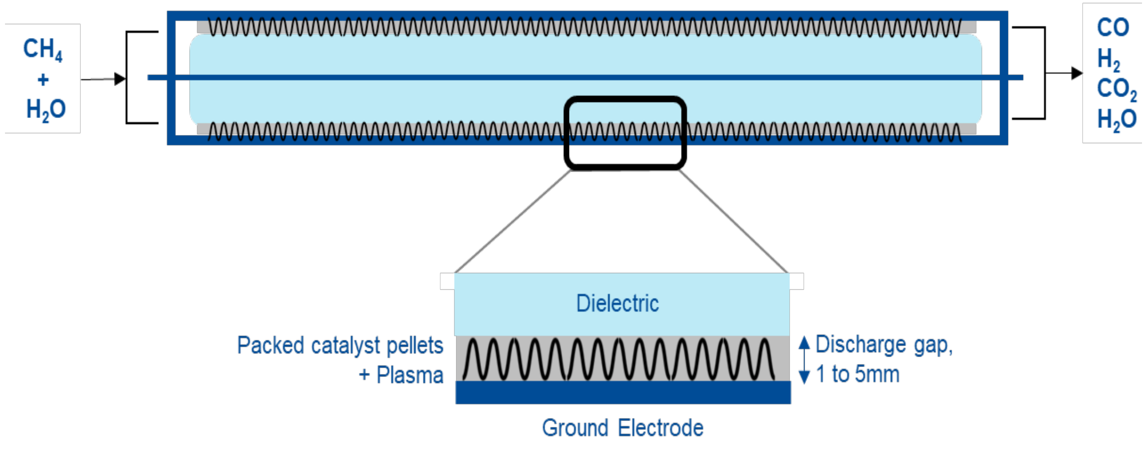
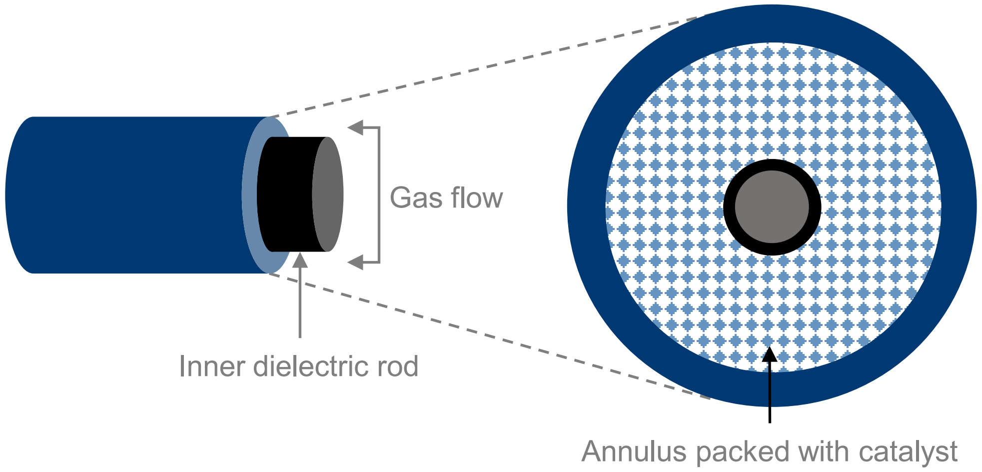


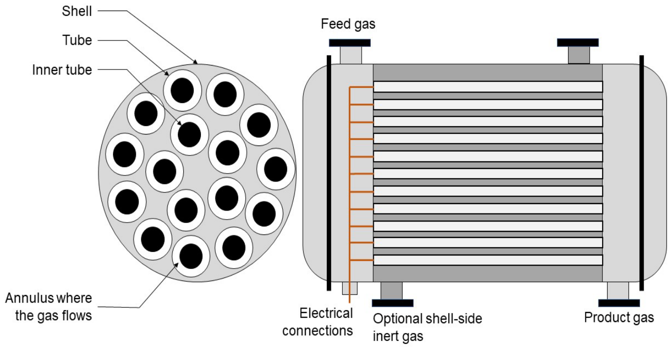


Technology

- Cold, non-thermal plasma driven-steam methane reformer reactor

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

- 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

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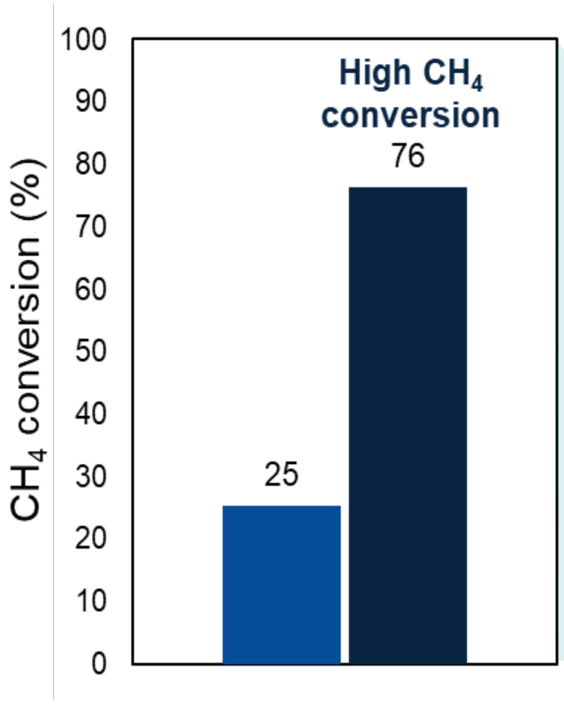
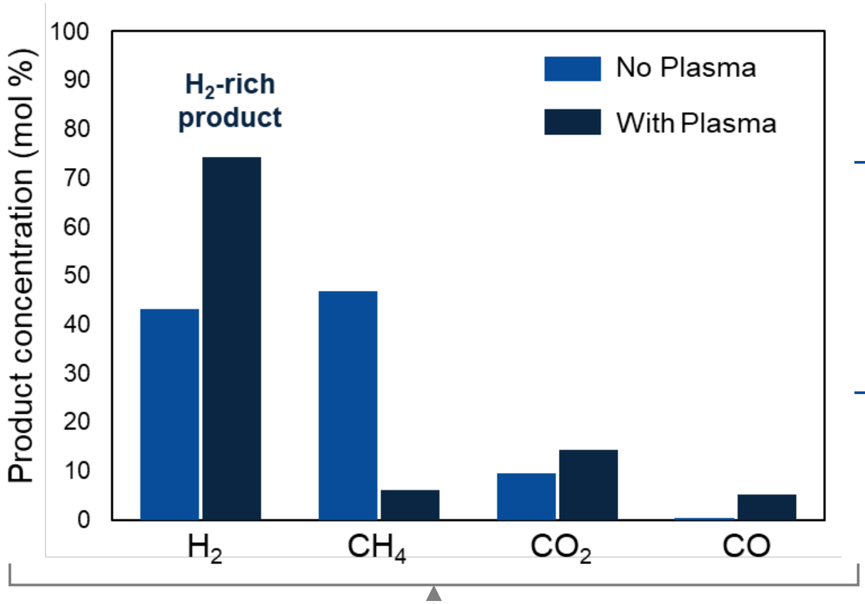
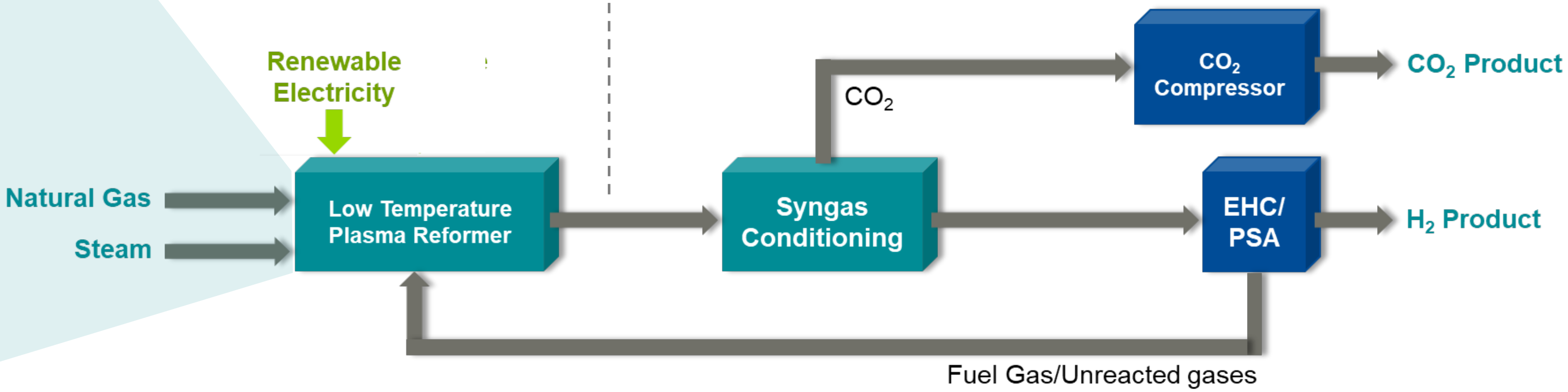




H_2	74.3%
CH_4	6.1%
CO_2	14.5%
CO	5.1%



SETON HALL UNIVERSITY 1856 CLARIANT SoCalGas

Comparison of Hydrogen Production Routes

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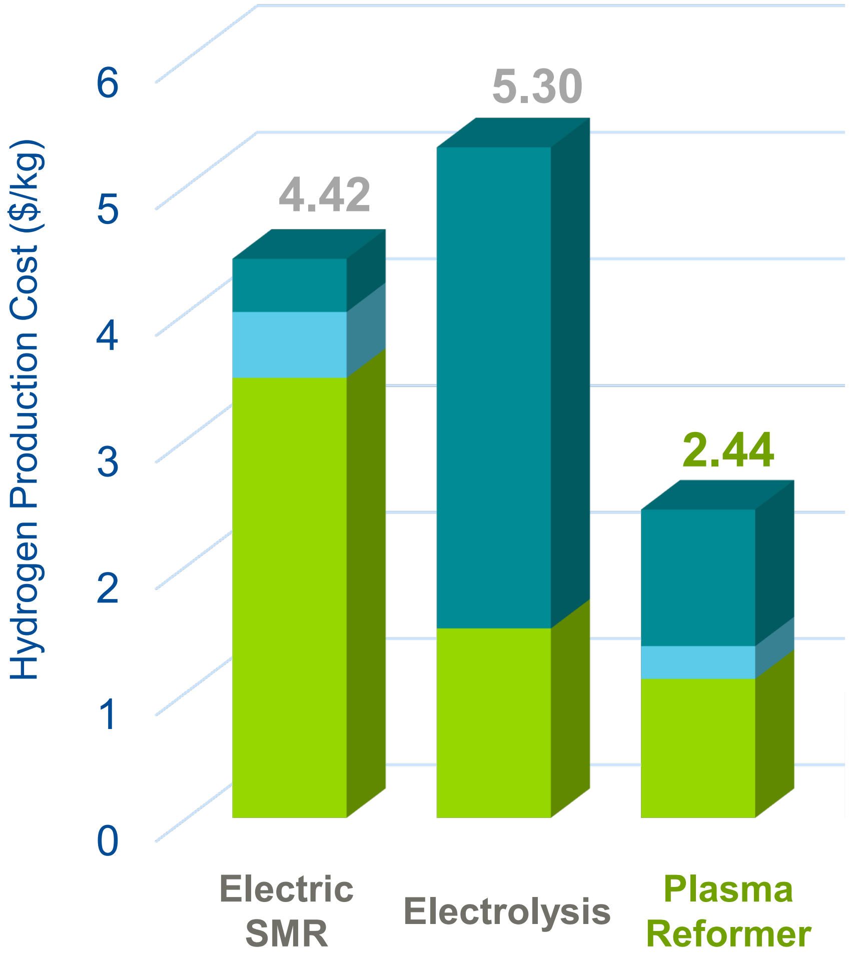
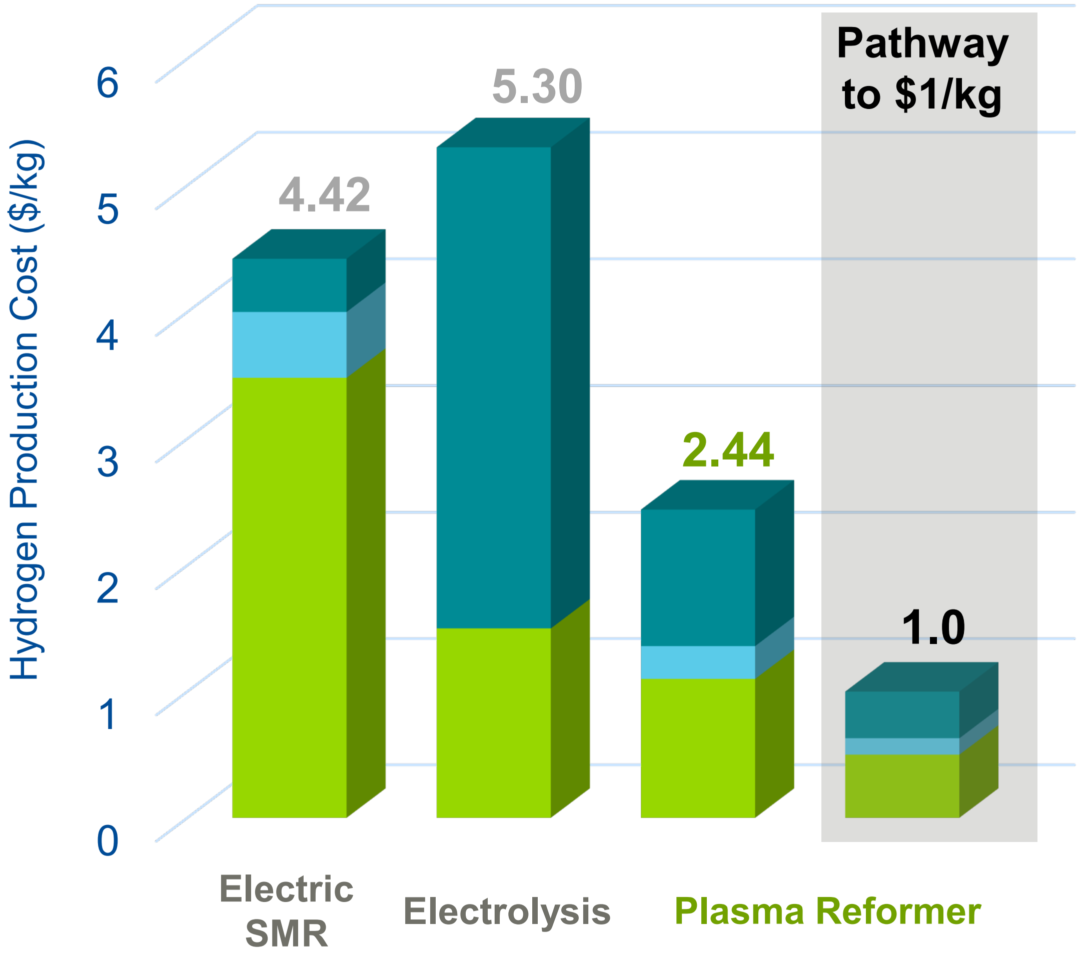


Cost Distribution among various sections[1] ($/kg H_2)

Category	**Electric SMR**	**PEM Electrolysis**	**Plasma Reformer** *Current*
Capital and Operating Cost	3.48	1.50*	1.10
Feedstocks**	0.52	0	0.26
Electricity***	0.42	3.80	1.08
Unit Cost of Hydrogen	**$4.42/kg**	**$5.30/kg**	**$2.44/kg**

All the three technologies include CO_2 capture and H_2 product compression to 350 bar
[1]Estimations done using the H2A model
*Electrolysis capital and other costs = $1500/kW
**Feedstock is natural gas @ $3/MMBTU; water for electrolysis
***Electricity price is $0.06/kWh

Comparison – Pathway to \$1/kg



Cost Distribution among various sections ($/kg H_2)

Category	Plasma Reformer *Current*	Plasma Reformer *Pathway*	
Capital and Operating Cost	1.10	0.50	45% of current cost
Feedstocks	0.26*	0.13	Natural gas @ \$1.5/MMBTU
Electricity	1.08**	0.37	Electricity @ \$0.02/kWh
Unit Cost of Hydrogen	**\$2.44/kg**	**\$1/kg**	

All the three technologies include CO_2 capture and H_2 product compression to 350 bar
*Feedstock is natural gas @ \$3/MMBTU; water for electrolysis
**Electricity price is \$0.06/kWh

Conclusions

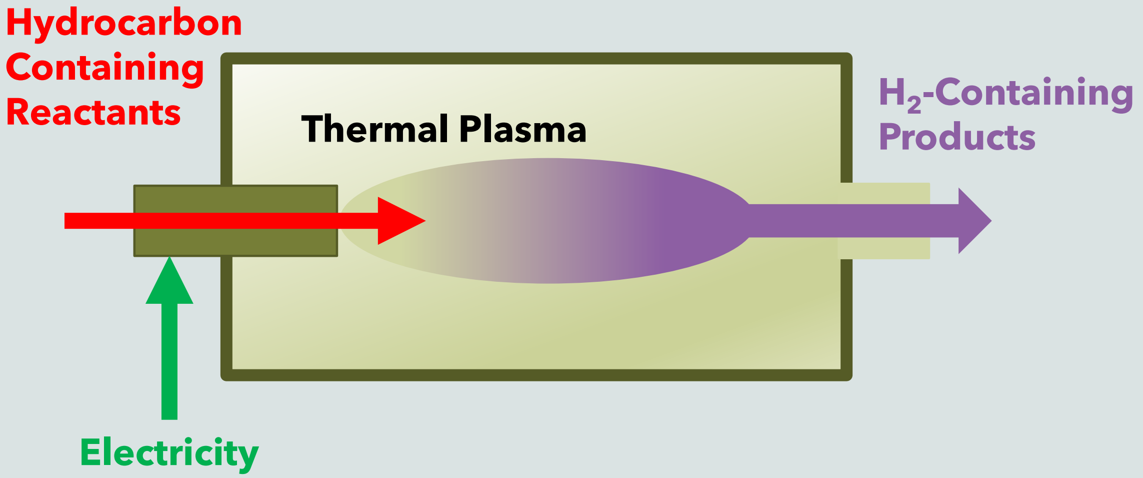
- **Plasma Reforming of natural gas** is an attractive route for distributed hydrogen production.
- Pioneered by JPL and SoCalGas, **Susteon developed this technology at bench-scale.**
- Results show that the plasma reformer manifests into significant process intensification to achieve **high natural gas conversions and H_2-rich product at <500^{o}C and 1 atm.**
- This technology can also **produce a pure CO_2 stream.**
- Has the **potential to produce hydrogen at $1/kg** with further R&D.

DOE-H_2 Earth-Shot Summit

Mark A. Cappelli, Ph.D.

Thermochemical Conversion

Thermal Plasmas provide the energy source needed to drive reactions involving hydrocarbons towards H_2 production



Reactants: Natural Gas, O_2, CO_2, Biogas

Products: H_2, CO, CO_2, Water

Thermal Plasma: DC Arc, RF, Microwave

Common Thermochemical Conversions:[1]

Steam Reforming

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \qquad \Delta H = +206 \text{ kJ/mole}$$

Dry Reforming

$$CH_4 + CO_2 \longrightarrow 2CO + 2H_2 \qquad \Delta H = +247 \text{ kJ/mole}$$

Partial Oxidation

$$CH_4 + \frac{1}{2}O_2 \longrightarrow CO + 2H_2 \qquad \Delta H = -36 \text{ kJ/mole}$$

- 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_2 product in conjunction with CO_2 sequestration
- Costs[2] range from \$1.50 ⟶ \$2.50/kgH_2
- Catalysts contribute >50% of the costs[3]

[1] Hrabovsky et al, Plasma Chem Plasma Process (2018) 38:743–758
[2] Kayfeci,et al., M., in Solar hydrogen production (2019), pp. 45-83, Academic Press.
[3] Ayodele, et al., Sustainability, 12(23) (2020), p.10148.

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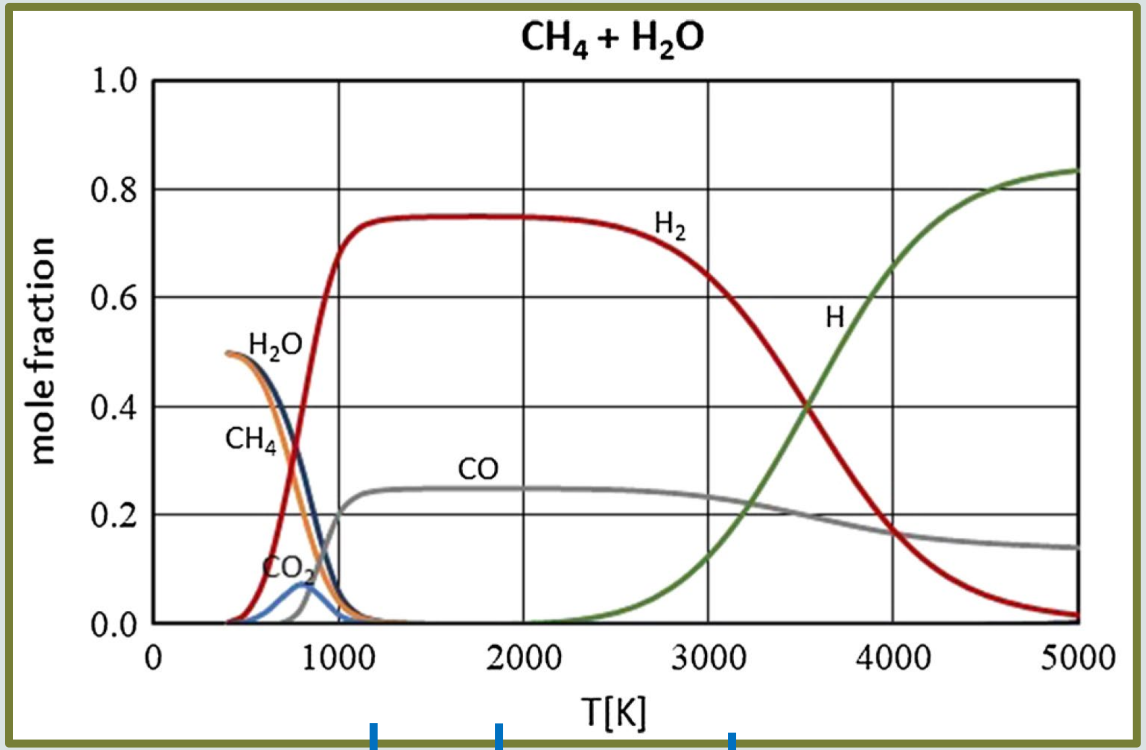
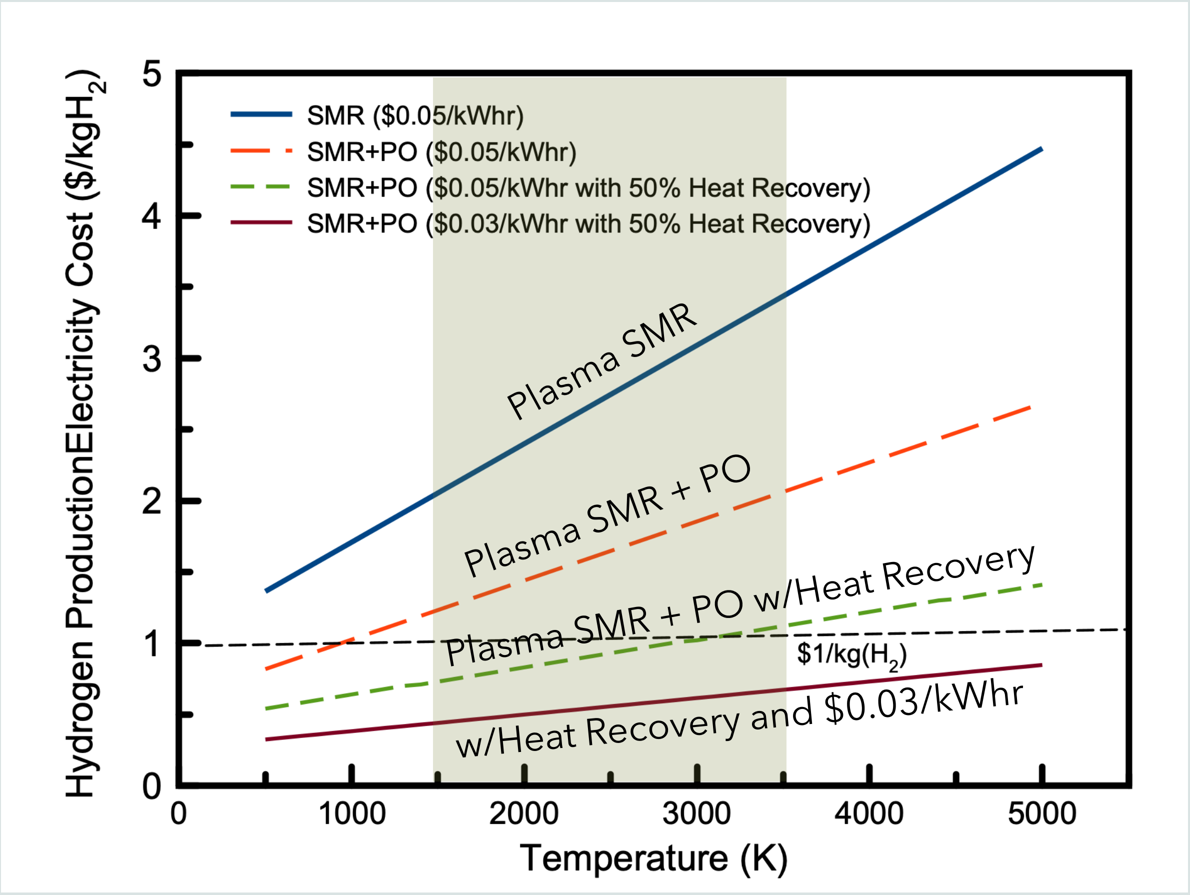
Thermochemical Plasma Conversion

Enables access to higher temperatures circumventing catalysts



conventional with catalyst

thermal plasma



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

$$CH_4 + \frac{1}{2}H_2O + \frac{1}{4}O_2 \longrightarrow CO + \frac{5}{2}H_2 \qquad \Delta H = +85 \text{ kJ/mole}$$

- heat recovery necessary to hit \$1/kgH_2 boundary
- electricity pricing of \$0.03/kWhr $\longrightarrow$ well in range

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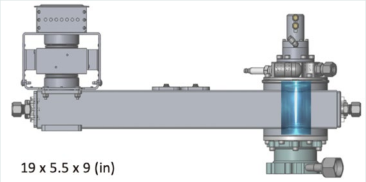
Thermochemical Plasma Conversion

Precommercial/Commercial

RECARBON, INC.



Industry Sector

- targeting landfill gas/bio-digestion gases
- **plasma** ATR with CO_2 instead of steam
- 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

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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

Funding to Accelerate Progress

Specific areas where government funding could accelerate progress for your approach?

- Financing/Loan guarantees not dependent on hydrogen offtake agreements
- H_2 infrastructure specific funding, such as CAPEX grants
- Electricity subsidies for ALL hydrogen production technologies (not just for electrolysis)

R&D Requirements

R&D required to scale technology up to industrial scale?

- Impurity management (up and 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/kgH_2 at scale

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