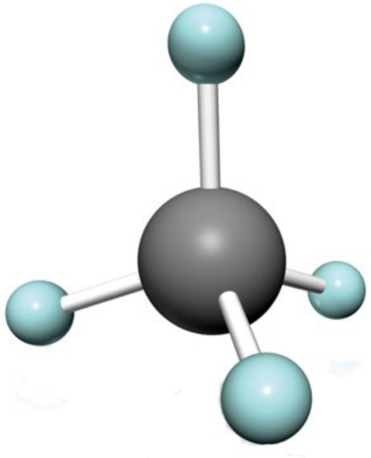
Methane Pyrolysis for Hydrogen– Opportunities and Challenges

Hydrogen Shot Summit
Thermal Conversion with Carbon Capture & Storage

Marc von Keitz
Program Director @ ARPA-E

August 31, 2021

Methane Pyrolysis – How to get to $1/kg of H_2?



750 - 1200°C →

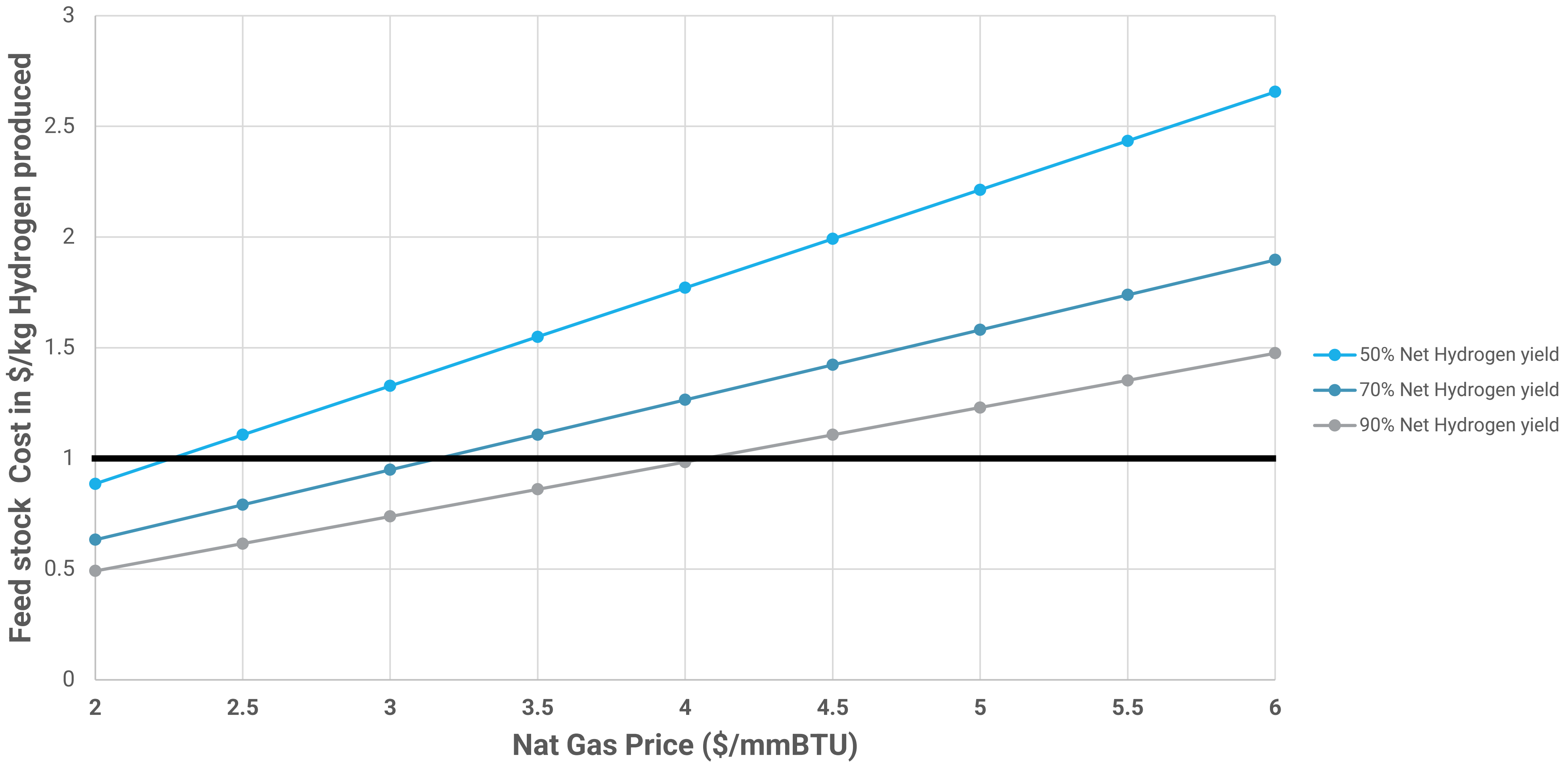
Gaseous hydrogen

+

Solid carbon

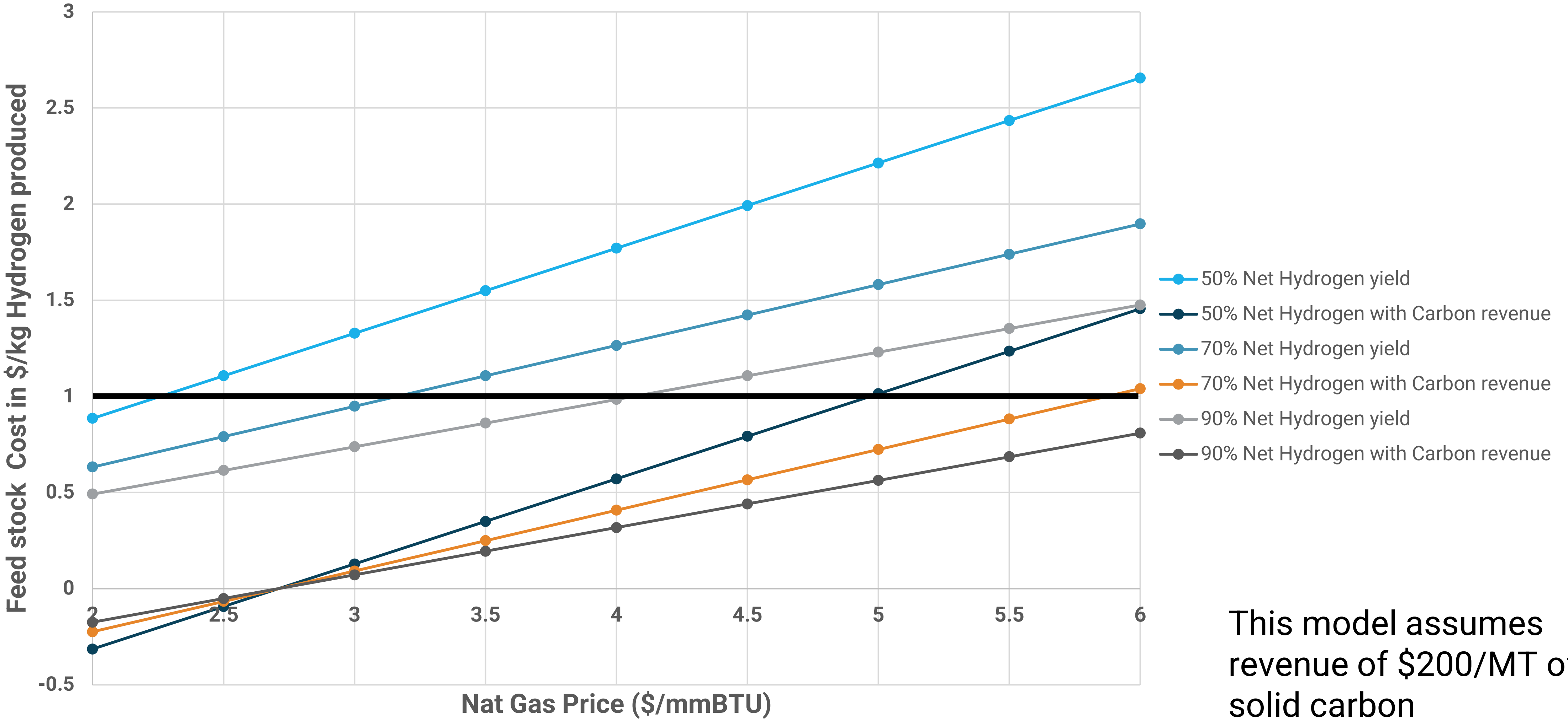
$$CH_4 \longrightarrow 2\,H_2 + C\,(s)$$

Nat Gas Price and Net Hydrogen Yield Drive Cost of H_2



Net hydrogen yield is a function of the source of process energy and efficiency

Valorizing the Carbon can reduce Feedstock Cost



This model assumes revenue of $200/MT of solid carbon

CHANGING WHAT'S POSSIBLE

Making a lot of Hydrogen means making a lot of Carbon

1 Quad of Hydrogen

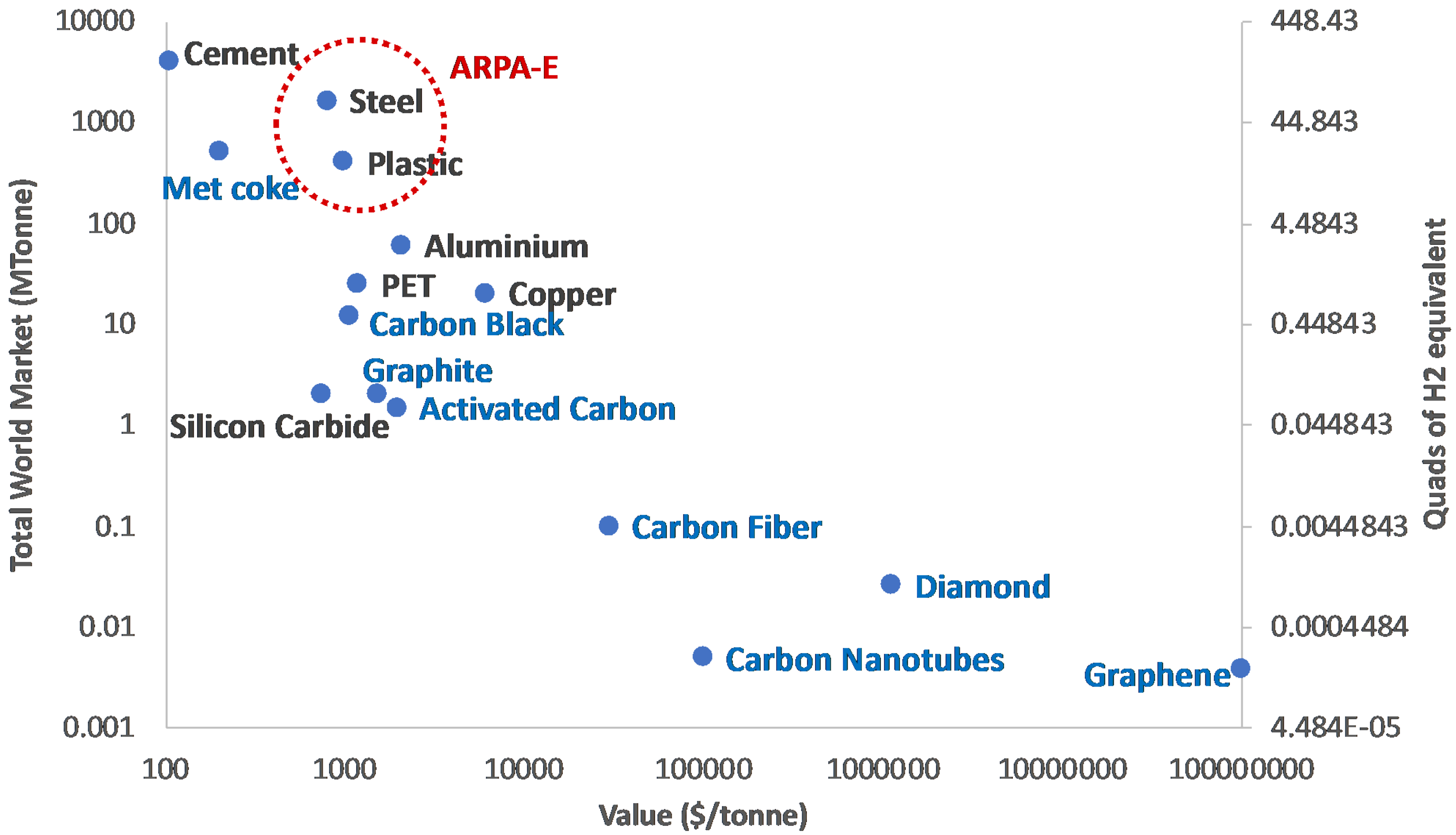
via Methane Pyrolyis also generates

~32 million MT of solid carbon

at 70% net hydrogen yield

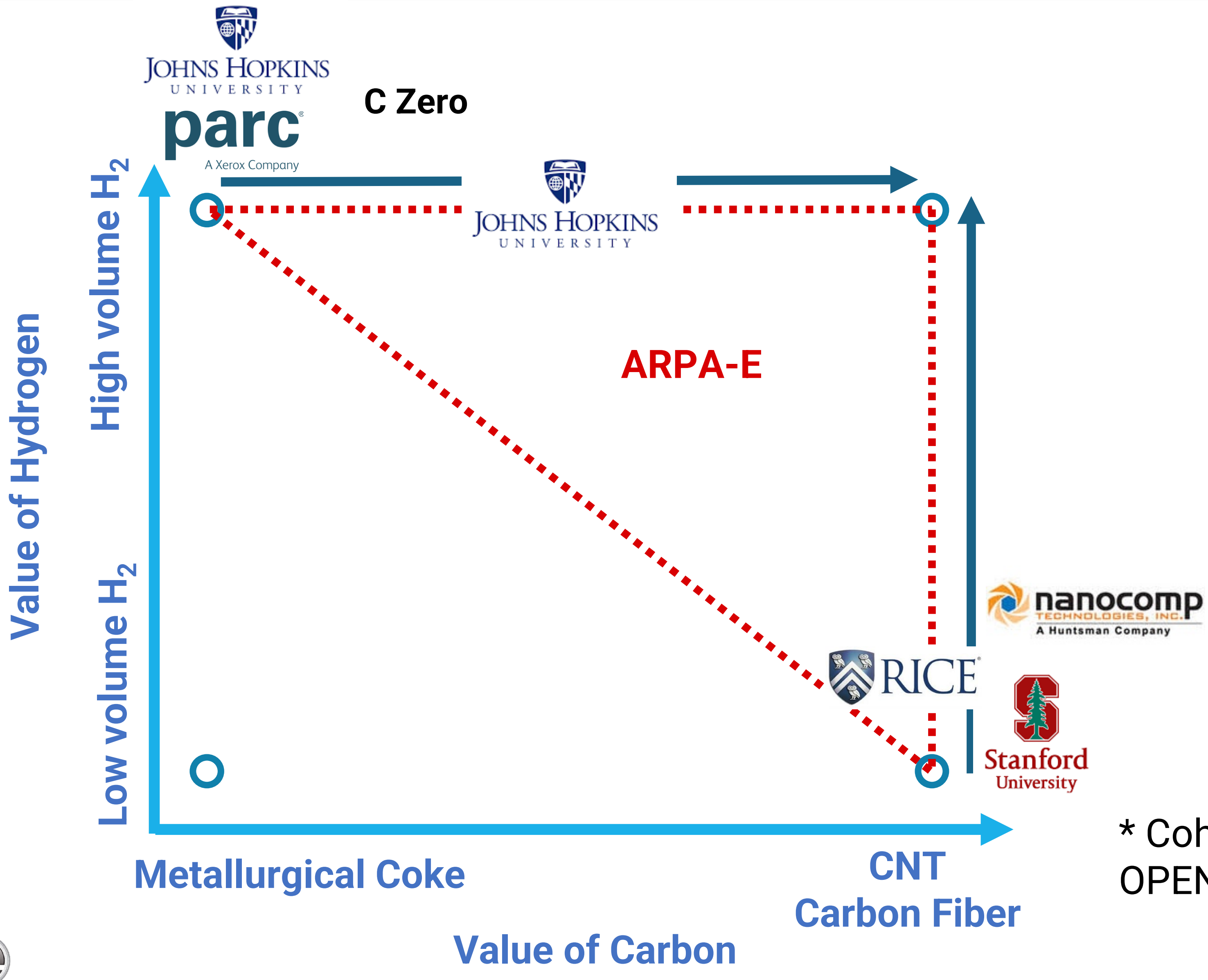
Image: dpa

Which markets can absorb this volume of carbon?



arpa·e
CHANGING WHAT'S POSSIBLE

ARPA-E Methane Pyrolysis Cohort* takes 2-pronged approach

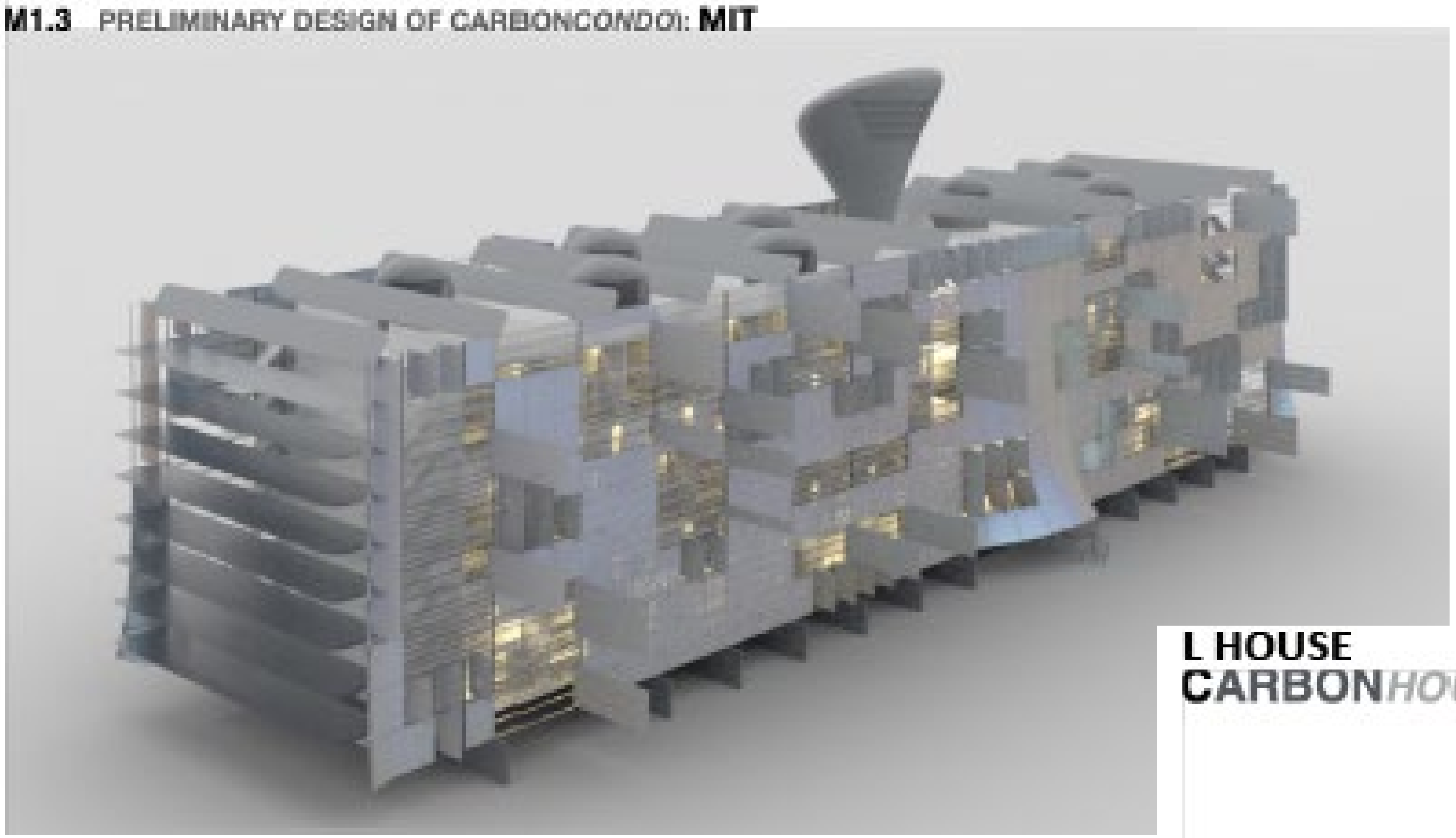


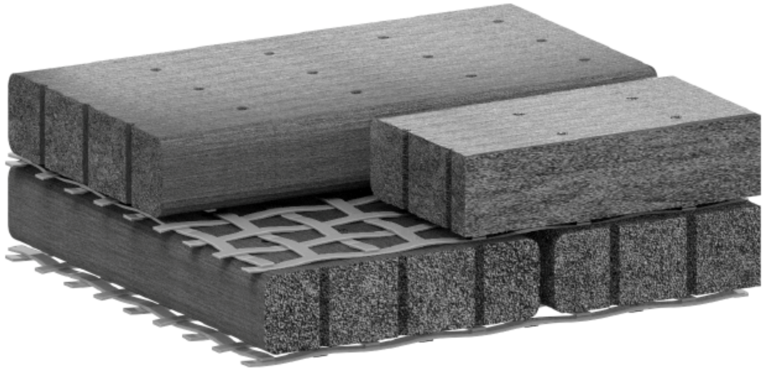
New Carbon Applications

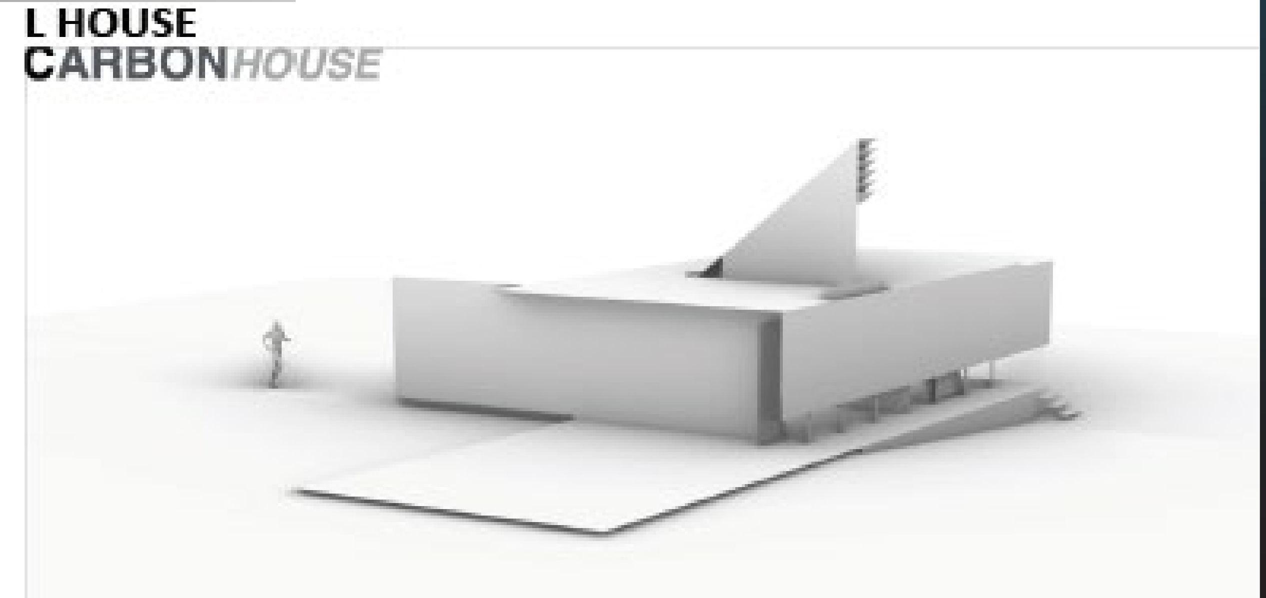
* Cohort has been assembled from OPEN 2018 and 2019 FOA projects

CHANGING WHAT'S POSSIBLE

MIT Carbon House – Carbon-based Composite Buildings







Stop the Leaks!

To realize "low/no-carbon" hydrogen from methane (by methane pyrolysis, SMR+CCS or other), we need to radically eliminate methane leaks in the supply chain and in the conversion process

Thank you!

https://arpa-e.energy.gov

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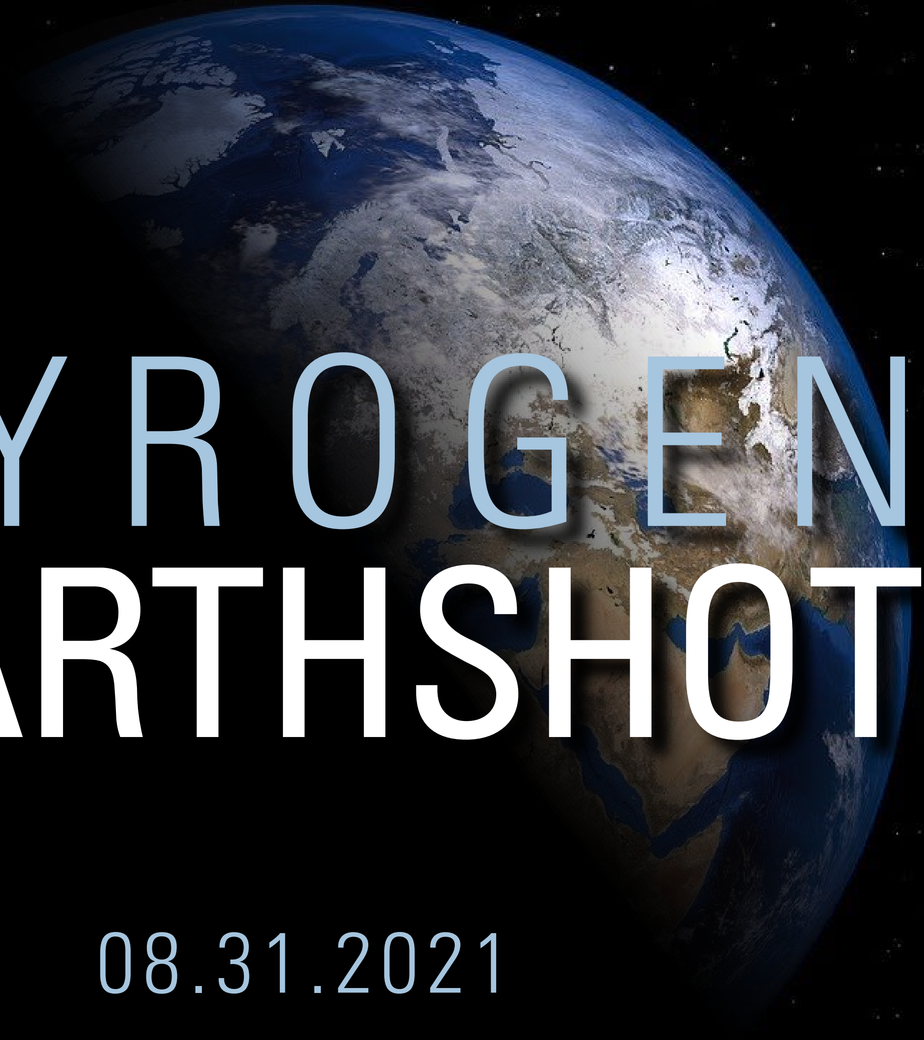


HYROGEN EARTHSHOT

08.31.2021

U.S. DEPARTMENT OF ENERGY

HYDROGEN EARTHSHOT SUMMIT

Thermal Conversion Pathway Panel
Methane Pyrolysis Technologies

Dane A. Boysen, PhD
Modular Chemical, Inc.

August 31, 2021

HYDROGEN "COLORS"

	HYDROGEN SOURCE	ENERGY SOURCE	PRODUCTION PROCESS	BY-PRODUCT	TONS CO_2 PER TON H_2
GREEN	water	renewable energy	electrolysis	pure oxygen gas (O_2)	0
YELLOW	water	grid electricity	electrolysis	CO_2 emitted	+16.4
TURQUOISE	natural gas	natural gas	thermochemical	solid carbon product (C)	0
?????	bio-methane	bio-methane	thermochemical	solid carbon product (C)	–10.9
BLUE	water, natural gas	natural gas, lignite coal	thermochemical	CO_2 sequestered	0
PURPLE	water	nuclear energy	thermal electrolysis	pure oxygen gas (O_2)	0
PINK	water	nuclear energy	electrolysis	pure oxygen gas (O_2)	0
RED	water	nuclear energy	thermochemical	pure oxygen gas (O_2)	0
GRAY	water, natural gas	natural gas	thermochemical	CO_2 emitted	+7.5
BROWN	water	lignite coal	thermochemical	CO_2 emitted	+13.4
BLACK	water	bituminous coal	thermochemical	CO_2 emitted	+13.4
WHITE	water	grid electricity	electrolysis	chemical product (Cl_2)	

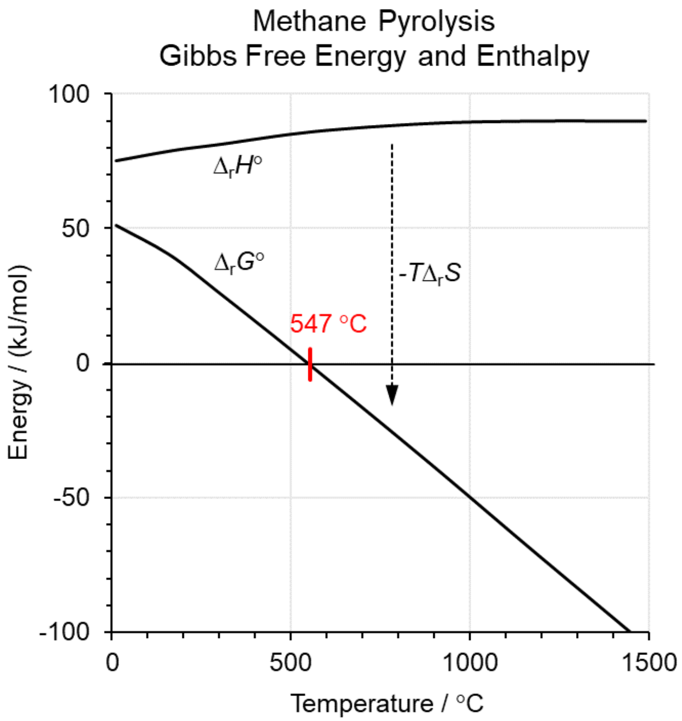
LEGEND
water
natural gas
bio-methane
renewable energy
grid electricity
nuclear energy
lignite coal
bituminous coal
electrolysis
thermochemical
thermal electrolysis
CO_2 emitted
CO_2 sequestered
solid carbon product
pure oxygen gas
chemical product

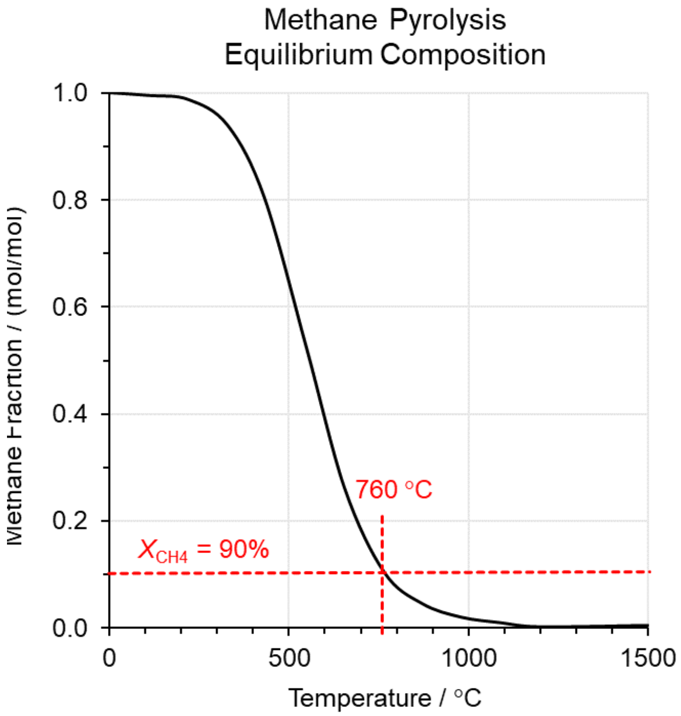
WHAT IS IT?

METHANE PYROLYSIS

the thermal breakdown of methane into hydrogen gas and solid carbon

- $1/2CH_4(g) = H_2(g) + 1/2C(s)$
- Thermodynamics
  - $\Delta_r H^\circ_{298K} = +37.4$ kJ/mol
  - $\Delta_r G^\circ_{298K} = +25.4$ kJ/mol
- Favorable reaction above 547°C
- High conversion above 760°C





CO_2 emission-free pathway for making hydrogen from natural abundant methane (natural gas or biomethane)

WHO CARES?

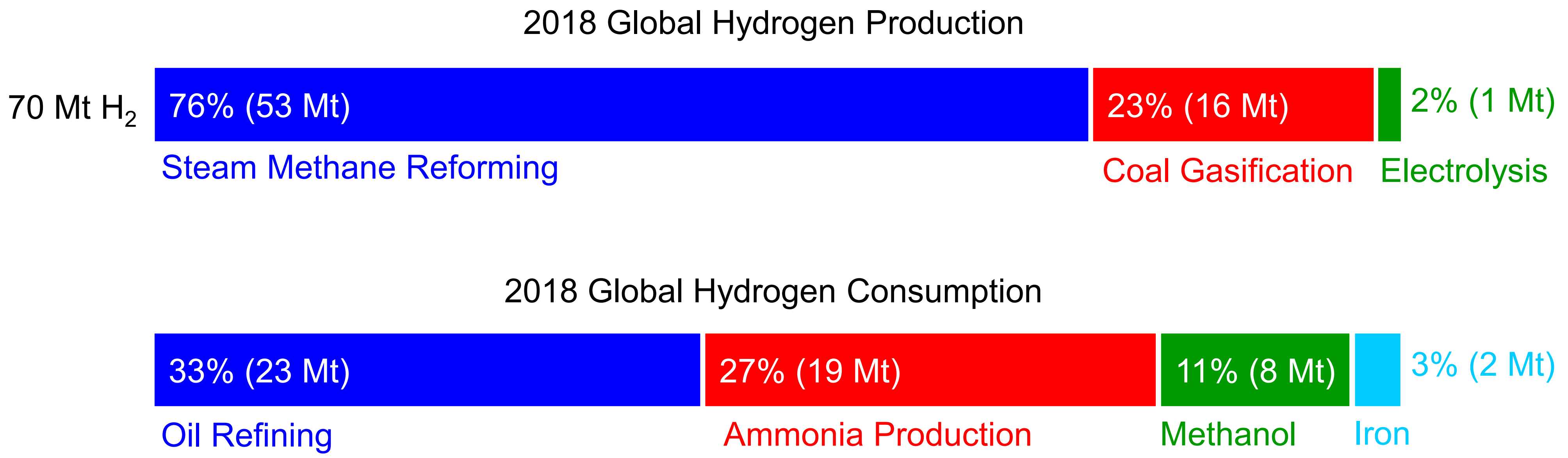
HYDROGEN PRODUCTION

- Climate Change
  - Primary driver – keep global temperature rise below 2°C
  - What it will take – must reduce GHG emissions to zero by 2050
  - Annual energy-related GHG emissions in 2018 – 33.1 Gt CO_2
  - Annual H_2-related GHG emissions – 0.83 Gt CO_2 (2.5%)
  - Carbon intensity – 12 t CO_2 per t H_2

WHO CARES?

HYDROGEN PRODUCTION

- Climate Change
- Industrial Hydrogen



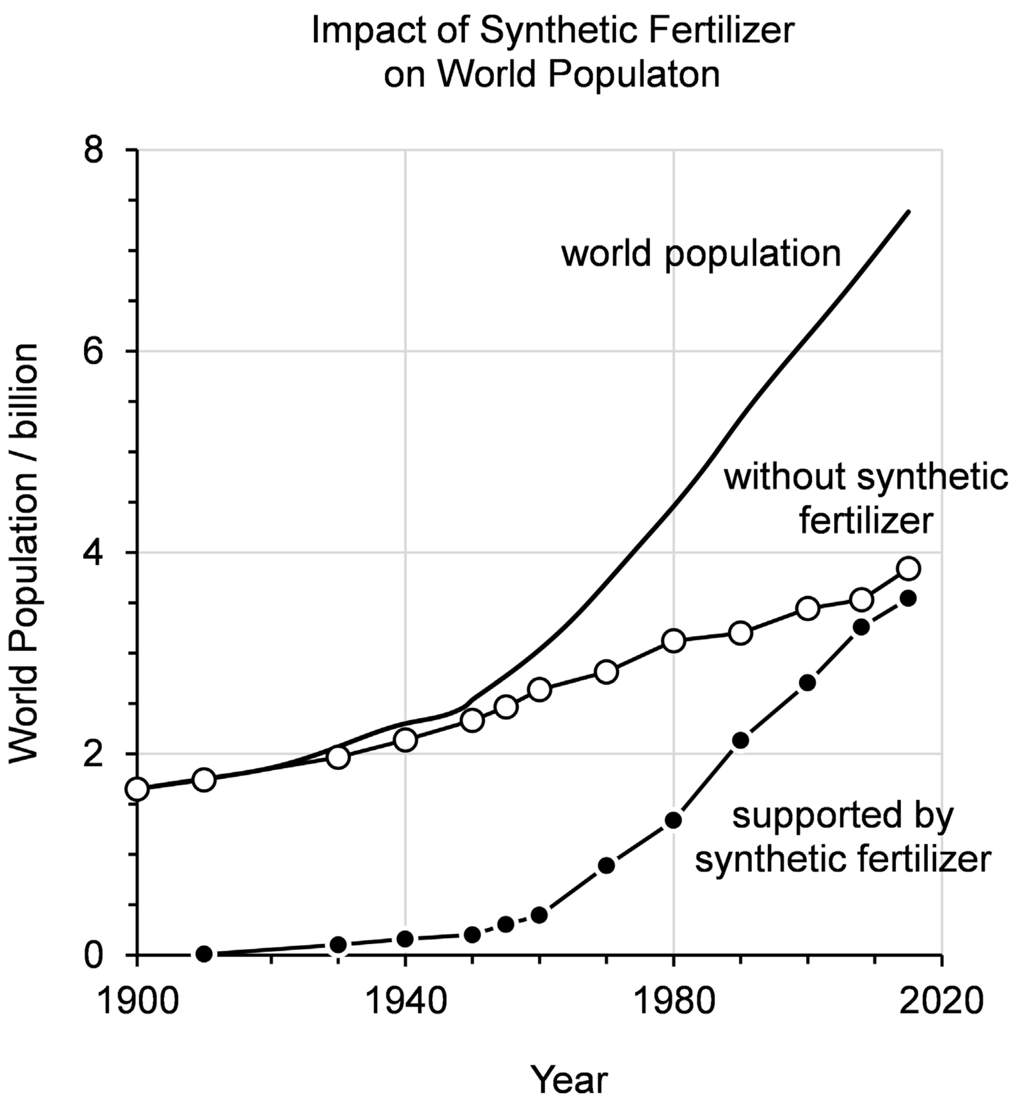
Birol F. *The Future of Hydrogen: Seizing Today's Opportunities*. Report prepared by the IEA for the G20, 82-83, Japan. 2019.

WHO CARES?

HYDROGEN PRODUCTION

- Climate Change
- Industrial Hydrogen
- Food Security
  - Annual demand to make ammonia – 19 Mt H_2 (27%)
  - Population fed by synthetic ammonia – 3.8 billion (48%)

Low-cost hydrogen supply is critical to the food security of over half of the world's population

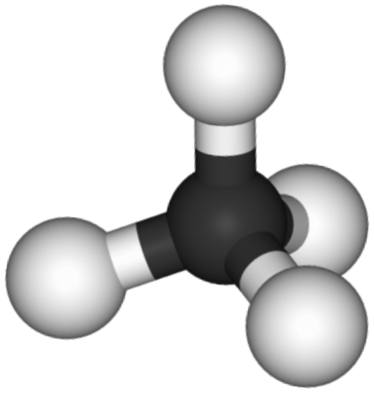


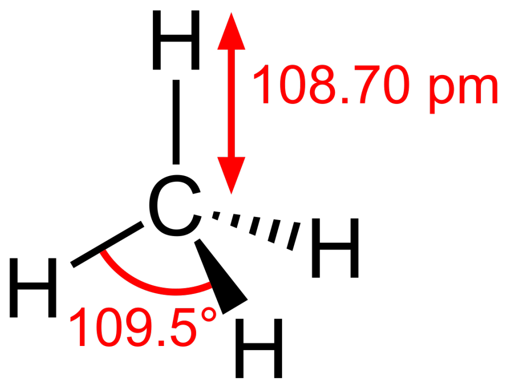
Erisman JW et al. *Nature Geoscience*, 1(10), 636-639. (2008).

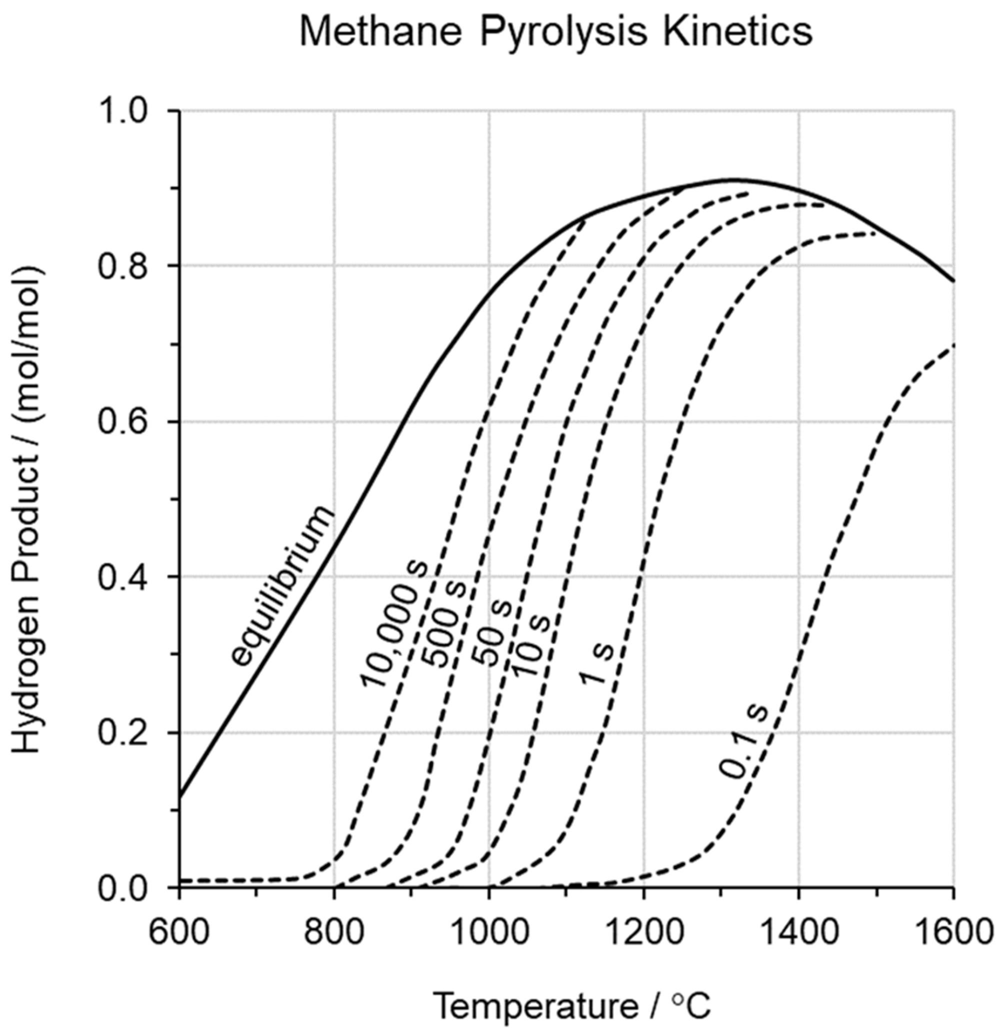
WHY IS IT HARD?

METHANE PYROLYSIS

- Slow reaction kinetics
  - methane = highly symmetric molecule
  - CH_3−H bond energy 440 kJ/mol
  - results in difficult C-bond activation





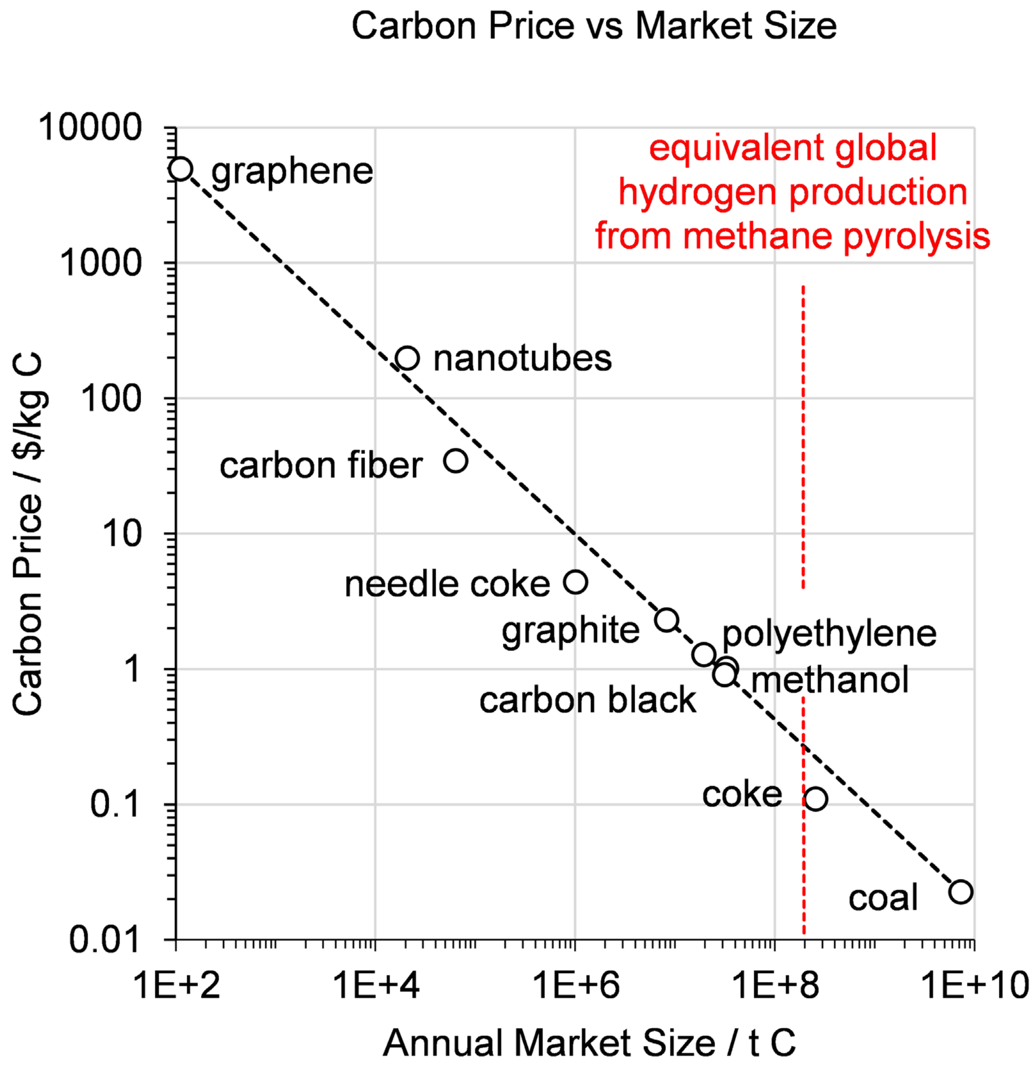


Younessi-Sinaki M, et al. *Int. J. Hydrogen Energy* 34(9): 3710-3716. (2009)

WHY IS IT HARD?

METHANE PYROLYSIS

- Slow reaction kinetics
- Carbon formation
  - $0.5CH_4(g) = H_2(g) + 0.5C(s)$
  - Carbon production = 3 tons per ton H_2
  - Good catalysts (Ni, Fe) deactivate quickly
  - Efficient separation is difficult
  - What can we do with all that carbon?



WHY IS IT HARD?

METHANE PYROLYSIS

- Slow reaction kinetics
- Carbon formation
- Economic disadvantage

ASSUMED COMMODITY PRICES

Coal	50 $/ton	2.04 $/GJ
Natural Gas	3.00 $/MMBtu	2.84 $/GJ
Electricity	0.07 $/kWh	19.44 $/GJ

ASSUMED CARBON INTENSITY

Grid Electricity (US, 2019)	0.92 lb CO_2/kWh (116 kg/GJ)

THEORETICAL MINIMUM

Description	Overall Reaction	Chemical	Thermal	t CO_2 / t H_2	$/kg H_2
Methane Pyrolysis	$1/2CH_4(g) = H_2(g) + 1/2C(s)$	CH_4	H_2	-10.9[i] to 0	0.72
Coal Gasification	$1/2C(s) + H_2O(l) = H_2(g) + 1/2CO_2(g)$	C	C	+13.4	0.24
Steam Methane Reforming	$1/2CH_4(g) + 1/2H_2O(l) = H_2(g) + 1/2CO_2(g)$	CH_4	CH_4	+7.5	0.43
Water Electrolysis	$H_2O(l) = H_2(g) + 1/2O_2(g)$	electrical	electrical	0 to +16.4[ii]	2.76

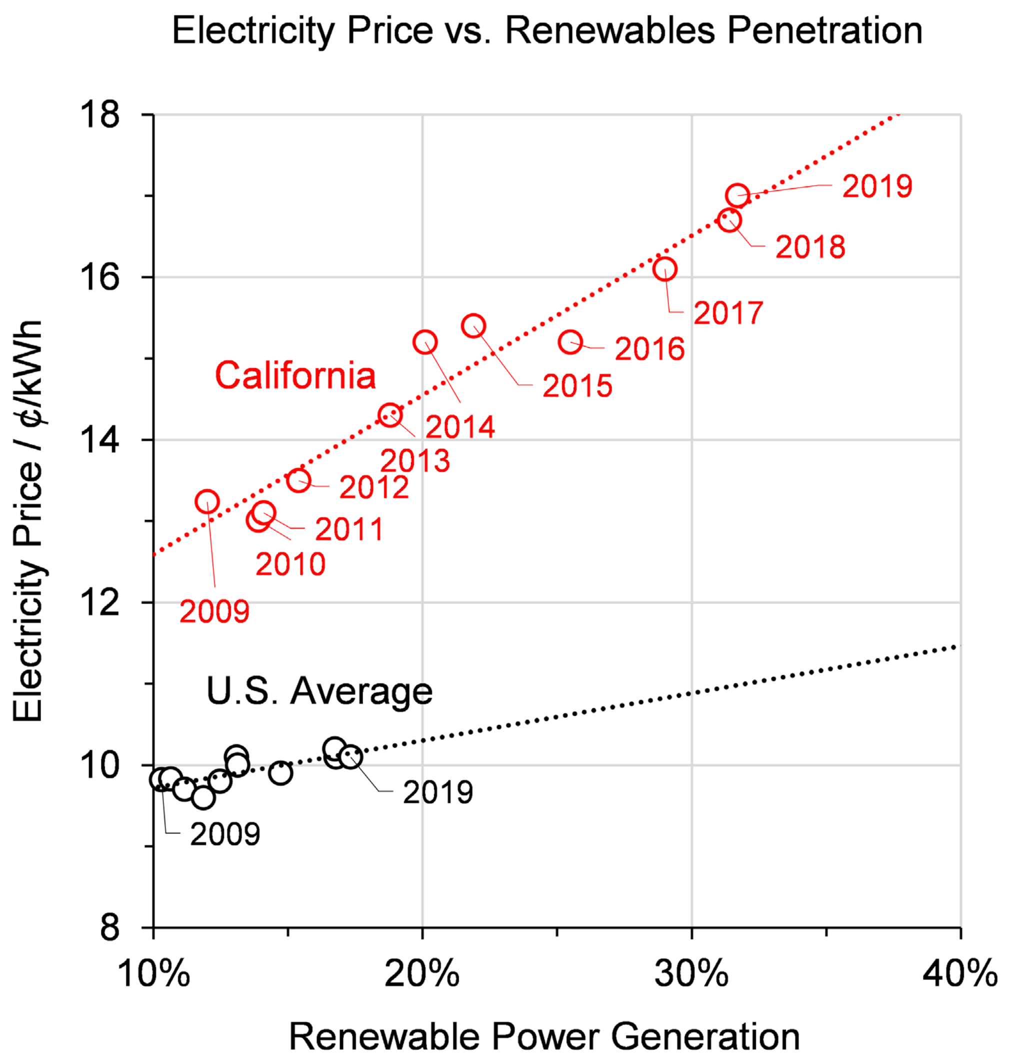
i. assuming biogas feedstock, ii. assuming U.S. electric grid carbon intensity

COMMENT ON ELECTRICITY PRICES

- Many claim that renewable electricity prices will reach < 3 ¢/kWh

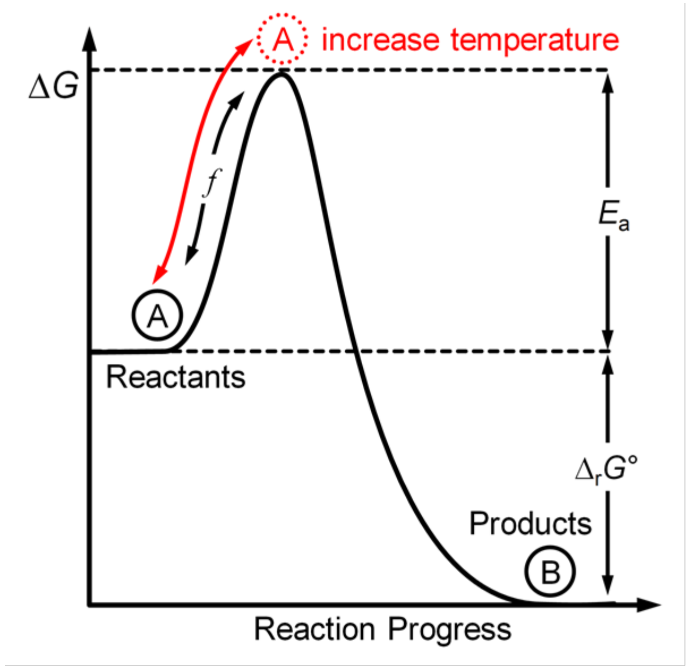
- While this may be true for a few select, site-specific cases (e.g., co-location near a hydro-electric power plant)

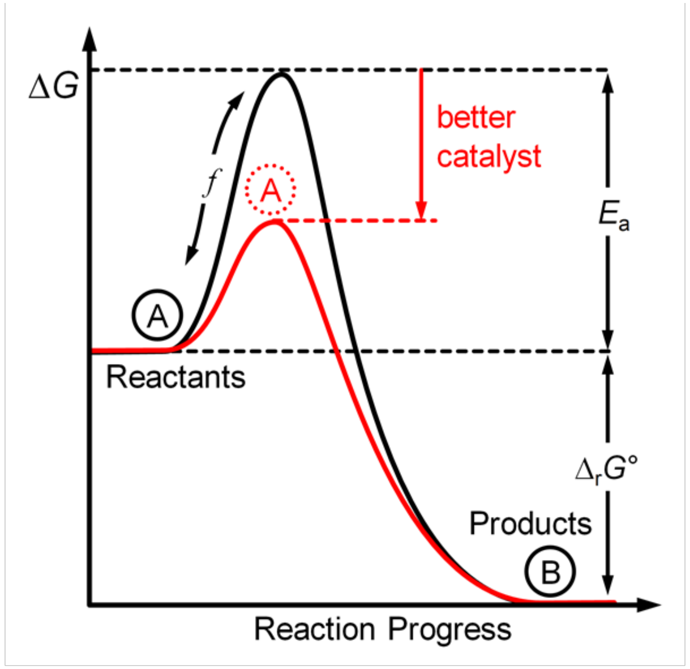
- In general, levelized electricity price data for increased renewables penetration do not support these claims

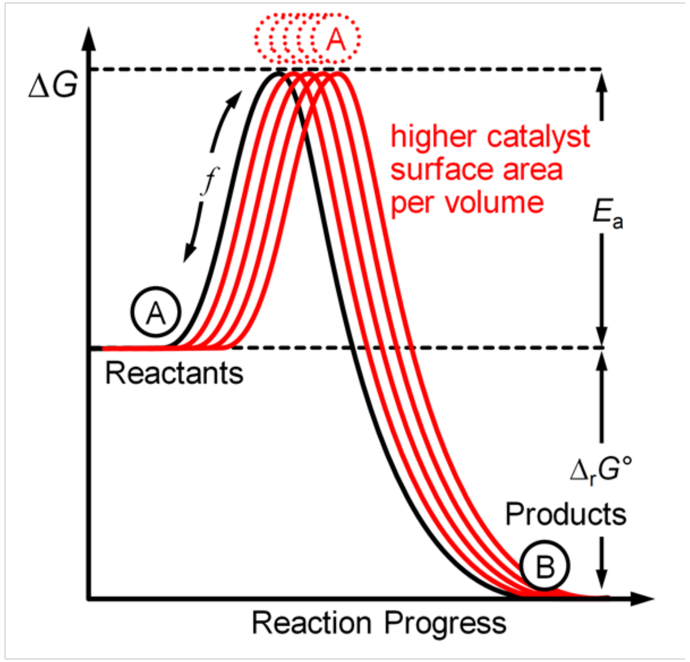


HOW IS DONE TODAY?

METHANE PYROLYSIS – FUNDAMENTAL WAYS TO INCREASE KINETICS



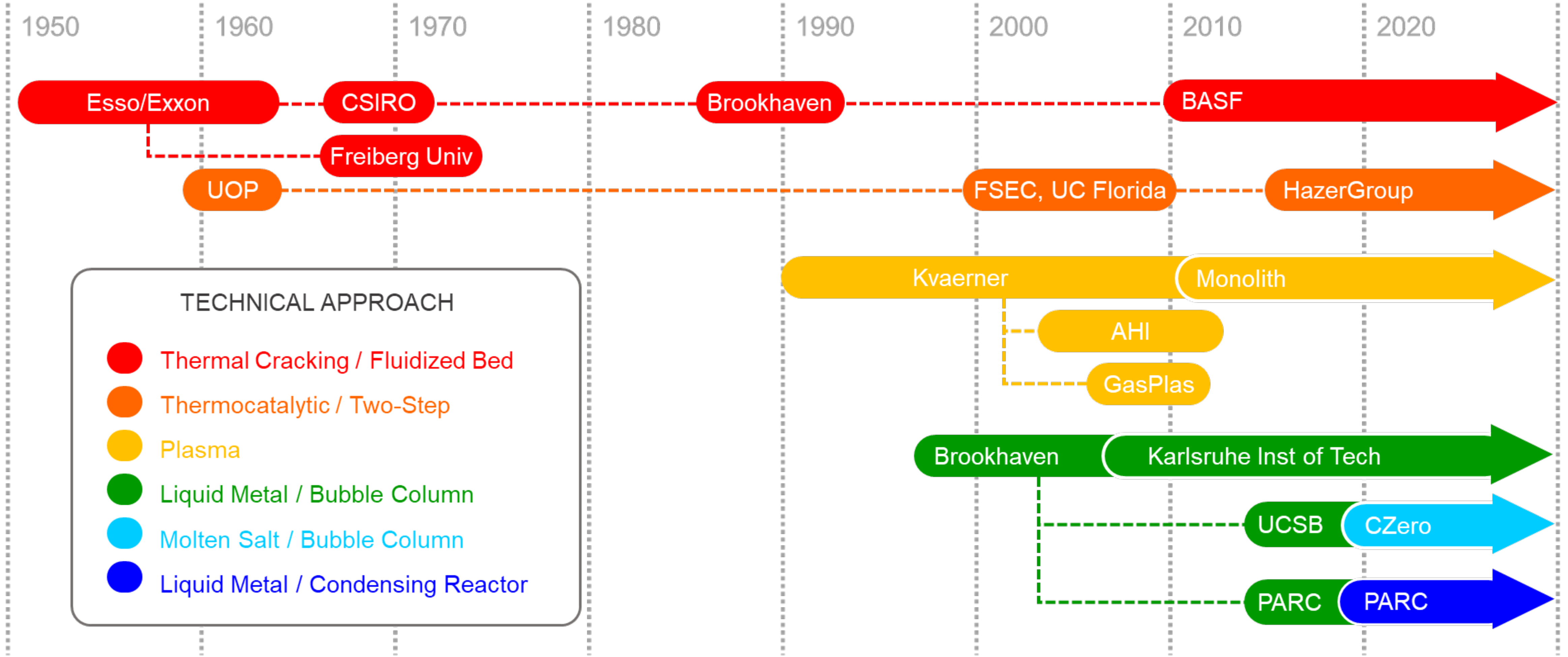




1. Increase **temperature**
2. Better **catalyst**
3. Higher **surface area**

HOW IS DONE TODAY?

METHANE PYROLYSIS – DEVELOPMENT HISTORY



Adapted from Bode A et al. BASF. *ProcessNet Jahrestagung*. Aachen, Germany. 14 Sep 2016.

HOW IS DONE TODAY?

METHANE PYROLYSIS – COMMERCIAL EFFORTS

THERMAL CRACKING

- BASF
- EKONA

THERMOCATALYTIC

- HazerGroup
- hycamite
- Stanford University
- Susteon

PLASMA / MICROWAVE

- MONOLITH
- NU:IONIC
- HiiROC
- Nanoplazz TECHNOLOGIES
- spark
- MAAT ENERGY

LIQUID METAL BUBBLE

- KIT
- TNO

MOLTEN SALT BUBBLE

- C-ZERO
- Shell

LIQUID METAL CONDENSING

- parc

CHEMICAL REDOX

- THIOZEN
- ETCH

PHOTOCATALYTIC

- SYZYGY PLASMONICS

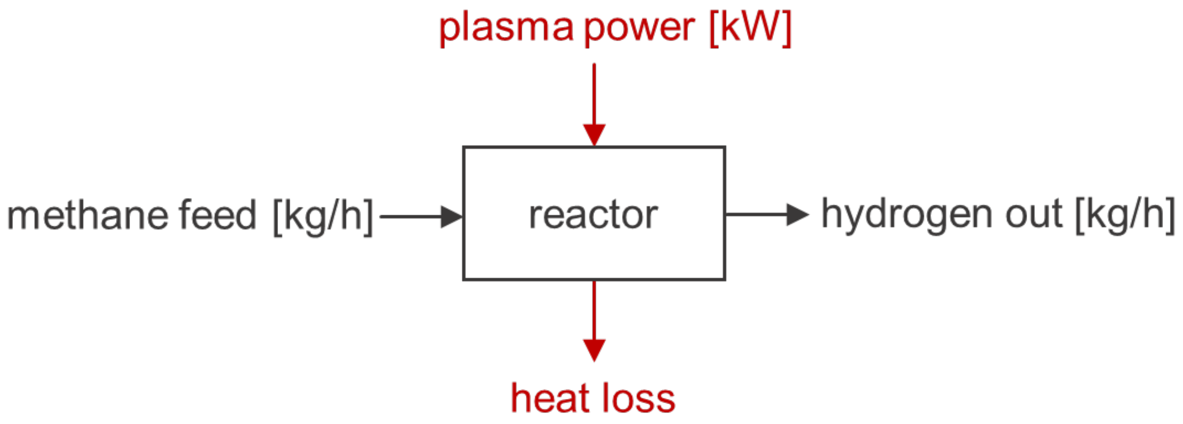
OTHER APPROACHES

- NEW WAVE HYDROGEN

COMMERCIAL EFFORTS DATABASE https://docs.google.com/spreadsheets/d/1IcMP7WImhntRz3hKvVjvr2IwrFprgCe-1bYAtY56eOk/edit?usp=sharing

COMMENT ON PLASMA & MICROWAVE APPROACHES

With many new companies doing plasma methane pyrolysis, it is critical investors look at mass and energy results to validate claims



$$\frac{\text{plasma power [kW]}}{\text{hydrogen out [kg/h]}} \times \text{electricity price [0.07 \$/kWh]} = \text{plasma cost [\$/kg } H_2\text{]}$$

EXAMPLE HiiROC

Company Data

- plasma voltage = 50 V
- plasma current = 260 A
- methane flow = 375 L/h
- methane conversion = 99%

Calculations

- plasma power = 13.0 kW
- methane feed = 0.246 kg/h
- hydrogen out= 0.061 kg/h

PLASMA COST = 14.9 \$/kg H_2

MARKET PRICE = 1.0 \$/kg H_2

QUESTIONS

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PARTNERS

parc A Xerox Company | Susteon | CABOT | Stony Brook University | BURNS ENERGY SYSTEMS

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Monolith + Methane Pyrolysis

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Topics

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Vision

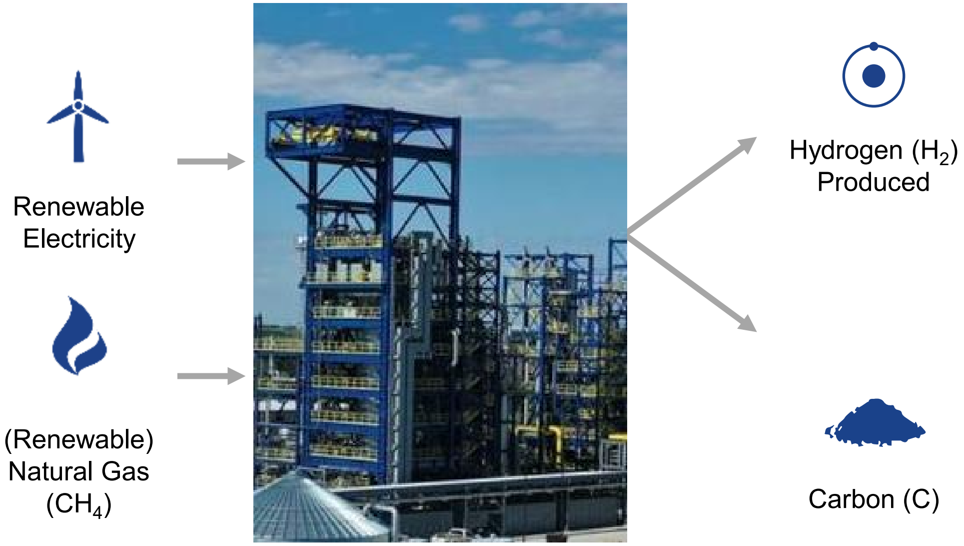
Build the World's Leading

Renewable Hydrogen &

Clean Materials Company

Unique Business Plan

Renewable Hydrogen from Renewable Electricity & Natural Gas

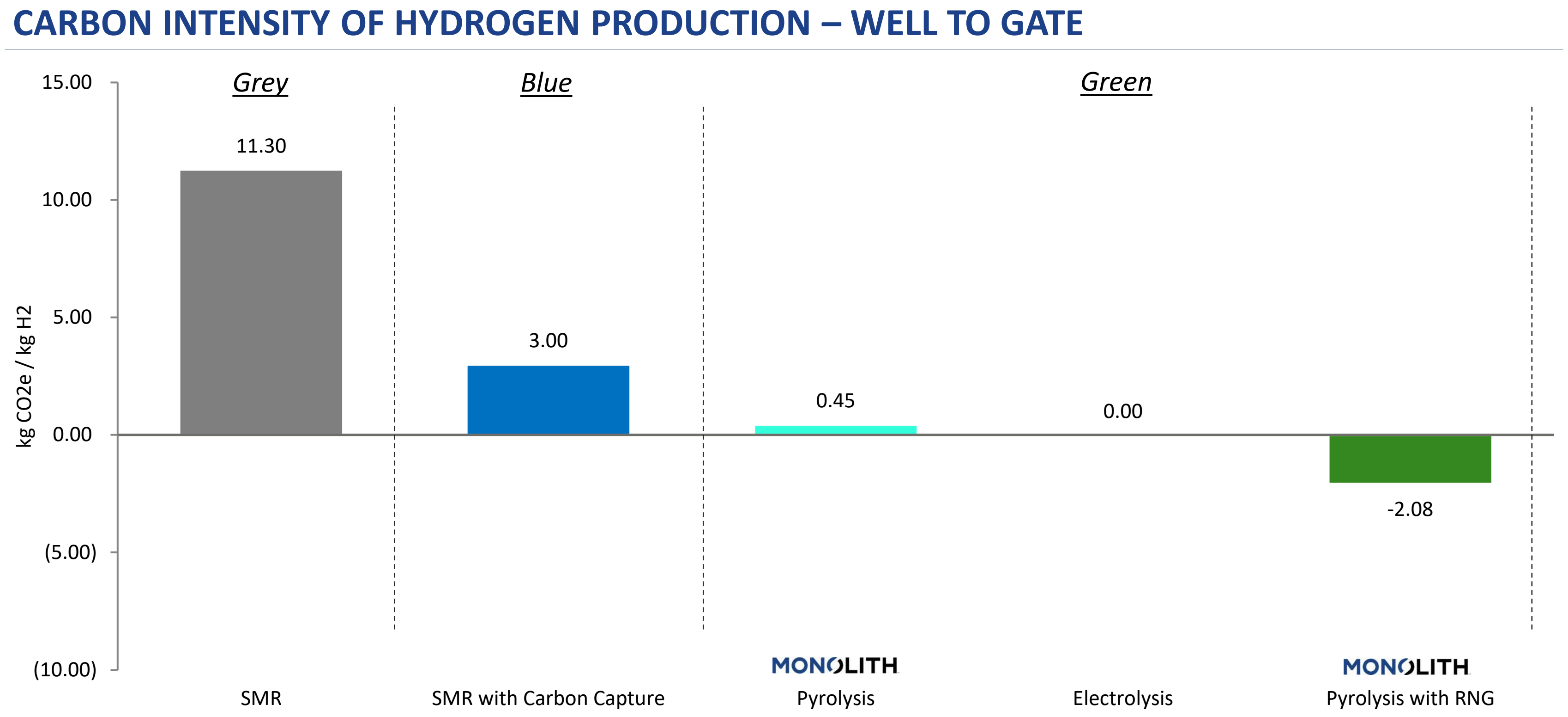


MONOLITH

Protected Methane Pyrolysis Technology

Monolith is the most sustainable and lowest-cost producer of hydrogen in the world, as its proprietary process unlocks significant value from high performance carbon products and its differentiated go-to-market strategy generates substantial cash flows under both existing and expanding markets

Carbon intensity comparison



Sources:

1. NREL Hydrogen Analysis (H2A) Production Models, Version 3.2108, Central SMR without CCUS
2. NREL Hydrogen Analysis (H2A) Production Models, Version 3.2108, Central SMR with CCUS
3. Based on third party study using GREET1_2020 and AR5 GWP (CO_2, N_20, CH_4)
4. NREL Hydrogen Analysis (H2A) Production Models, Version 3.2108, Central Electrolysis (Process emissions only)
5. Based on third party study using GREET1_2020 and AR5 GWP (CO_2, N_20, CH_4)

Notes:

1. Electrolysis and Pyrolysis assume 100% renewable electricity

MONOLITH

Commercial Scale

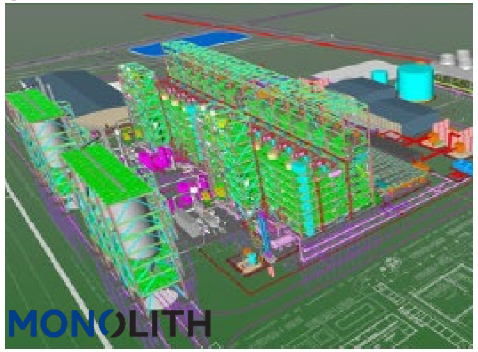
Stage 1: Development | **Stage 2: Commercial Launch** | ***Stage 3: Market Expansion***

2013	Monolith founded and IP acquired	*Monolith is founded in Palo Alto, California and builds its pilot plant in the San Francisco Bay area.*
2017	Technology proven (demonstration scale)	*Seaport pilot facility successfully demonstrates Monolith's core technology at demonstration scale over a 4-year R&D phase.*
2021	OC1 online Technology proven (commercial scale)	*OC1 facility is completed and successfully demonstrates Monolith's core technology at commercial scale.*
2024	OC2 online	*OC2 facility comes online as the largest methane pyrolysis plant in the world.*
2025+	Plant 3 online	*Monolith replicates existing technology to build operated and licensed future plants.*

Ongoing R&D at Monolith's laboratory in Lincoln, tech office in California, and pilot plant in France

Seaport, California
Commissioned: 2014

Olive Creek I (OC1), Nebraska
Commissioned: 2020



Olive Creek II (OC2), Nebraska
Commissioned: 2024 (planned)

Monolith is 8 years into a 15 year business plan to become the worlds leading clean hydrogen producer

Hydrogen’s Role in the Energy Transition

MONOLITH

Hydrogen's Diverse Set of Potential Use Cases

H_2

Fuel
- *Transportation*
- *Power*

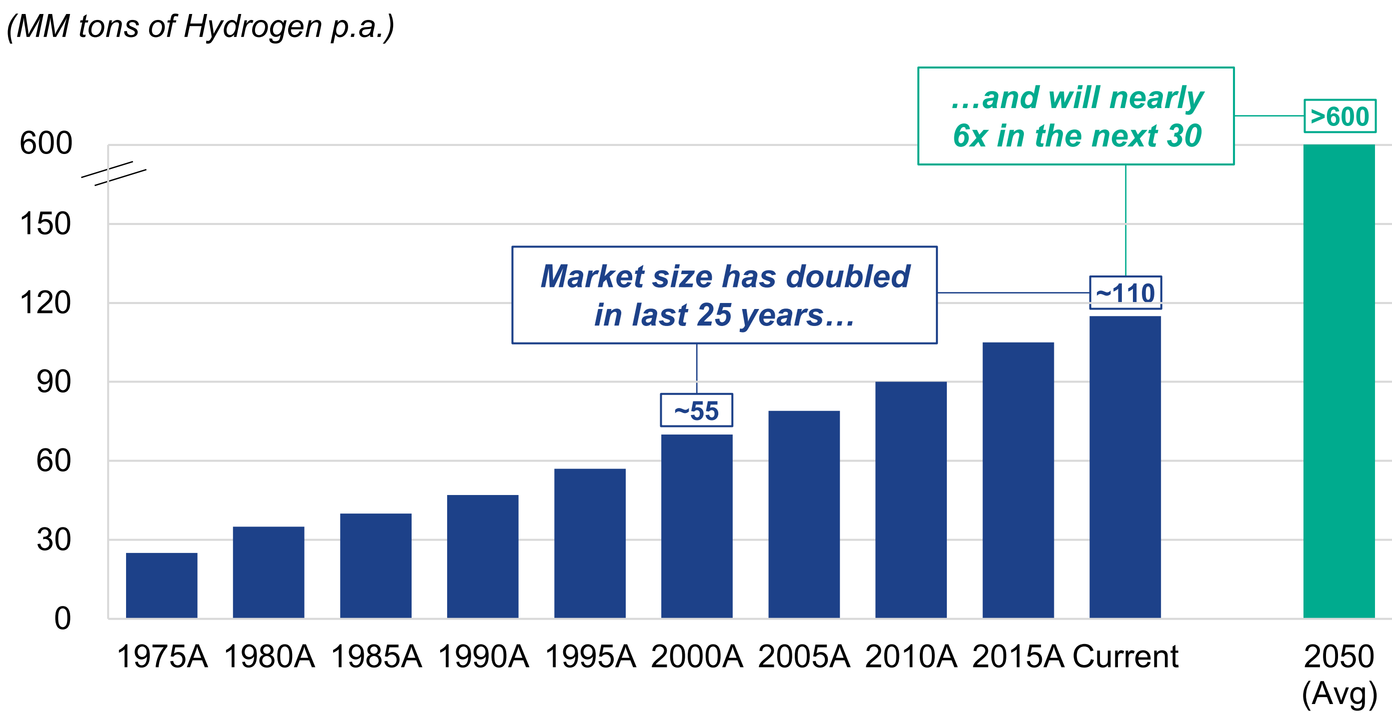
Heat
- *Industry*
- *Buildings*

Feedstock
- *Chemicals*
- *Materials*

Hydrogen is a $100+ billion market today and projected to reach $2.5+ trillion by 2050

Source: BNEF, Hydrogen Council, Grandview Research.

Hydrogen's Rapid Demand Growth Has Begun



With only 0.25% market share, Monolith can generate ~$1bn of plant-level EBITDA, without subsidies

"Being a clean-burning, zero emission source of energy, hydrogen appears an attractive way to decarbonize with many potential uses" – BAML, 2020

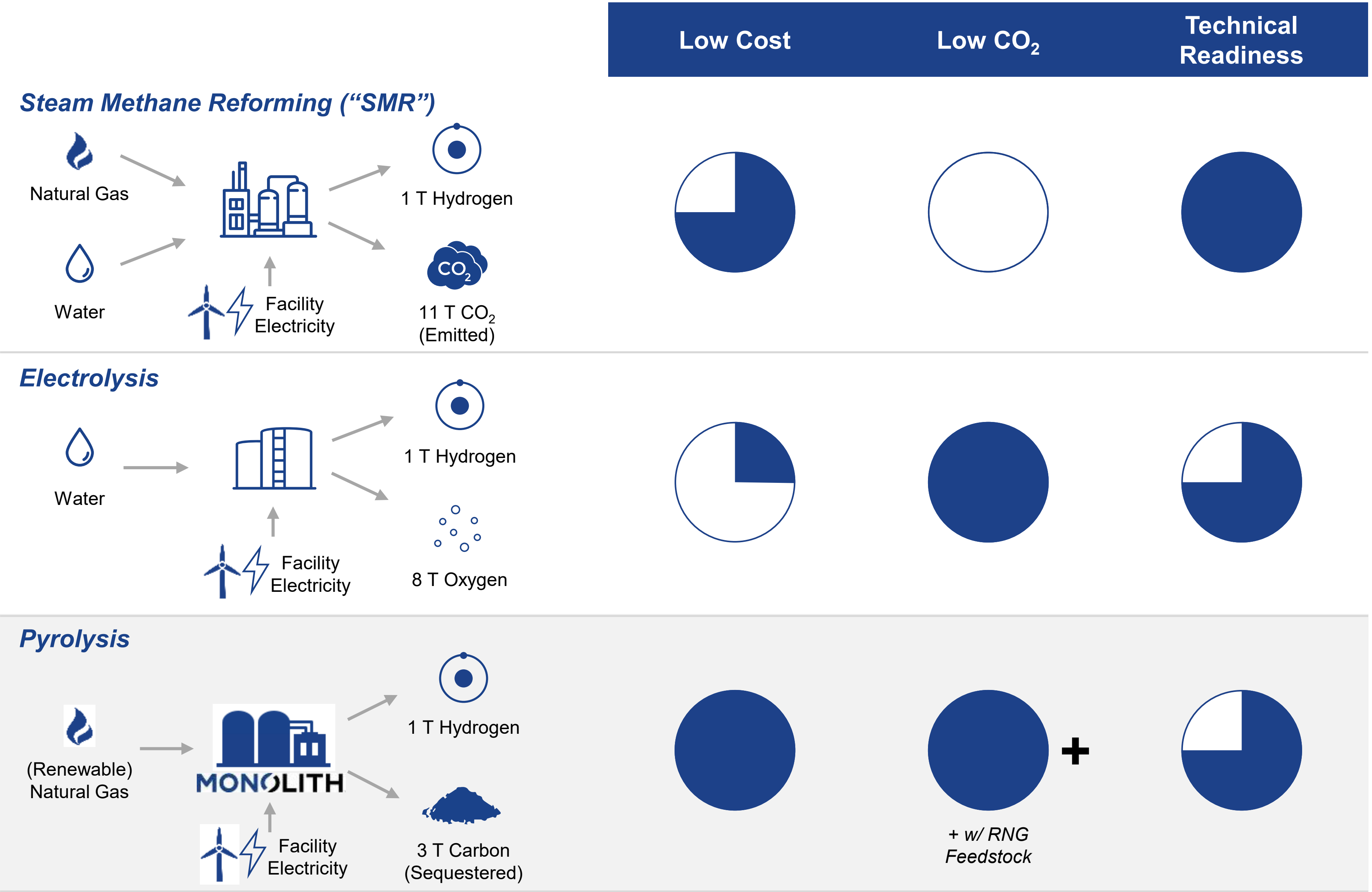
"We're really excited about hydrogen, in particular when we think about getting not to a net-zero emissions profile but actually to a zero-emissions carbon profile" – NextEra, 2020

"The time is right to tap into hydrogen's potential to play a key role in a clean, secure and affordable energy future" – EIA, 2019

Source: BAML, IEA, Hydrogen Council.

Monolith’s Hydrogen Advantage

Monolith is the Clear Leader in Hydrogen



Monolith’s Position of Leadership

Olive Creek Project

Olive Creek I Facility at Mechanical Completion

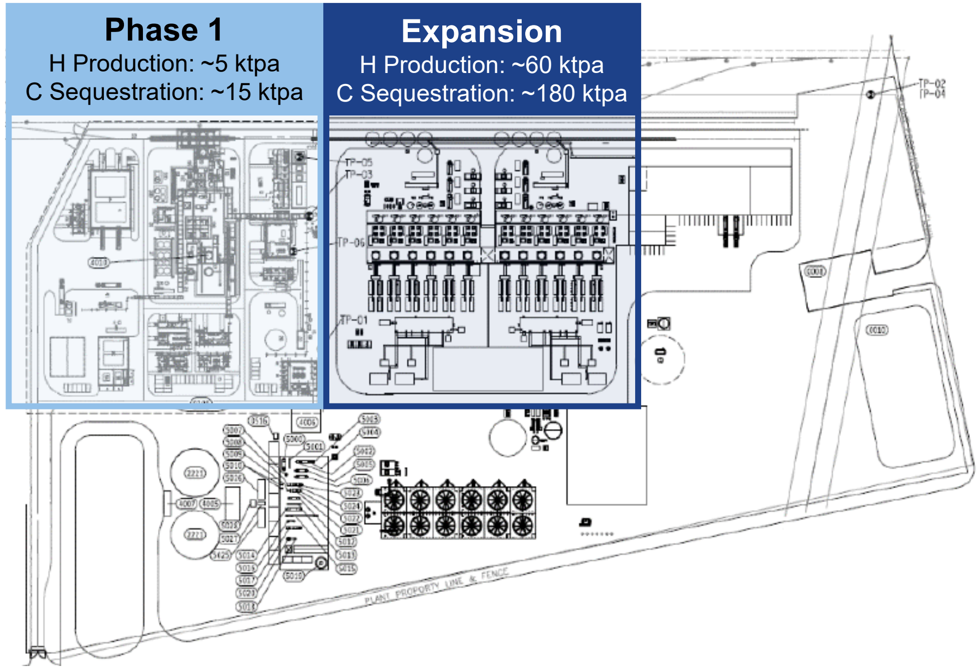
Olive Creek I (OC1) Facility	
Capacity	Hydrogen Production: ~5 ktpa Carbon Sequestration: ~15 ktpa
Completion	June 2020
Location	Nebraska, United States
Technology	Full commercial scale

The Olive Creek 1 Facility is the world's largest CO2-free hydrogen production plant and is the first commercial scale methane pyrolysis facility on the globe.

Olive Creek Project Overview

Preliminary Engineering Rendering for Expansion Pre-Feed

- Monolith is advancing a facility expansion on its existing Nebraska site with FID expected in late 2021
  - No technology scale-up is required



Technical Status

- Proven core technology
- FEED nearing completion
- Advancing lumpsum-turnkey EPC contract with Kiewit

Commercial Status

- No federal permit requirement
- 20+ year feedstock agreement
- Long-term low cost electricity agreement
- Advanced discussions with offtakers and hedging counterparties

Creates 100 direct and 550 indirect jobs, significantly reduces GHG emissions, and creates value for customers, governments, and local communities

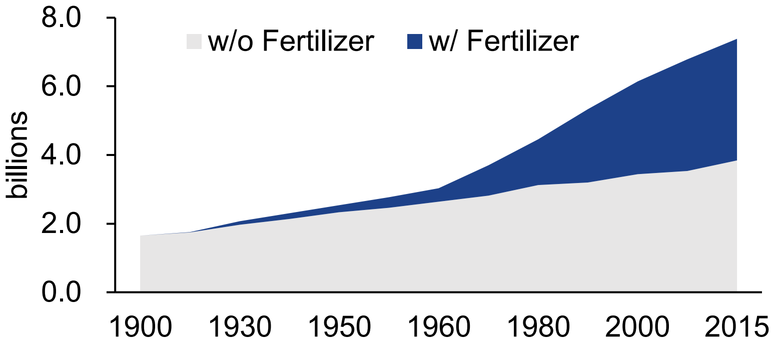
MONOLITH

Olive Creek End-Market: Clean Ammonia

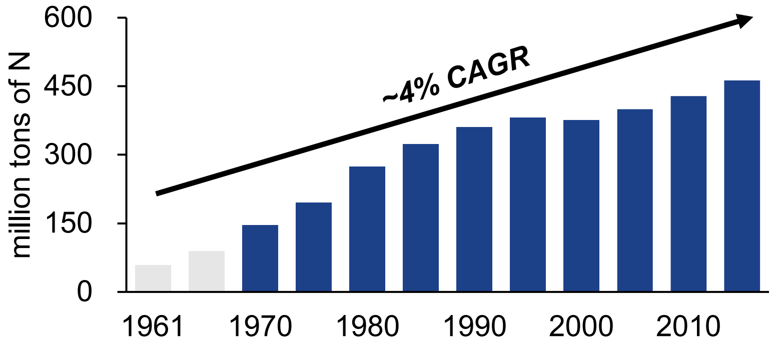
Sizable Market with Significant Decarbonization Opportunity

- The ammonia market is valued at **~$55bn** and is projected to grow to >$80bn by 2025 based on agriculture & other existing uses(1)
  - 80% of ammonia is currently used to create nitrogen-based fertilizers, which feed and support ~50% of the world's population(2)
- Ammonia production from the legacy SMR process generated ~500 million tons of CO_2 in 2018, over 1% of global emissions(3)
  - One of the "big four" industrial processes where decarbonization is critical in order to meet net-zero emissions targets(4)
- Monolith's methane pyrolysis process produces drop-in, clean ammonia which further increases the TAM by unlocking additional use cases (e.g. storage / transportation of hydrogen fuel due to its high energy density and significant infrastructure in-place)

Global Population Supported by Nitrogen Fertilizer(2)

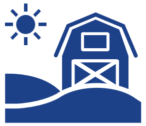


Global Nitrogen Fertilizer Production(2)

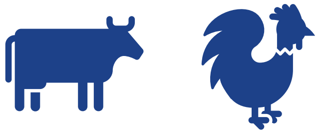


Select Demand Drivers

Population Rising from 7.4bn to 9.7bn in 2050



Scarce Arable Land w/o New Environmental Risks



Changing Dietary Patterns of Developing Economies

New Applications Driven by Innovation

1) Fior Markets, 2020.
2) Our World in Data.
3) The Royal Society, Ammonia: zero-carbon fertiliser, fuel and energy store, 2019.
4) McKinsey & Company. 2018 Decarbonization of Industrial Sectors: the next Frontier.

MONOLITH

Olive Creek End-Market: Clean Carbon Black

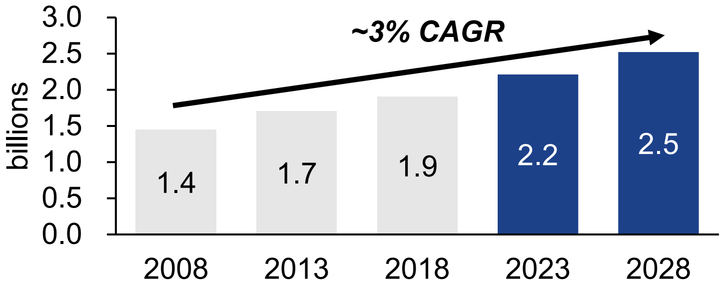
Sizable Market with Significant Decarbonization Opportunity

- Carbon black is among the top-50 industrial chemicals in the world
  - 100-year old commodity product w/ a **~$17bn** addressable market
  - Unique properties help reinforce and color rubber—1/3 of every tire is made of carbon black—and other everyday products
- Current production process requires the combustion of oil- or coal-based feedstocks, creating significant GHG and particulate emissions
  - Generated 3.5+ million tons of CO_2 emissions in the US (2018)
  - Incumbents face massive EPA-related fines and compliance costs
- Monolith's process produces drop-in, green carbon black with several technical and performance advantages relative to traditional products

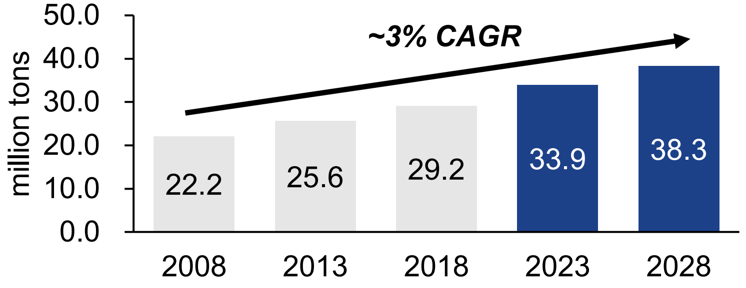
Market Breakdown by Application[1]

Tires	*Industrial Rubber*	*Specialty*
		
~$11 bn/year	~$4 bn/year	~$2 bn/year
~10 mT/year	~3 mT/year	~1 mT/year

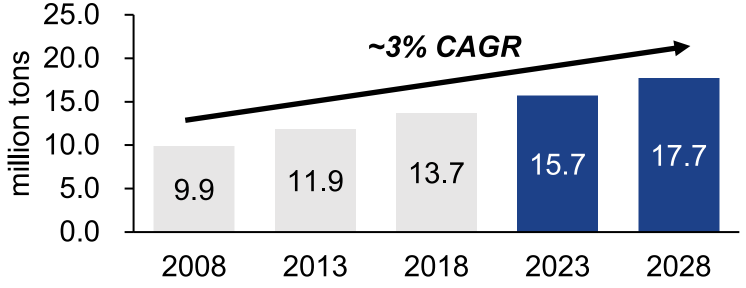
World Tire Production[1]



World Rubber Demand[1]



World Carbon Black Demand[1]



1) Notch Consulting

Thank You!