CHANGING WHAT'S POSSIBLE

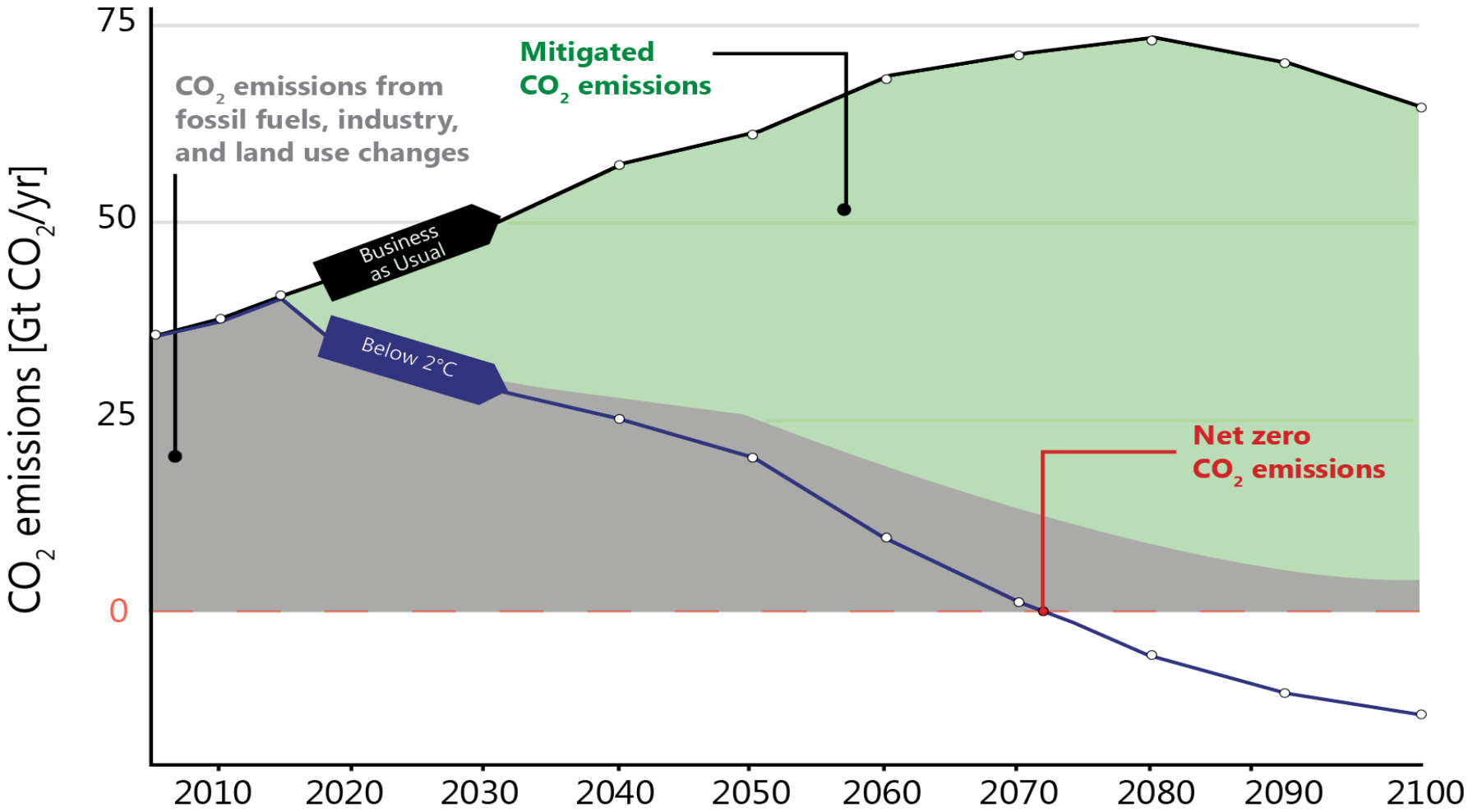
ARPA-E/DOE
Methane Pyrolysis Cohort Kickoff

Houston, TX
Dec. 9 & 10, 2019

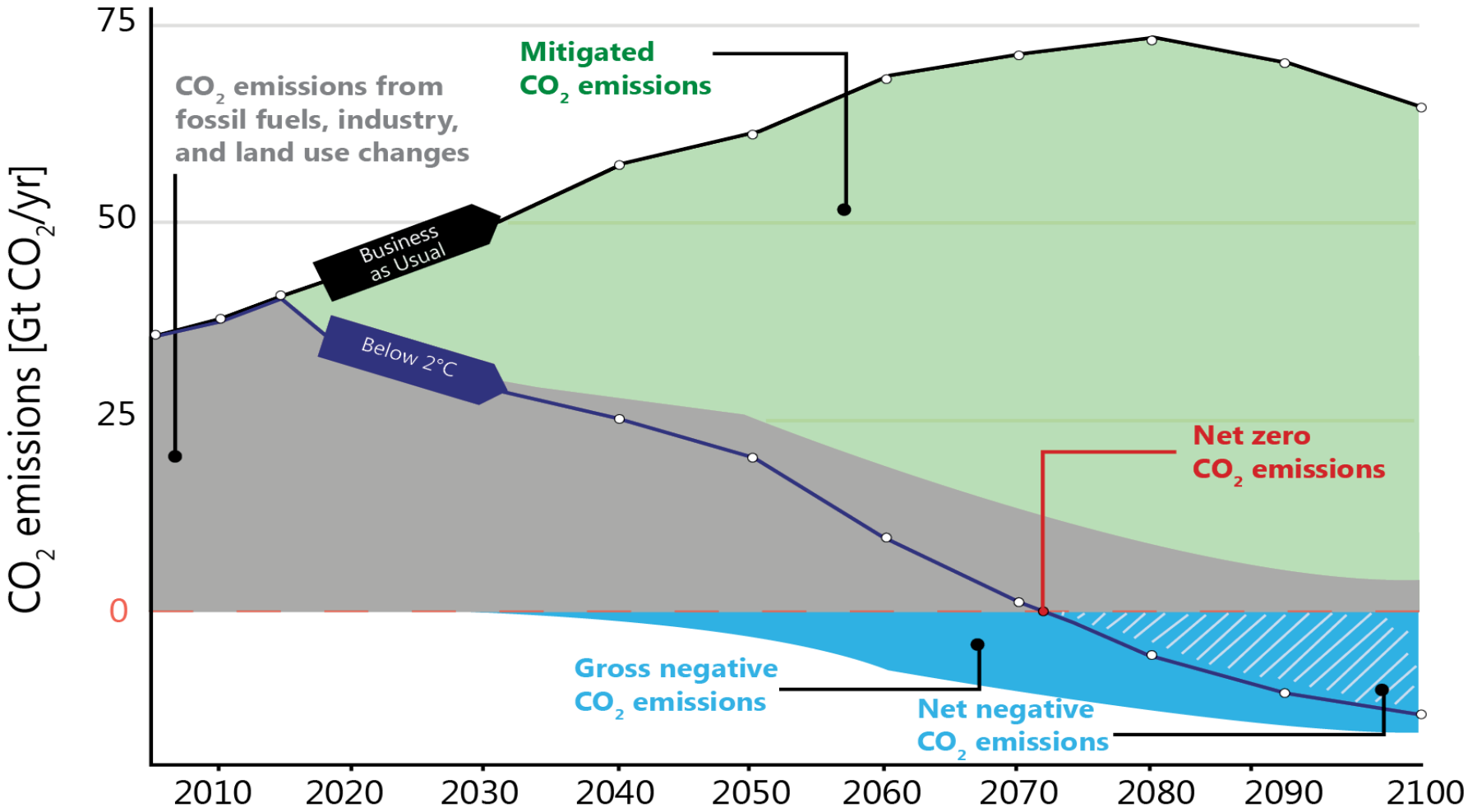
Why is ARPA-E Interested in Methane Pyrolysis?

Catalyze and support the development of transformational, high-impact energy and emissions technologies

Keeping the Temperature Rise Below 2^0C

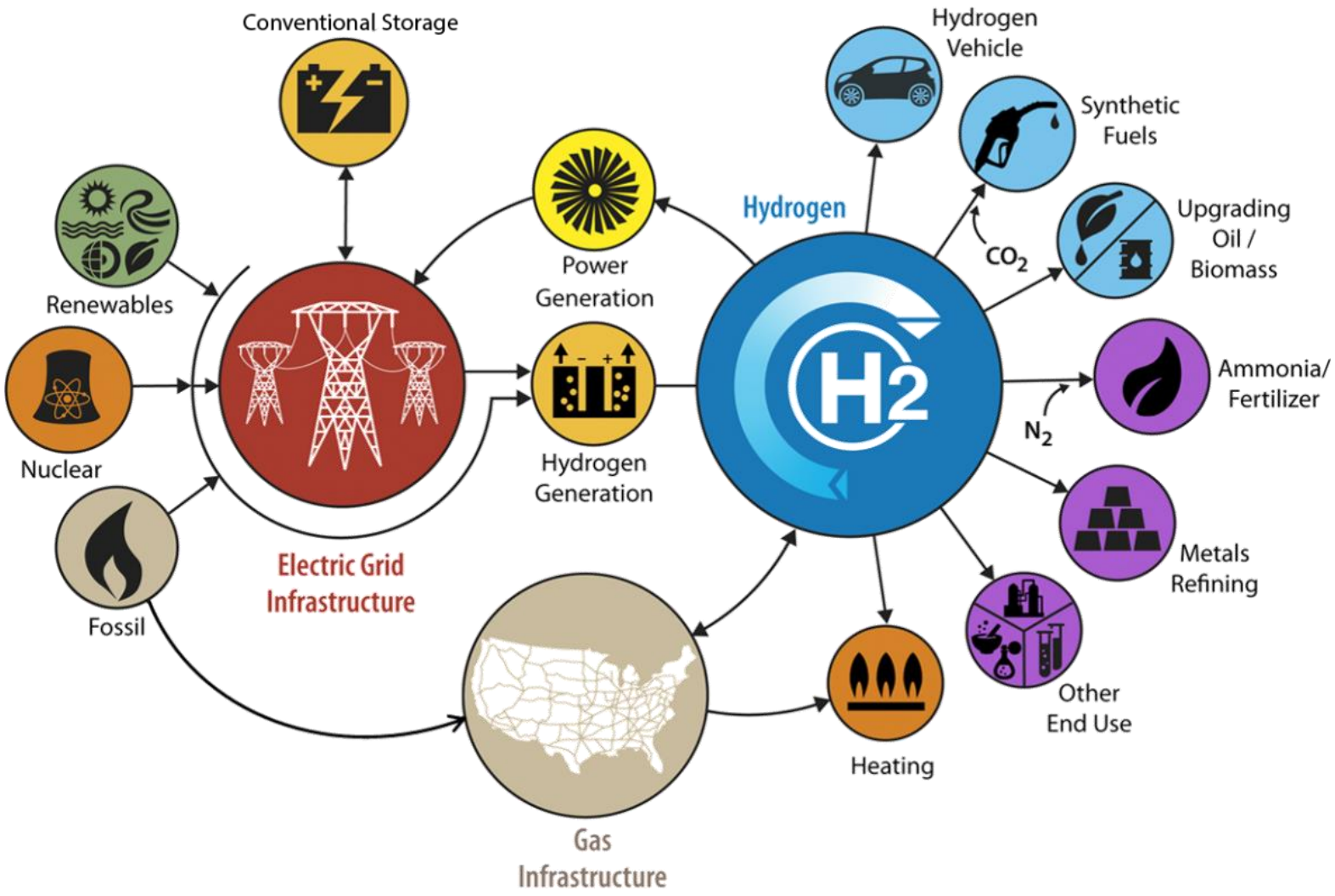


Keeping the Temperature Rise Below 2^0C




How can we best leverage U.S. gas wealth to transition to a low carbon economy?

The Hydrogen Economy as Potential Path

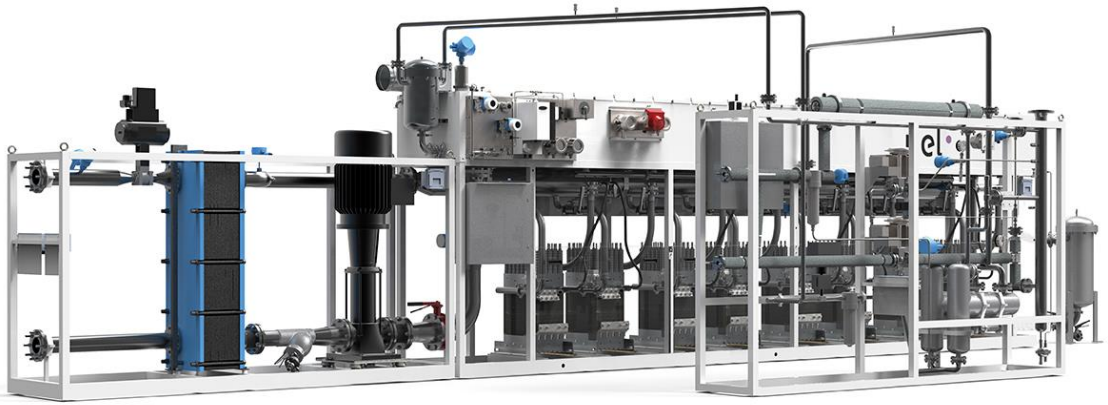


https://www.energy.gov/eere/fuelcells/h2scale

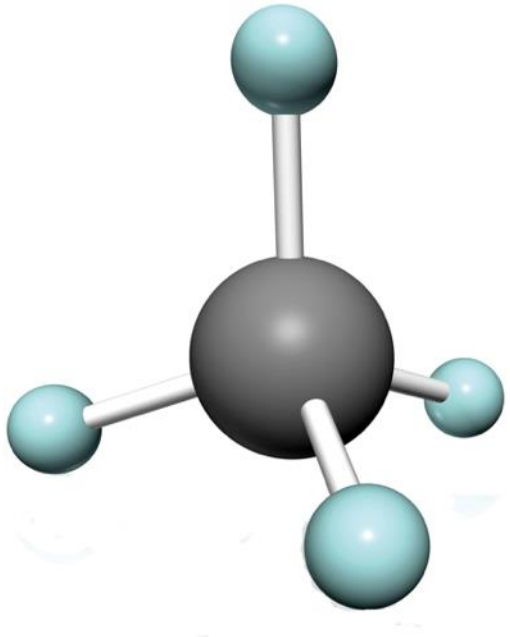
Need *Scalable*, *Low Cost*, *Low Carbon Intensity* H_2 generation

Gold Standard for carbon-free hydrogen generation:

- **Water electrolysis using renewable electricity**
- **Can be deployed in distributed fashion, minimizing transport**
- **However, water electrolysis is still very expensive:**
  - **~$4/kg H_2**
  - **Requires at least 33 kWh/kg**



Methane is also a hydrogen repository



CH_4

Hydrogen represents

¼ of the **weight**, but

½ of the **energy**

We already make hydrogen from methane at large scale for…

Ammonia Production (Haber-Bosch)

Petroleum Refining

GTL

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

Challenges: economical only at large scale & high CO_2 emissions

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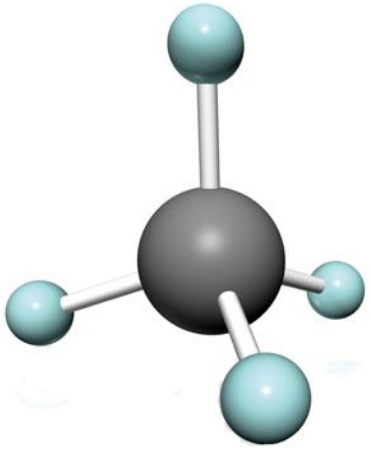
Alternative Approach: Thermal Cracking of Methane



750 - 1200°C

Gaseous hydrogen

+

Solid carbon

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

CO_2 vs Solid Carbon from 1 Quad of Hydrogen

SMR – CO_2

Image: pbs

70 million MT @1,200 psi
117 million m^3 (738 million barrels)

Methane Pyrolysis – Solid Carbon

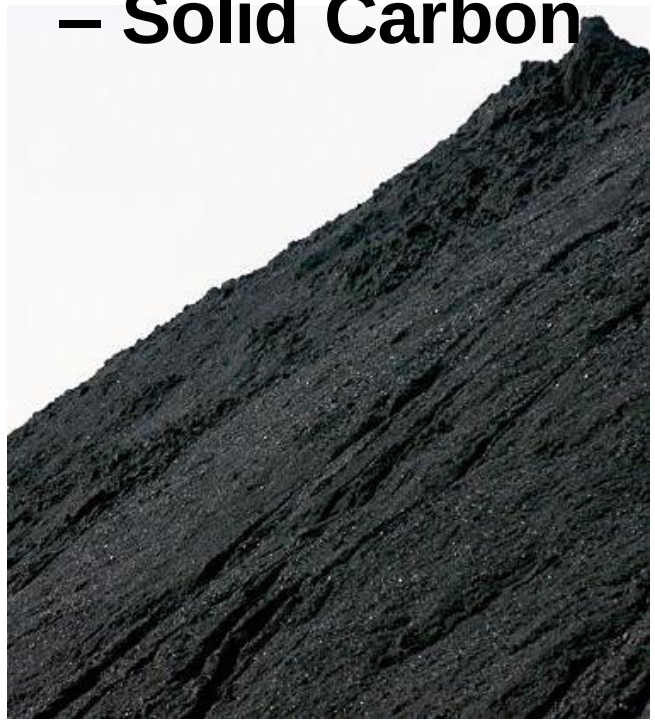


Image: dpa

>22.3 million MT
~ 45 million m^3

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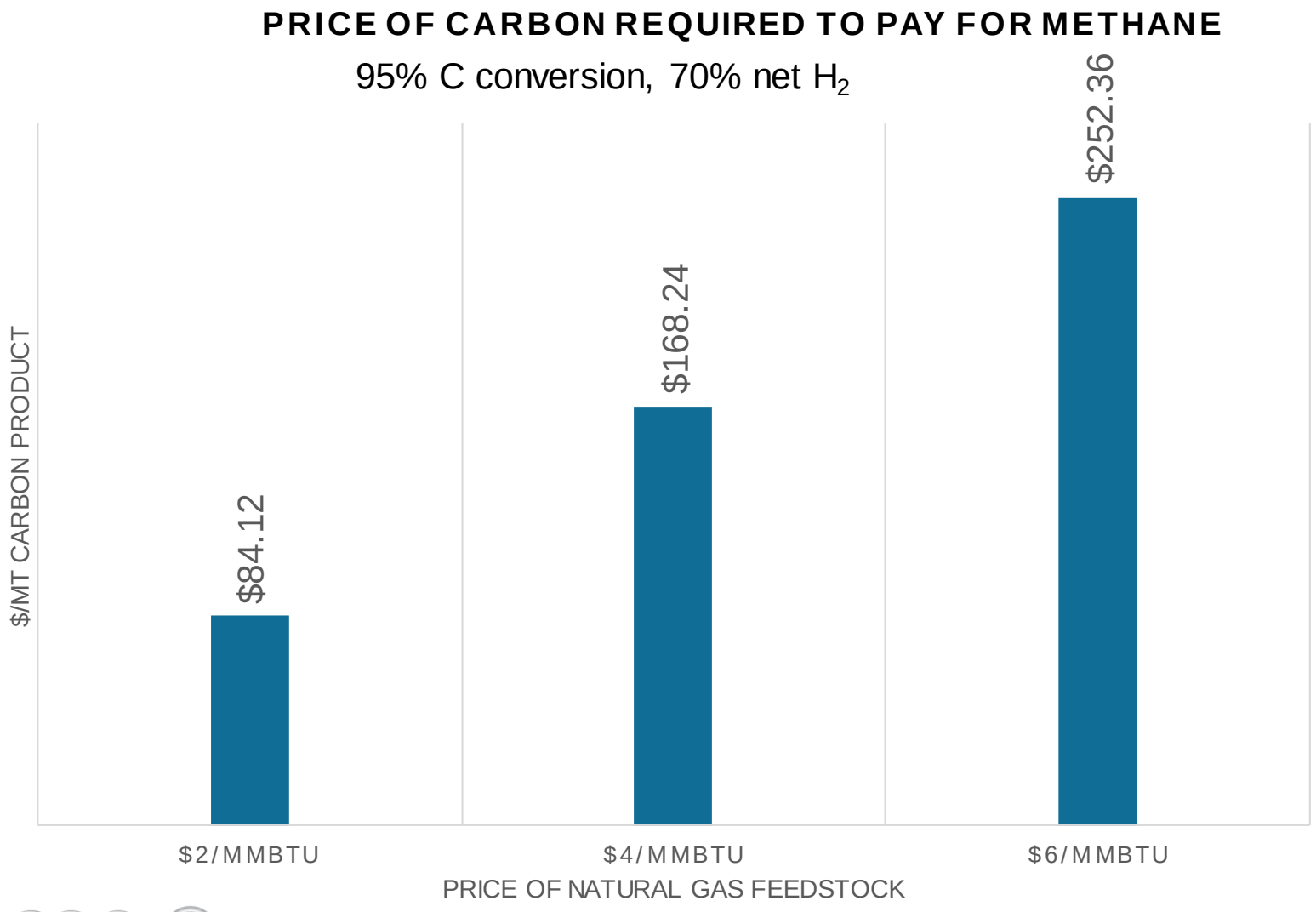
H_2 Generation.. Competitive Landscape

Process	Yield (mol H2 / mol CH4)	H2 Cost ($/kg)	C Intensity (g CO2/g H2)	Value of C/CO_2 ($/tonne)	H_2O required
SMR	4	~1-1.2	10	0	Yes
SMR + CCS	< 4	2	2	50 $/tonne$_{CO2}$	Yes
H_2O electrolysis	~ 60% energy efficient	4	0	N/A	Yes, significant
Methane pyrolysis	2	<1.5 $/kg (Target)	< 2	>100 $/tonne$_C$ (Target)	No

- ✓ **Methane pyrolysis..** a scalable option for low C intensity, low cost H_2 Generation
  - **Need**.. High volume market for C by-product

Value of Carbon Important to Pay for Extra Methane



Conversion efficiency is very important.

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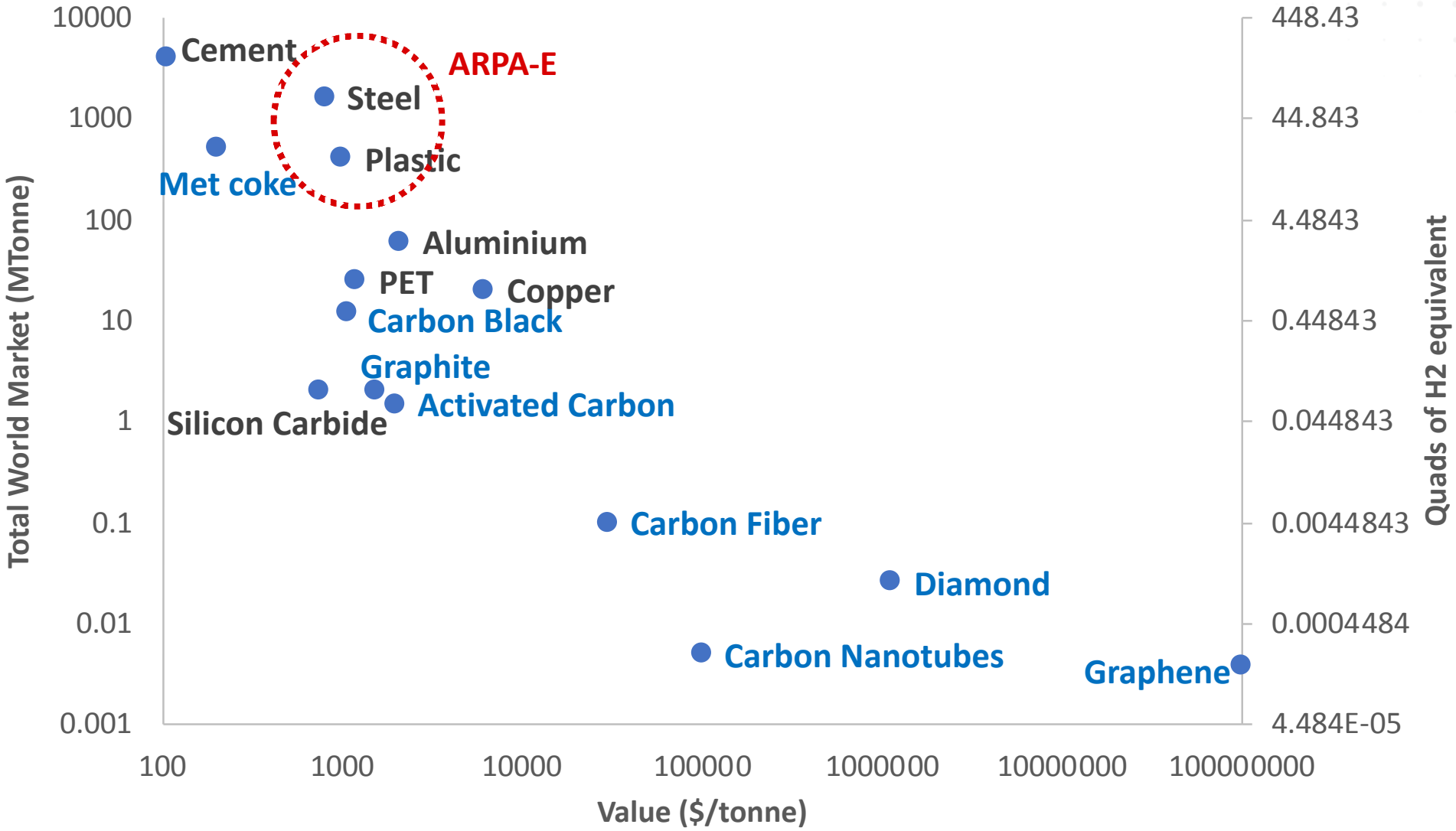
Which markets can absorb this volume of carbon?



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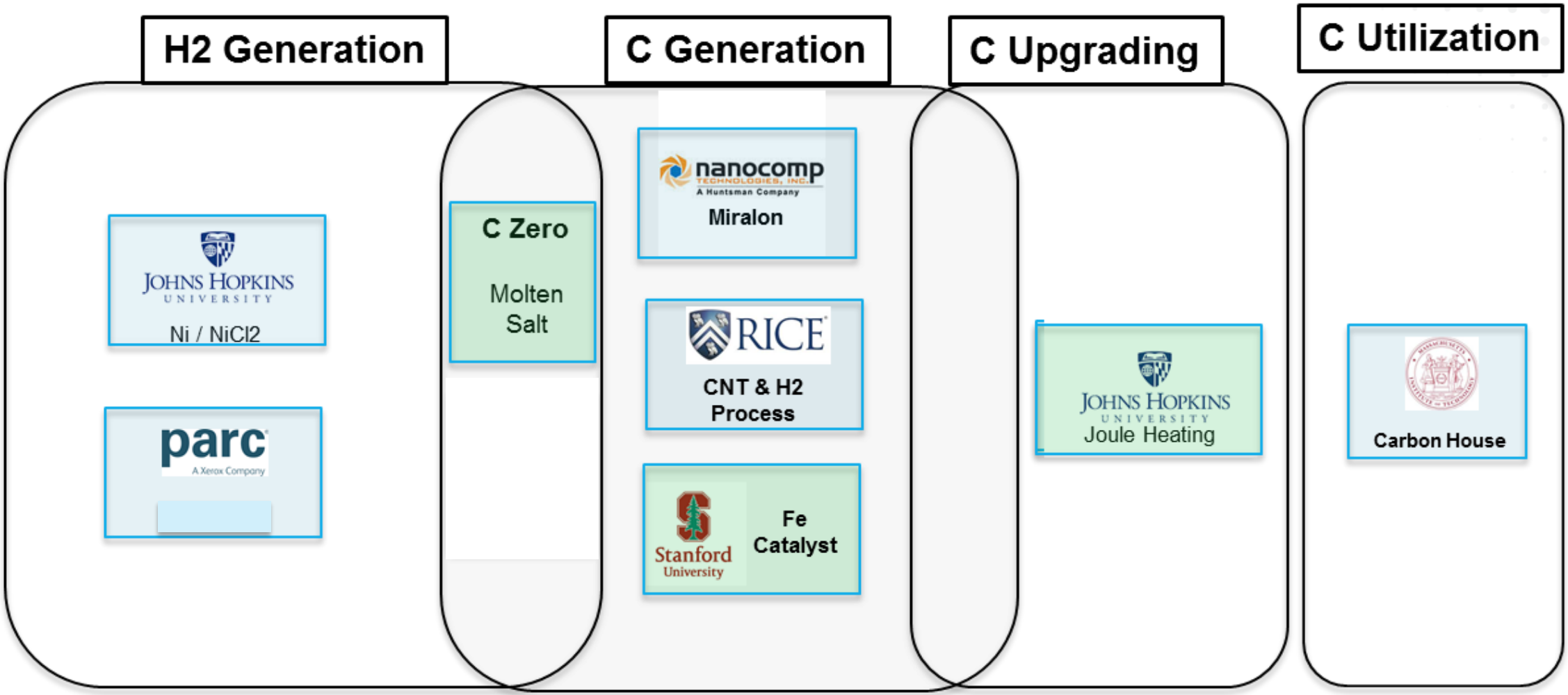
ARPA-E Methane Pyrolysis Time Line

- **Oct. 2016:** Idea for a methane pyrolysis program at ARPA-E seeded
- **Feb. 2017:** Methane Pyrolysis Fast Pitch at ARPA-E Summit
- **Sep. 2017:** Methane Pyrolysis Workshop in DC
- **Dec. 2017:** Release of OPEN 2018
- **Mar. 2018:** RFI on Carbon allotrope inter conversion
- **Dec. 2018:** OPEN 2018 Methane Cohort selection announced
- **May 2019:** Methane Pyrolysis TINA FOA released
- **Oct. 2019:** TINA FOA Selections announced
- **Dec. 2019:** Methane Pyrolysis Cohort Kick-off

Goals for this Methane Pyrolysis Kick-off

- Delineate opportunity space for methane pyrolysis and its products
- Accelerate learning and the move towards commercialization
- Clearly benchmark methane pyrolysis against incumbent and emerging technologies
- Foster development of a strong community of scientists, engineers, business, investors and government

Methane Pyrolysis Cohort.. 2018 OPEN & 2019 FOA



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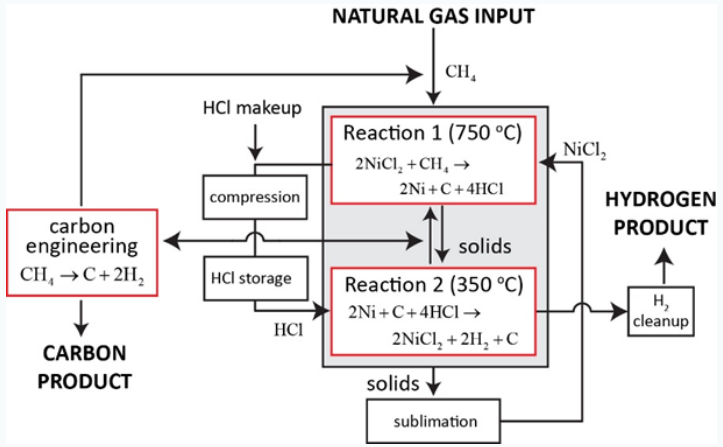
Teams.. H_2 Generation Focus

Ni / $NiCl_2$

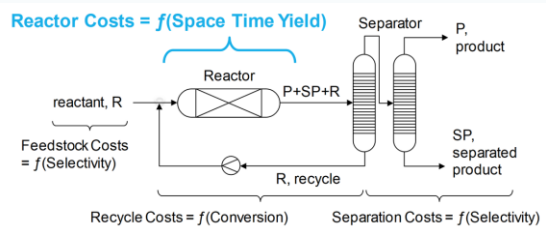


JOHNS HOPKINS UNIVERSITY

Molten Salts

C Zero

High Throughput Catalytic Process



parc
A Xerox Company

- **Catalyst activity..** Increase H2 yield @ high space velocity
- **Catalyst life**.. Reduce C deactivation
- **C product**.. Upgrade/lower metal contamination
- **Process**.. Scalable & High T / corrosion resistant alloys

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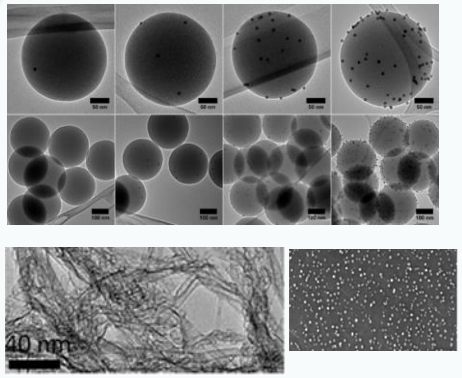
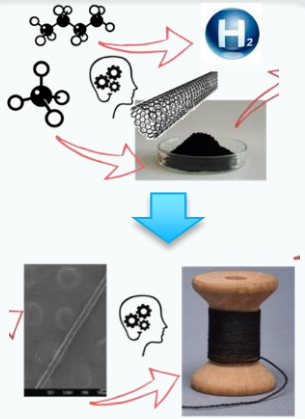
Teams.. Carbon Production & Upgrading Focus

CNT Heterogeneous Catalyst & Recyclability



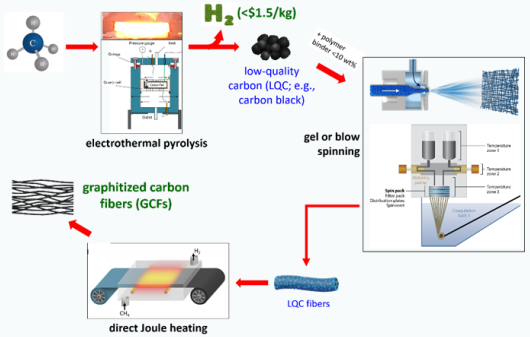
Stanford University

CNT Homogenous Catalyst & Fiber spinning Scale-up



RICE

Carbon Upgrading / Joule Heating



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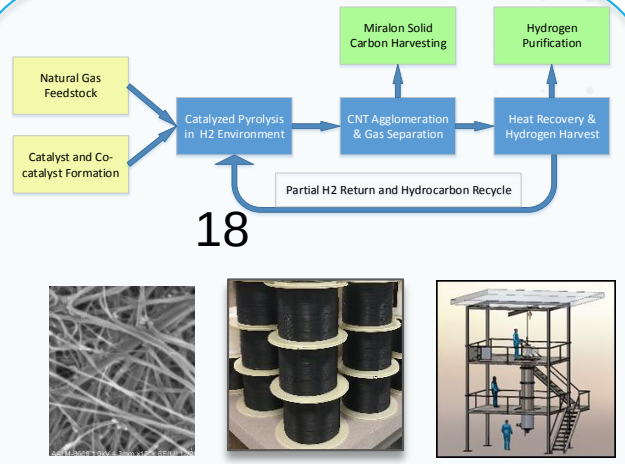
Miralon Scale-up / NG Feedstock



nanocomp TECHNOLOGIES, INC. A Huntsman Company

- **Feedstock**.. Improve activity with NG, with net positive H_2 yield
- **Catalyst recycle**.. Reduce metal contamination in C product
- **C product**.. Tailor properties for large volume markets
- **Process**.. Scalable

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What we are going to do for the rest of the day

1:05 PM	**H_2 Economy: Present status and future directions**	Uday Turuga (ADI Analytics)
1:35 PM	**Panel 1: H_2 Economy** Moderator: Greg Thiel (ARPA-E)	David Dankworth (Exxon Mobil) Joe Powell (Shell) Colin Alie (Suncor) Ron Kent (SoCalGas)
2:45 PM	**Coffee Break**	
3:00 PM	**Performers Presentations: H_2 Focus Programs**	Order of Presentation (10 min/presenter): (1) PARC (OPEN 2018) (2) JHU/ETCH (OPEN 2018) (3) CZero (TINA 2019) (4) CZero (H_2 @scale) (5) U of Colorado (H_2 @scale)
4:00 PM	**T2M Approach**	Madhav Acharya (T2M Advisor, ARPA-E)
4:20 PM	**H2A Model TEA**	Michael Penev (NREL)
4:50 PM	**Day 1 Wrap-up**	Marc von Keitz (ARPA-E)
5:00 PM	**Poster Set-up**	
5:20 PM	**Poster Session**	Performers, NREL, Carbon Hub

Kick-off Meeting: Day 2

7:30 AM	**Registration & Continental Breakfast**	
8:00 AM	**Welcome - Day 2**	Marc von Keitz (ARPA-E)
8: 05 AM	**Panel 3: Challenges moving Methane Pyrolysis to Scale** **Moderator: Dan Hancu (ARPA-E)**	William Daloz (BASF) Brian Chambers (Shell)
9:05 AM	**Production of carbon and hydrogen from natural gas via catalytic pyrolysis**	Ranjani Siriwardane (NETL)
9:20 AM	**Tri-generation Pyrolysis**	Gary Schubak (Ekona Power)
9:35	**Carbon House**	Mark Goulthorpe (MIT)
10:05 AM	**Coffee Break**	
10:25 AM	**Panel 3: Carbon Markets** **Moderator: Zara L'Heureux (ARPA-E)**	David Matheu (CABOT), Marie Contou (Carbon Hub) David Hatrick (Huntsman)
11:25 PM	**Performers Presentations:** **Carbon Focus Programs**	Order of Presentation (10 min/presenter): (1) Rice (OPEN 2018) (2) Stanford (TINA 2019) (3) Nanocomp (OPEN 2018) (4) JHU (TINA 2019) (5) MIT (OPEN 2018)
12:15 PM	**Lunch**	
1:30 PM	**Panel 4: Investors and Start-up** **Moderator: Madhav Acharya (ARPA-E)**	Jana Hanova (Evok Innovations) Ganesh Kailasan (OGCI) Tom Griffin (Breakthrough Energy)
2:30 PM	**Panel 5: Government Agencies** **Moderator: Marc von Keitz (ARPA-E)**	Jared Ciferno (FE) Eric Miller (EERE) Emilie Sioch (NASA)
3:30 PM	**Concluding remarks**	Marc von Keitz (ARPA-E)
3:45 PM	**End of Meeting**	

Let’s get started!