Integrating CO_2 Utilization into a Full System: Exciting Opportunities for New Innovation

— opus 12

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Founding Team: leaders in CO_2 electrochemistry

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Stanford Forbes 30 UNDER 30

U.S. DEPARTMENT OF ENERGY · NASA · NSF · cyclotronroad · DCVC

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CO_2 Electrochemical Conversion into chemicals and fuels

1

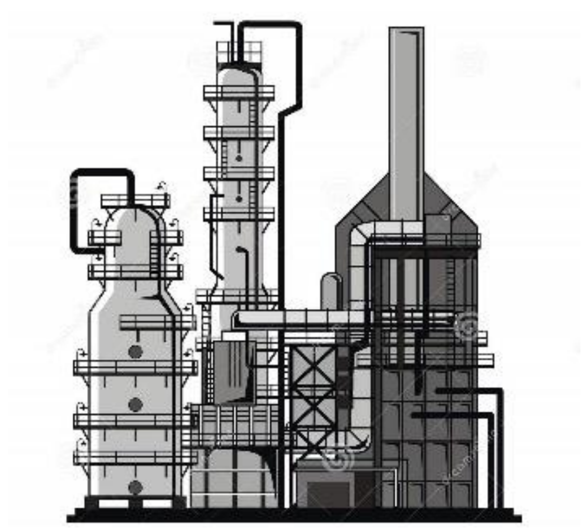
INPUTS: CO_2, WATER, ELECTRICITY

2

ELECTROCHEMICAL REDUCTION OF CO_2

3

OUTPUTS: PRODUCTS THAT DROP INTO EXISTING SUPPLY CHAINS



CO_2

H_2O

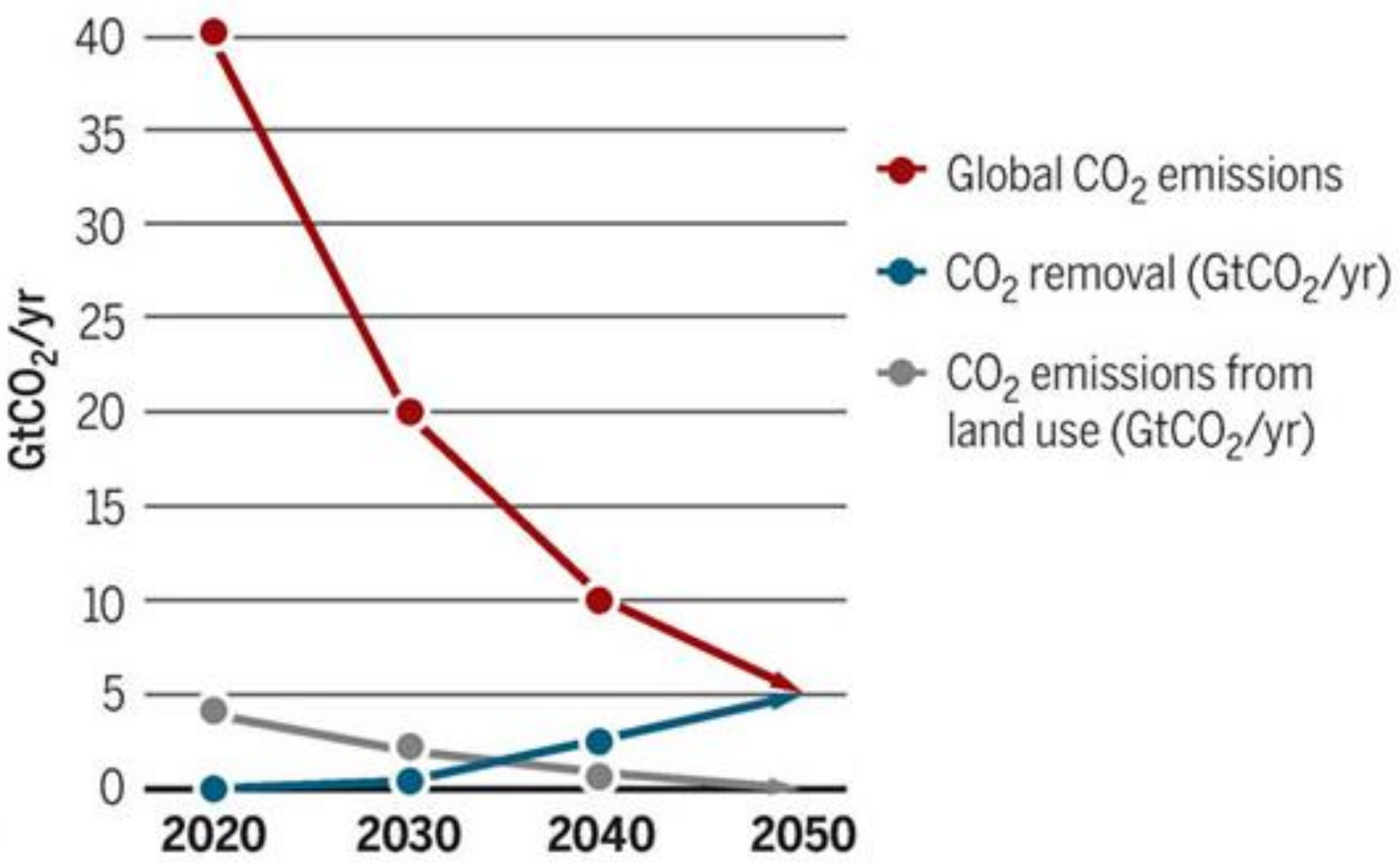
Electricity

Fuels & Chemicals

O_2

Global carbon law: Halving Emissions every decade

- To meet the Paris goal a Global Carbon Law would need to be in effect where ½ of the global emissions are cut each decade.
- In addition, there would be a double of CO_2 removal starting in 2030.



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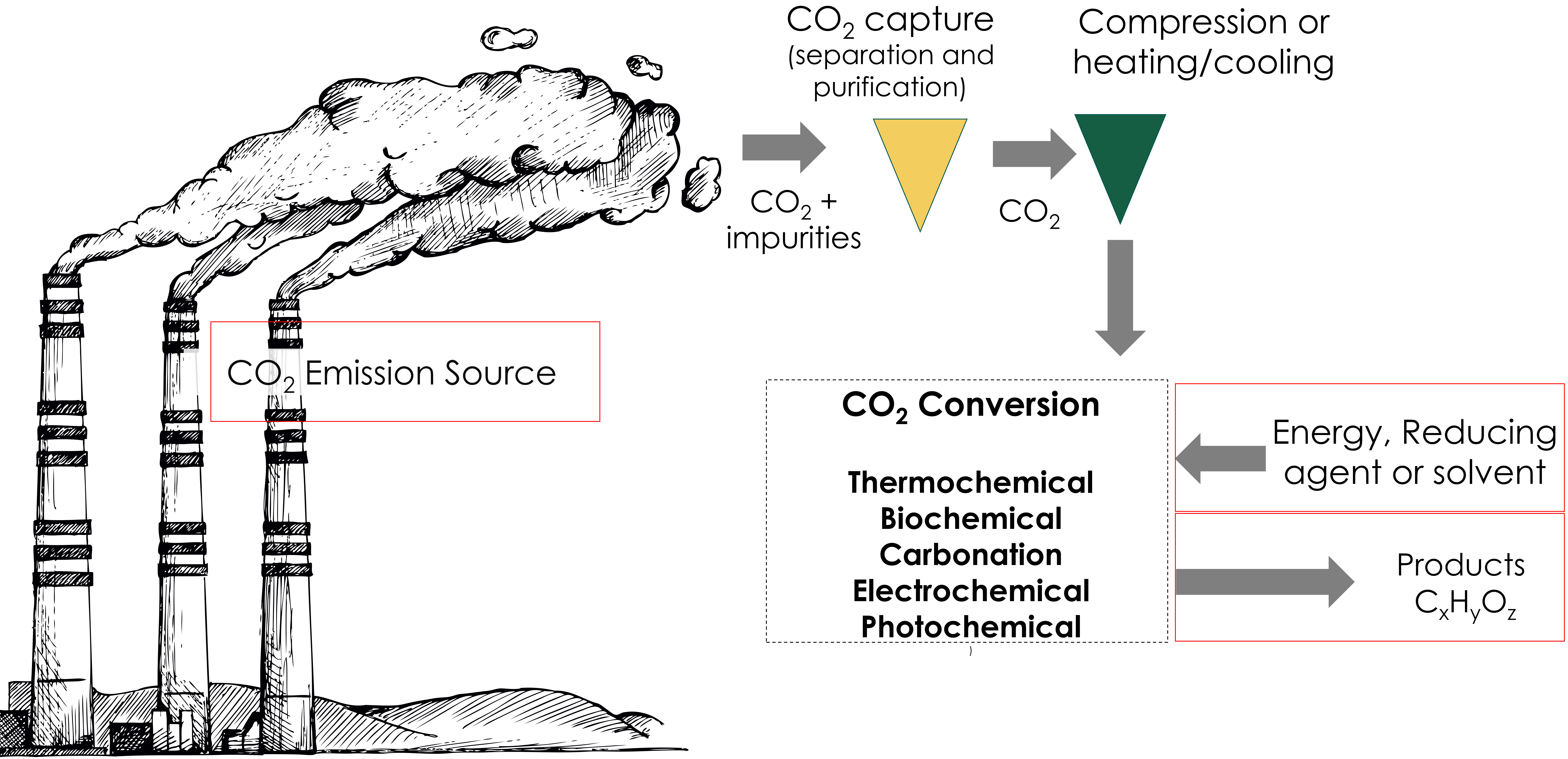
Why CO_2 Utilization?

Transforming global CO_2 emissions

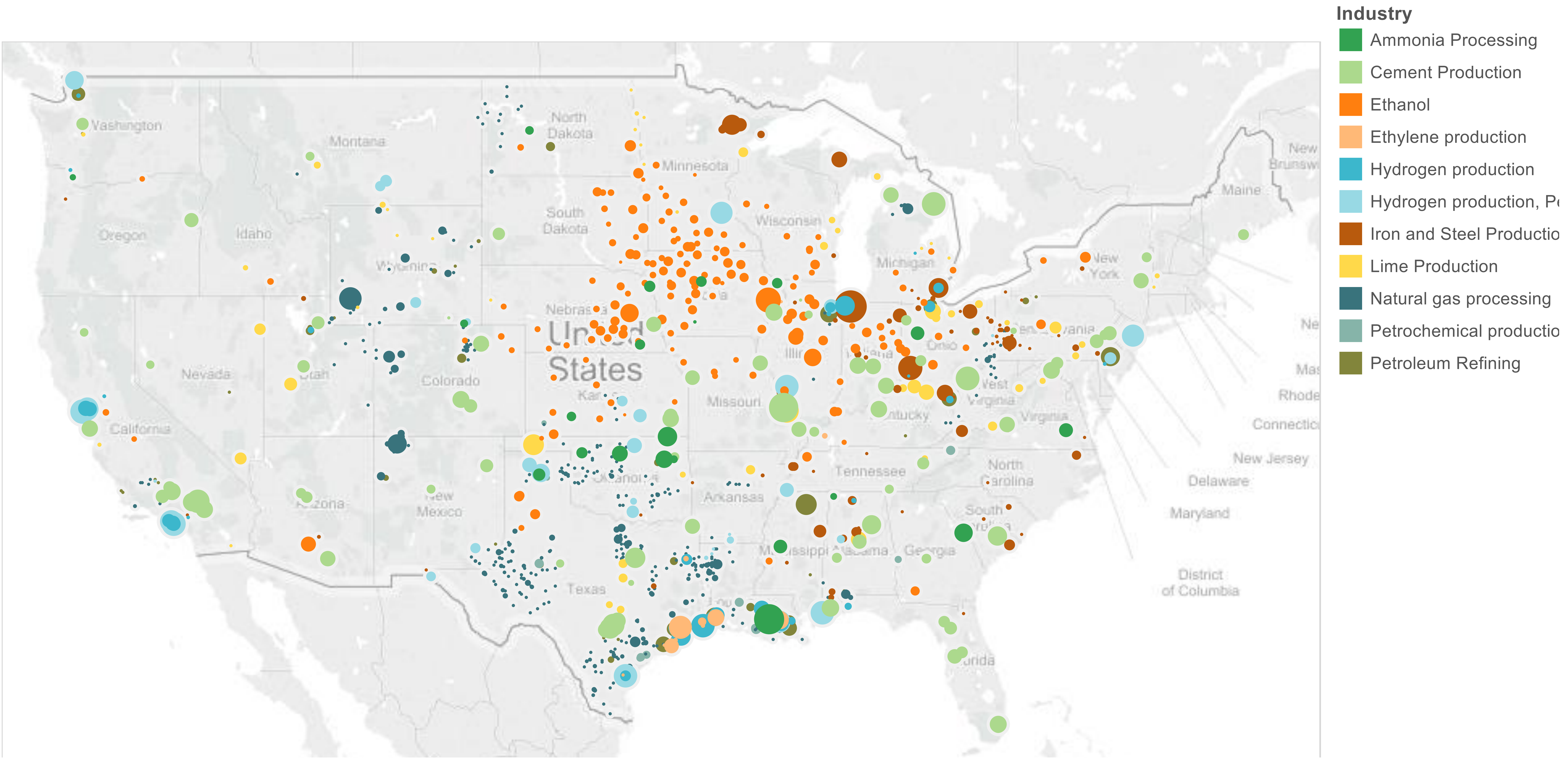
…into a multi billion dollar opportunity

Overall System Requirements



Tri-location Challenge: Identifying the existing lower hanging fruit thru Mapping

- **Challenge:** How to find the lower hanging fruit of CO_2 management where all three requirements exist?
- **Opportunity:** Mapping to identify the co-location of CO_2 emissions, surplus heat, electricity or reducing agents.



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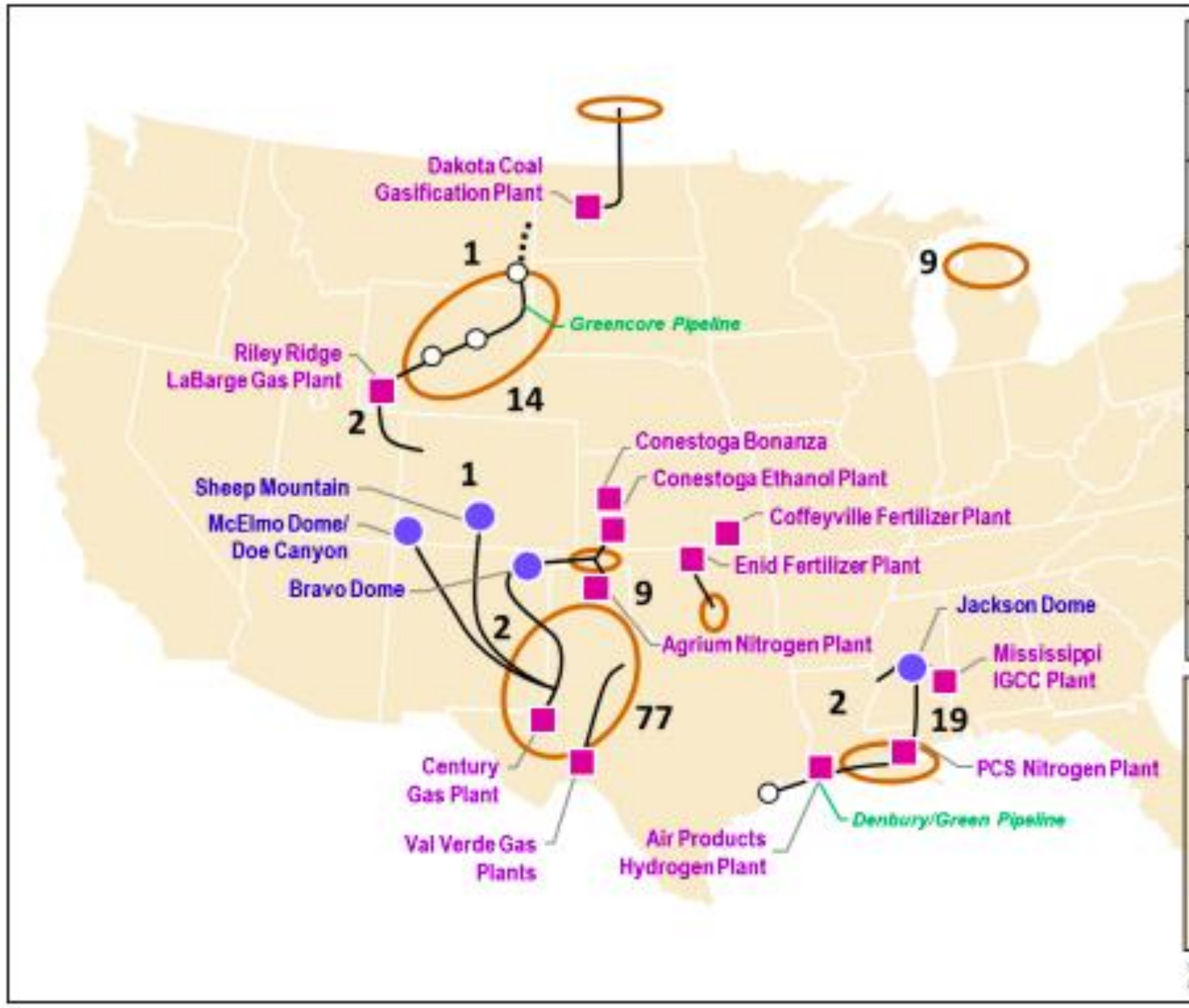
CO_2 Pipeline: Decouple the Tri-location Challenge



Oil Production (2014)	
CO_2-EOR Projects	136
Oil Production (MBbl/d)	300
CO_2 Supplies (2014)	
Number of Sources	17
• *Natural*	5
• *Industrial*	12
CO_2 Supply (Bcf/d)	3.5
• *Natural*	2.8
• *Industrial*	0.7

Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2014 and industry sources.

- **Current Pipeline:** Consisting of 50 individual CO_2 pipelines and with a combined length over 4,500 miles.
- **CO_2 Pipeline Expansion opportunities:** How to sync federal, state, and local permitting processes? How to establish tariffs, grant access, administer eminent domain authority, and facilitate corridor planning.
- **Opportunities:** Pipeline optimization and placement.

New construction technology to reduce infrastructure cost.

Wallace, M.; Goudarzi, L.; Callahan, K.; Wallace, R. *A Review of the CO2 Pipeline Infrastructure in the U.S.*; National Energy Technology Laboratory: 2015.

Surplus Electricity: Decouple the Tri-location Challenge

Challenge: Given the absence of a CO_2 pipeline, how to best decouple the electricity.

Opportunity: Power Purchase Agreement (PPA) to capture low cost surplus electricity and decouple locations.

Is there a "PPA"-type contract that can be created for hydrogen? Could hydrogen be added to existing pipelines? Could rural areas become digital farming locations to generate hydrogen?

LCAs and TEAs: TurnKey Solutions for end-users

Challenge: How to create the right solution for a particular industry or end-user. Installers care about the LCA. How to increase policy driven implementations.

Opportunity: Process intensification to allow for smaller units to capture CO_2 emissions. Use CO_2 to match the need for the product and have modular solutions.

CO_2 Capture Components

Challenge: low TRL of capture and other use technologies.

Opportunity: Create an ecosystem around CO_2 utilization to increase the TRL of all components

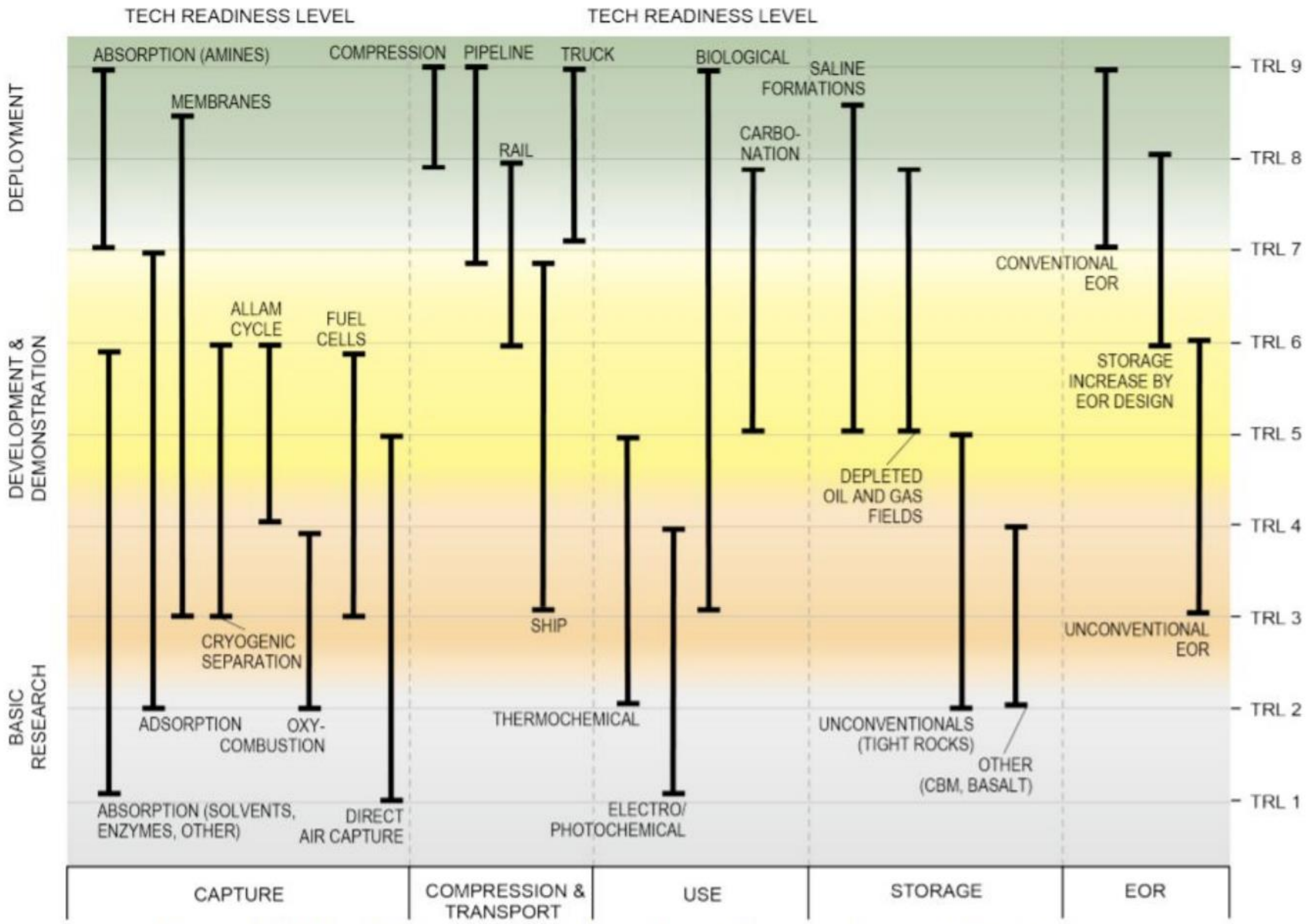
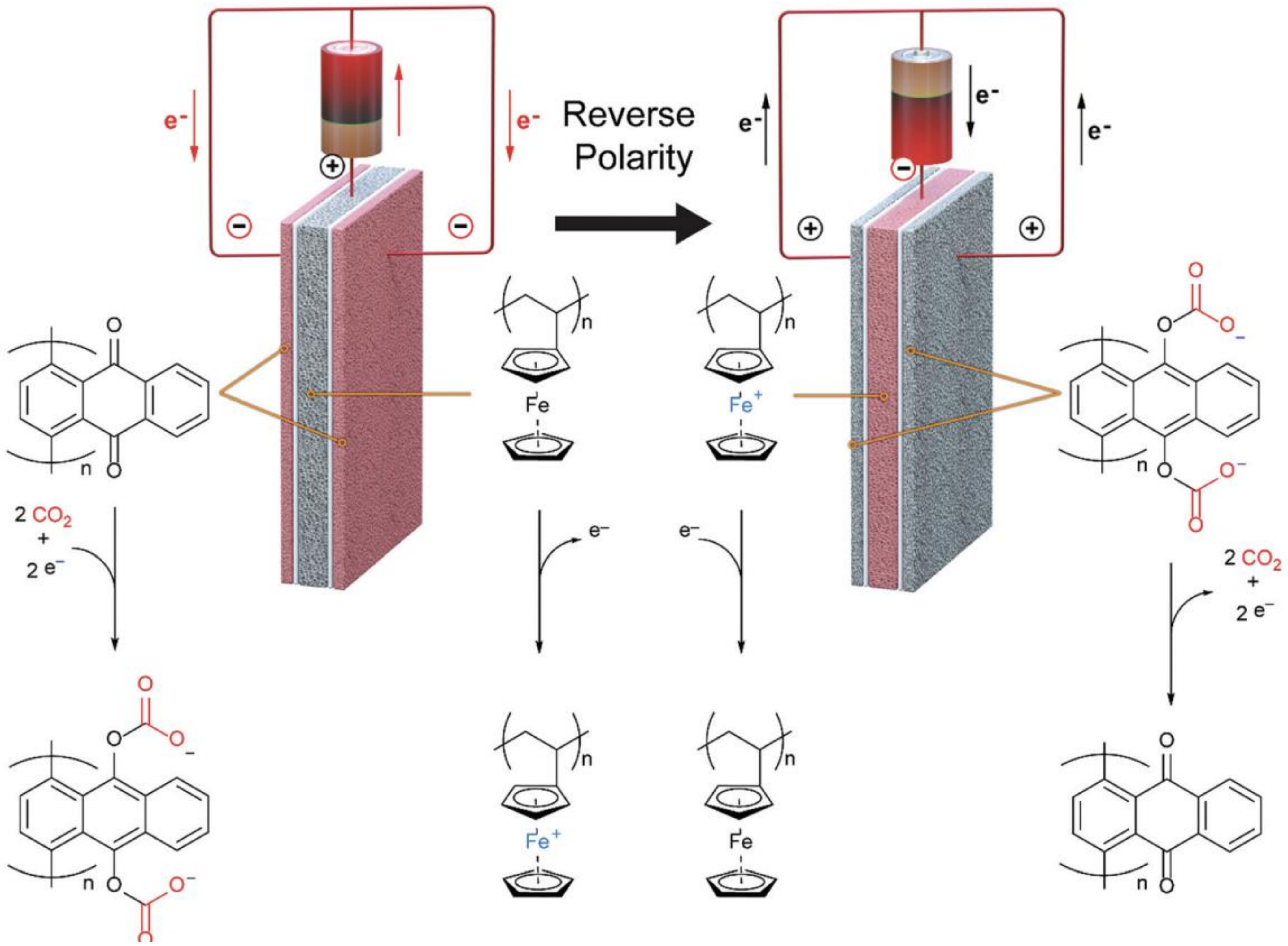


Figure ES-18. *Technology Readiness Level Ranges for CCUS Technologies*

Petroleum Council: Meeting the Dual Challenge A Roadmap to At-Scale
ıent of Carbon Capture, Use, and Storage

Capture + CO_2 Use combined?



Schematic of a single electro-swing adsorption electrochemical cell with porous electrodes and electrolyte separators.

- Electro-swing adsorption for capture with paired with electrochemical conversion.
- **Opportunity:** Could reduce capex of a turn-key system
- **Challenges:** Stability of the materials, especially in the presence of water vapor and air? Economics of system at scale; can the system have a high power density?

Voskian, S.; Hatton, T. A., Faradaic electro-swing reactive adsorption for CO2 capture. *Energy & Environmental Science* **2019,** *12*, 3530-3547.

Explore the Effect of Impurities

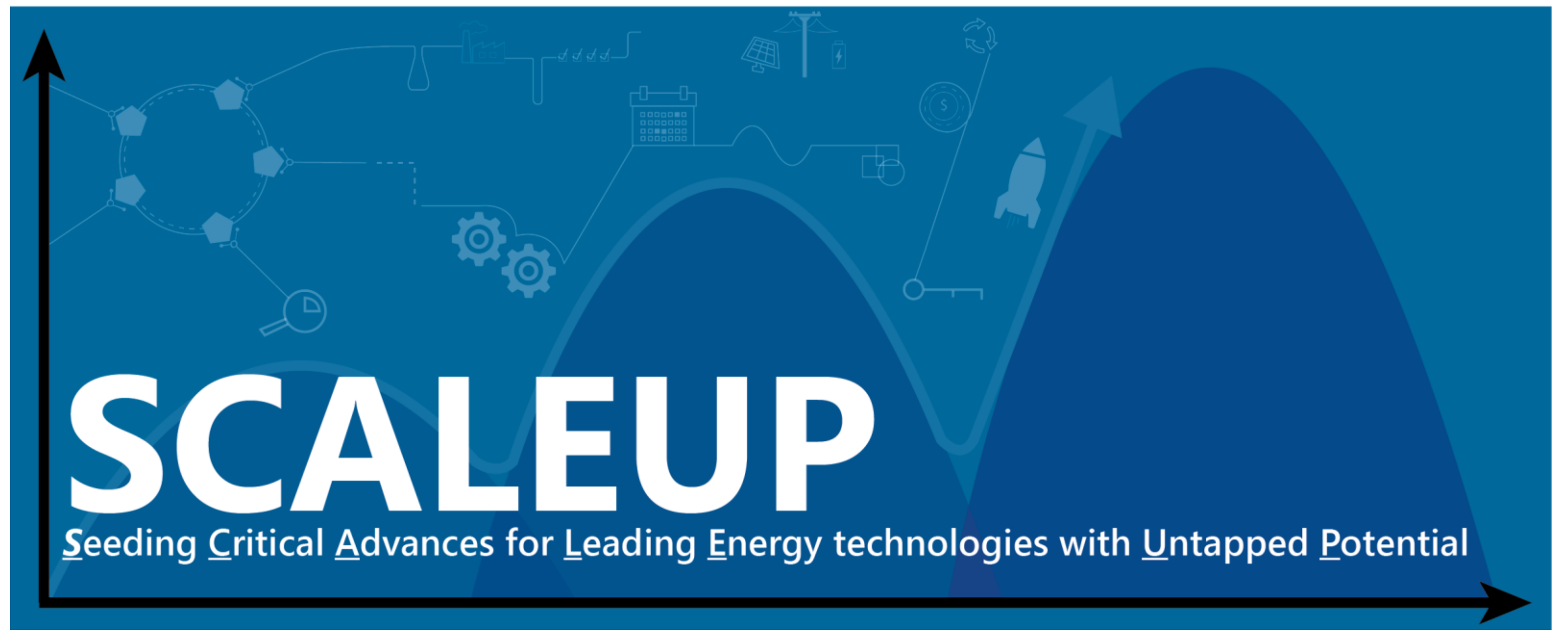
- **Challenge:** Often CO_2 waste streams carry impurities. Individual components can be susceptibility to parasitic, irreversible reactions with other species in the flue gas.
- **Opportunity:** Understand how the quality of the CO_2 stream could affect different CO_2 processes. i.e. sulfur impurities, No_x, alcohols, ammonia (from Amine capture), mercury, and particulates.
- Understand the cost of installing additional scrubbers to enable CO_2 capture across many streams.
- Develop emerging continuous stream scrubbers i.e. pulsed electron beams or shockwaves

New Federal Scale up Funds: Phase III 1M+

U.S. DEPARTMENT OF ENERGY

Targeted Programs for Carbontech through NETL and BETO: 1M-3M+ in support

arpa·e



Supports promising energy technologies that require scale-up or pre-pilot projects to enable a path to market and ultimately lead to realized commercial impact. 1.4 M-14 M federal funding. 30% cost share requirement.

U.S. AIR FORCE

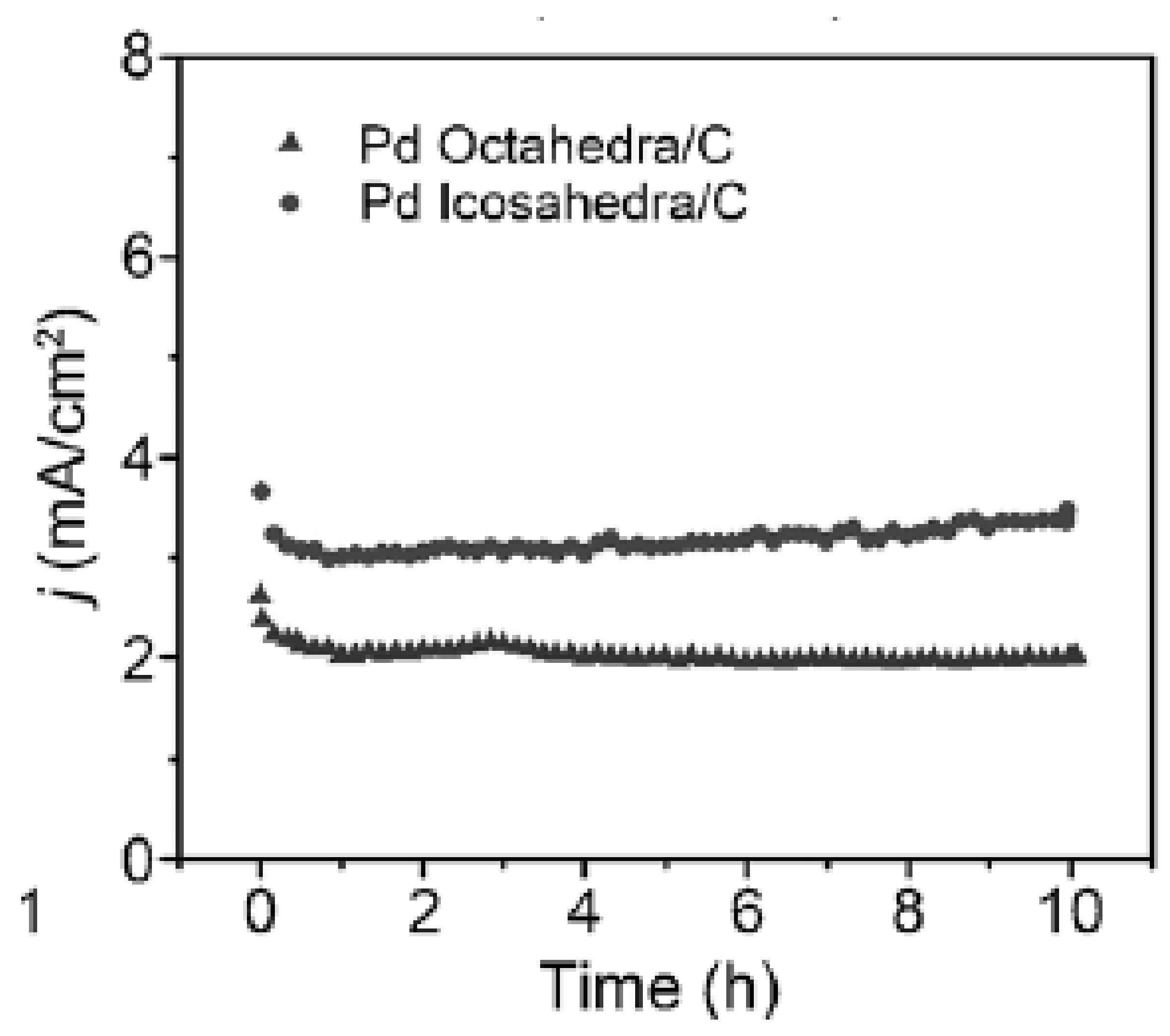
AFWERX

A catalyst for agile Air Force engagement across industry, academia and non-traditional contributors to create transformative opportunities and foster an Air Force culture of innovation

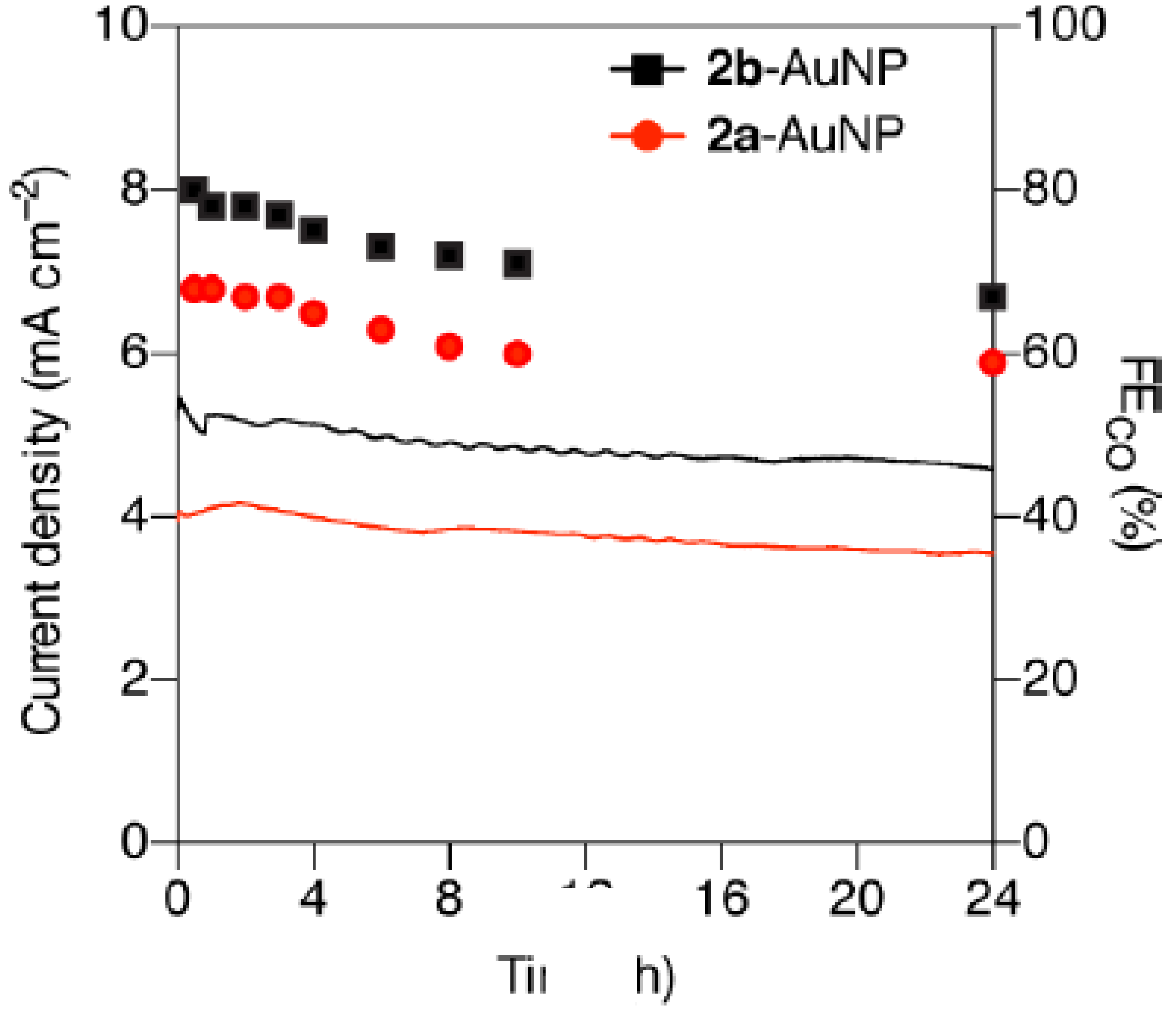
Long-term durability test in the literature

Challenge: Stability of system is a key component of cost. 50,000 or more is a target. 1,000 or 10,000 hours is sufficient for a pilot/demo.

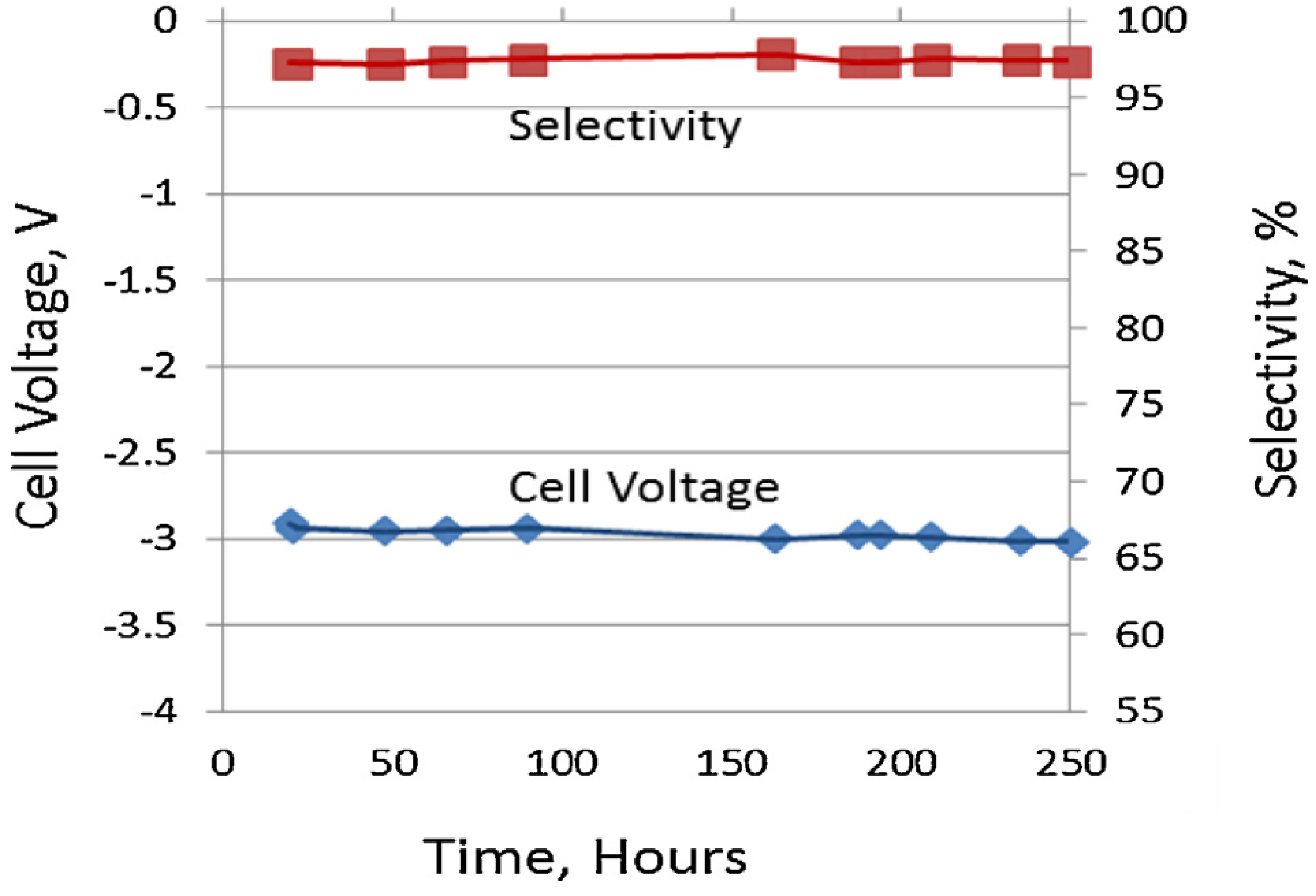
Opportunity: How to support long term studies for emerging technologies? Is there accelerated testing procedures that can be standardized?



Zeng *et al.*, *Angew.Chem.Int. Ed.*, **2017**, 56,3594 –3598



Fischer *et al.*, *J. Am. Chem. Soc.* **2017**, 139, 4052−4061



Lutz *et al.*, *J. CO_2 Util.*, **2017**, 56,3594 –3598

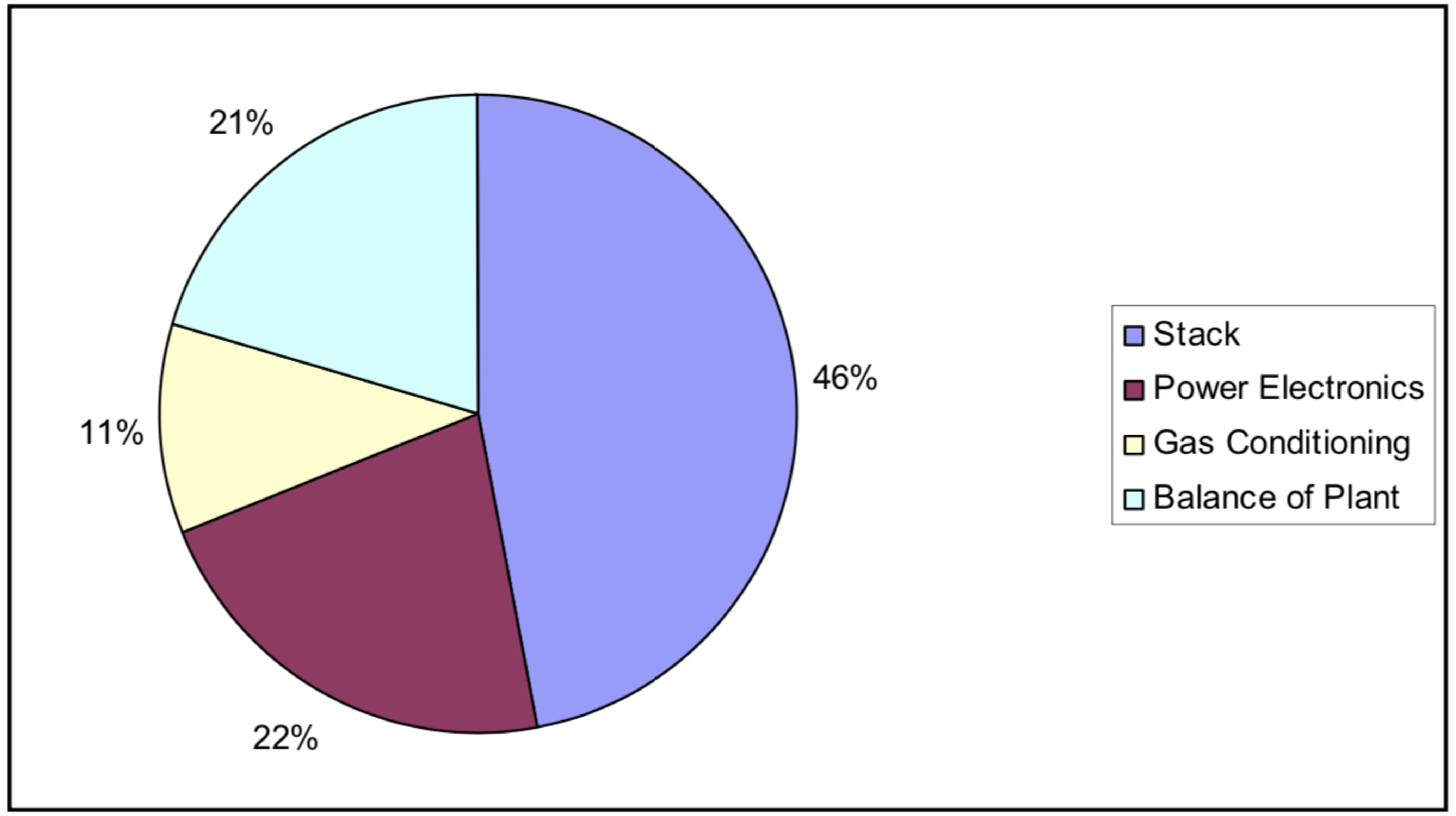
Reducing cost: Electrolyzer capex

Challenge: Hydrogen is key part of all utilization schemes. Biochemical and thermochemical processes use it directly. Electrochemical processes use the hardware of water electrolysis.

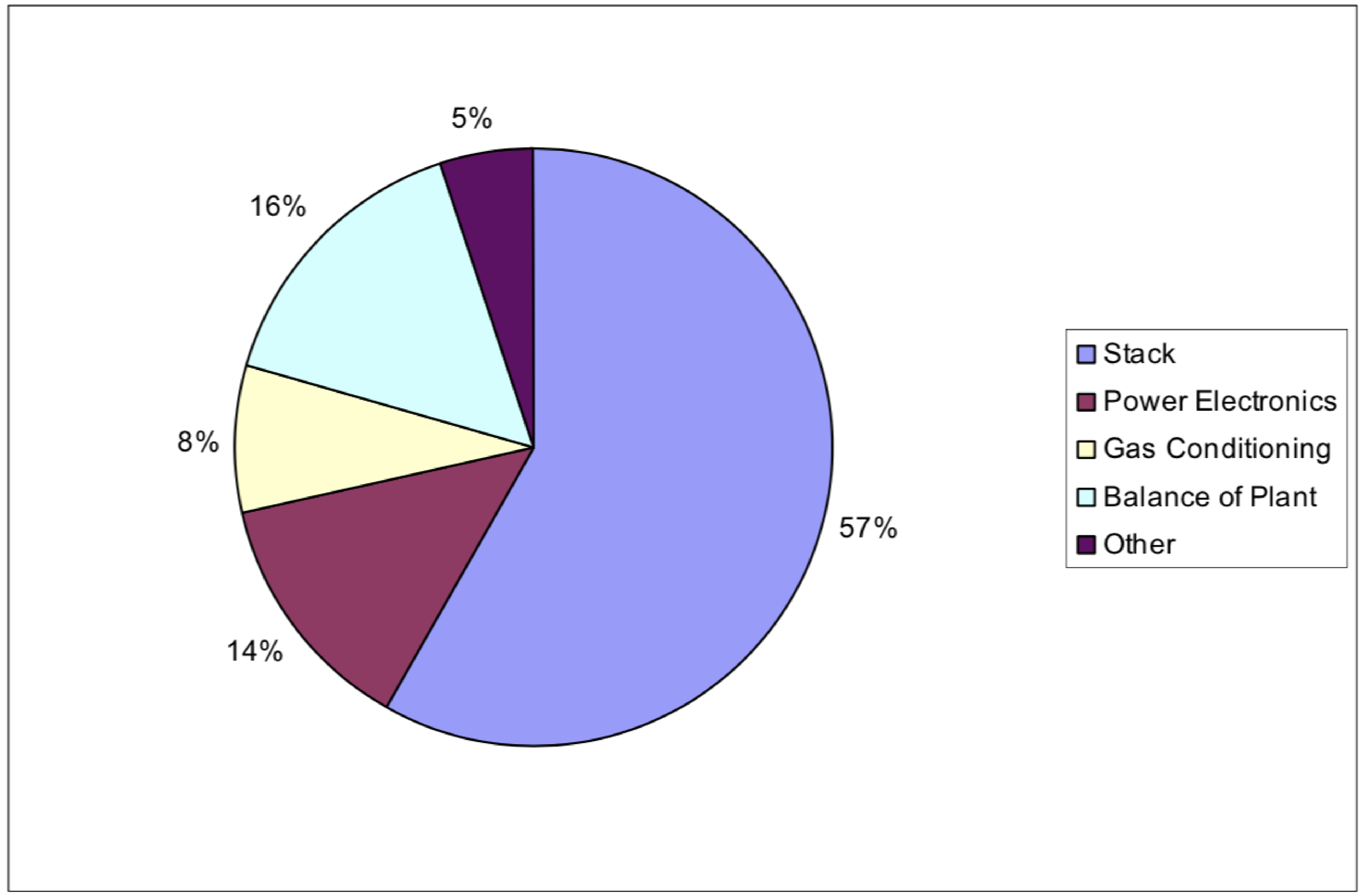
Opportunity: Reduce cost of capex for hydrogen electrolyzers.

A focus on the reducing the stack cost would have the most outsized impact.

Utilization of cheap renewables becomes more attractive.



Cost breakdown for a PEM water electrolyzer



Cost breakdown for alkaline water electrolyzer

Saur, G., Wind-To-Hydrogen Project: Electrolyzer Capital Cost Study. *National Renewable Energy Report* **2008**

Coupling CO_2 Uses

- **Challenge:** thermochemical, electrochemical and carbonation often have limited product outputs. Biochemical processes have a wide array of product formation, have trouble utilizing CO_2 directly.
- **Opportunities:** Coupling biochemical processes with electrochemical and thermochemical systems increases the yield of biological conversion.
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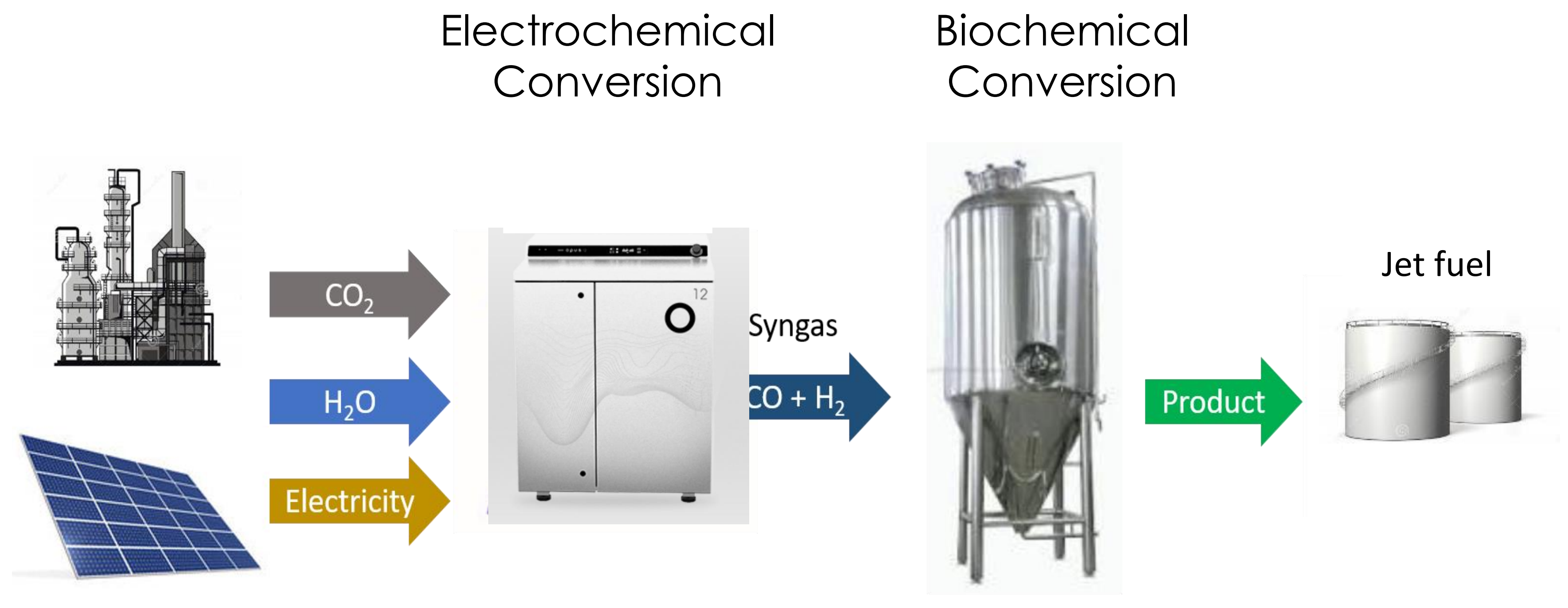
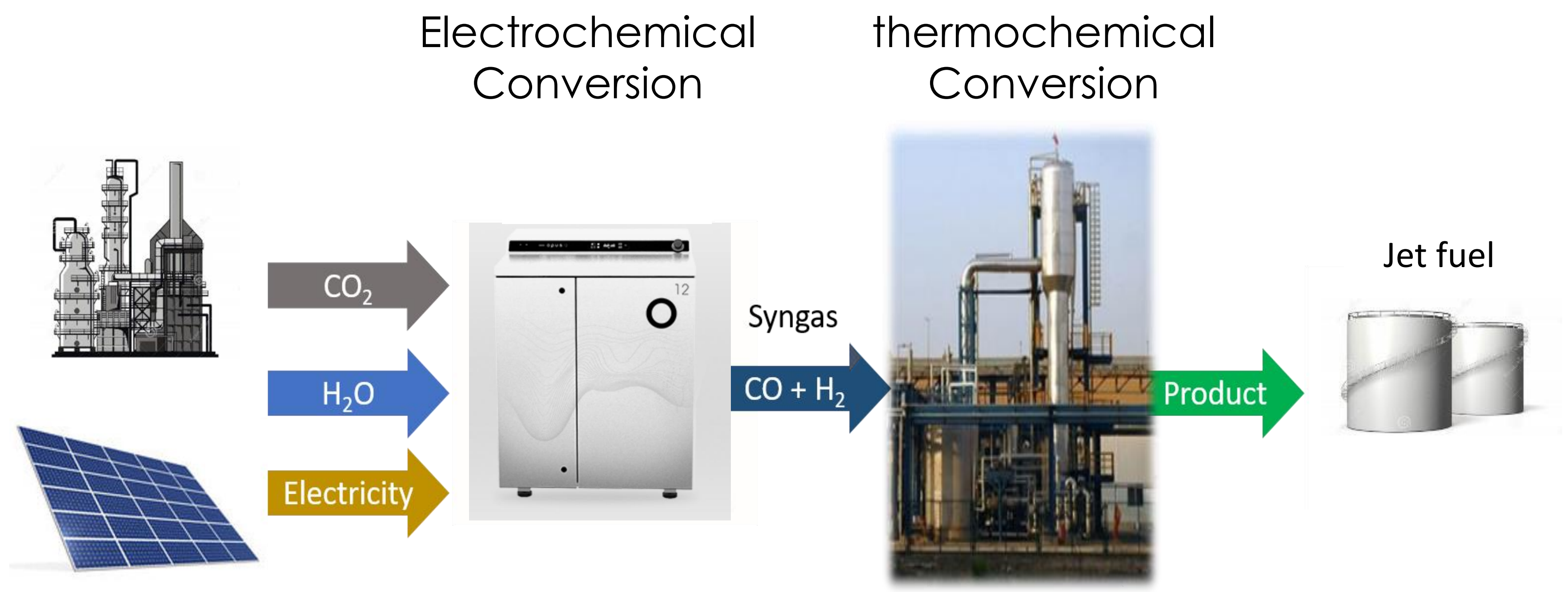




New Policy for Carbontech

- **Low Carbon Fuel Standards & Renewable Fuel Standards**
  - rule enacted to reduce carbon intensity in transportation fuels
- **U.S. Code § 45Q.Credit for carbon oxide sequestration**
  - 12 year credit for $22.66 to $50/ton for sequestering and $12.83 to $35/ton for utilization
- **H.R.3607, the Fossil Energy Research and Development Act / S.1201 the EFFECT Act**
  - Update the current structure of the DOE's Office of Fossil Energy, including creating a larger Carbon Use program.
- **S.383/H.R.1166, the USE IT Act**
  - Would support carbon utilization and direct air capture research. Supports development of carbon capture, utilization, and sequestration (CCUS) facilities and carbon dioxide (CO_2) pipelines.

Emerging funds specializing in project financing

AsterraPartners

- Support the scaling of new environmental technologies focused on addressing the Sustainable Development Goals

GENERATE CAPITAL

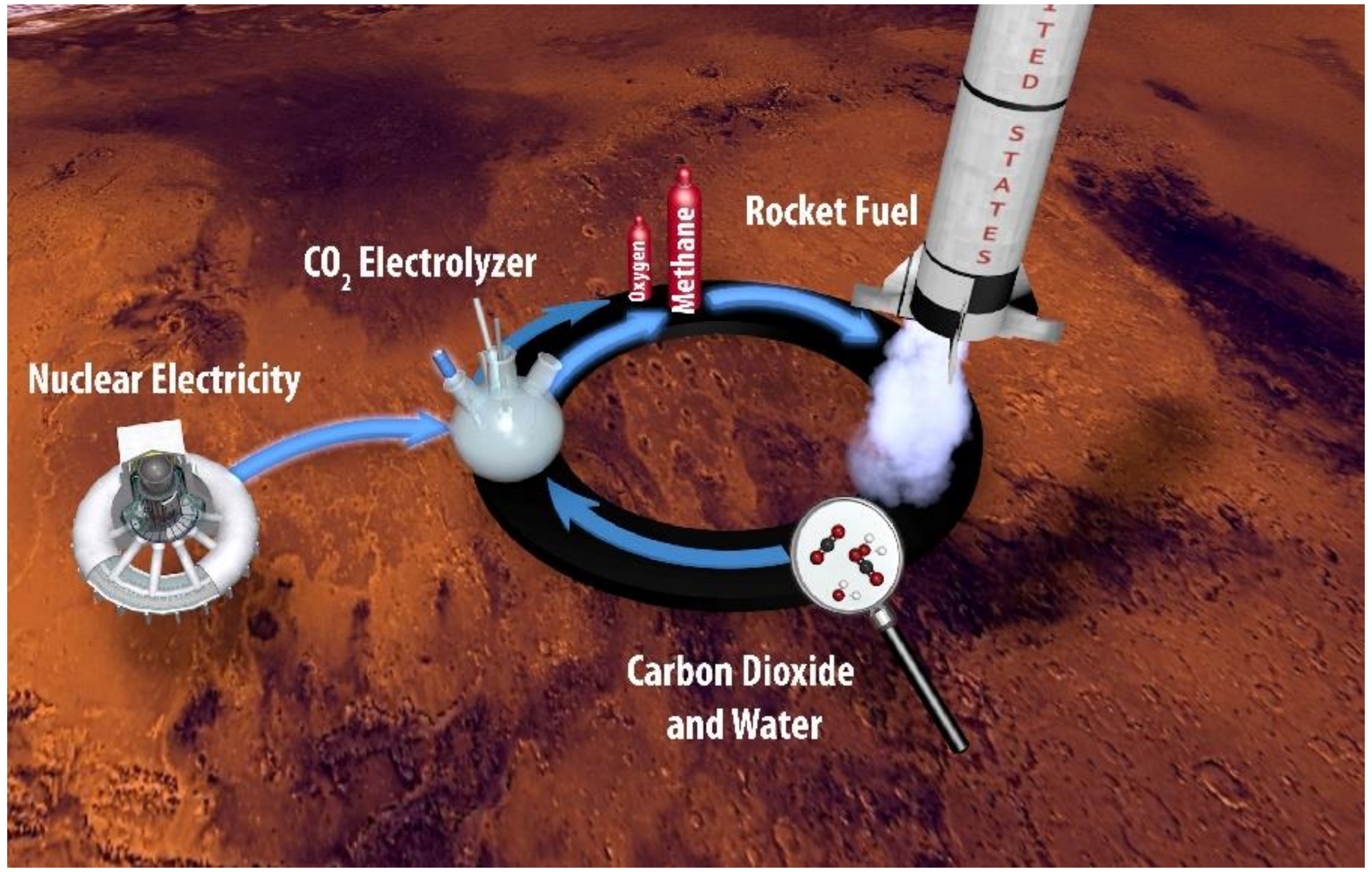
- Supports project developers and technology manufacturers globally to finance sectors in renewable energy, technology, finance, and sustainability sectors.

CLIMATE TECH FINANCE

SUBSIDIZED LOANS AND LOAN GUARANTEES TO SUPPORT THE PURCHASE OF EMERGING CLIMATE TECHNOLOGIES

ELIGIBILITY	Public agencies and small businesses in the Bay Area
TECHNOLOGIES	Emerging or early-commercial stage technologies that reduce greenhouse gas emissions
LOANS	**For public sector:** Direct loans of \$500k to \$30m with up to 30-year terms. Below-market interest rates and subsidized fees **For small business:** Loan guarantees of up to \$2.5m on loan sizes up to \$20m. Projects may be eligible for up to 90% guarantees

Leverage Other Applications: Space & Defense Use of CO_2



- 95% of the Martian atmosphere is CO_2,
- CO_2 has been detected on the moon.
- CO_2 removal in the main cabin of human space flight is essential to keep levels below 1000ppm

- CO_2 as a feedstock for on-site production of fuel and other critical compounds reduces transport and convoys, which saves lives and increases readiness.

Acknowledgements

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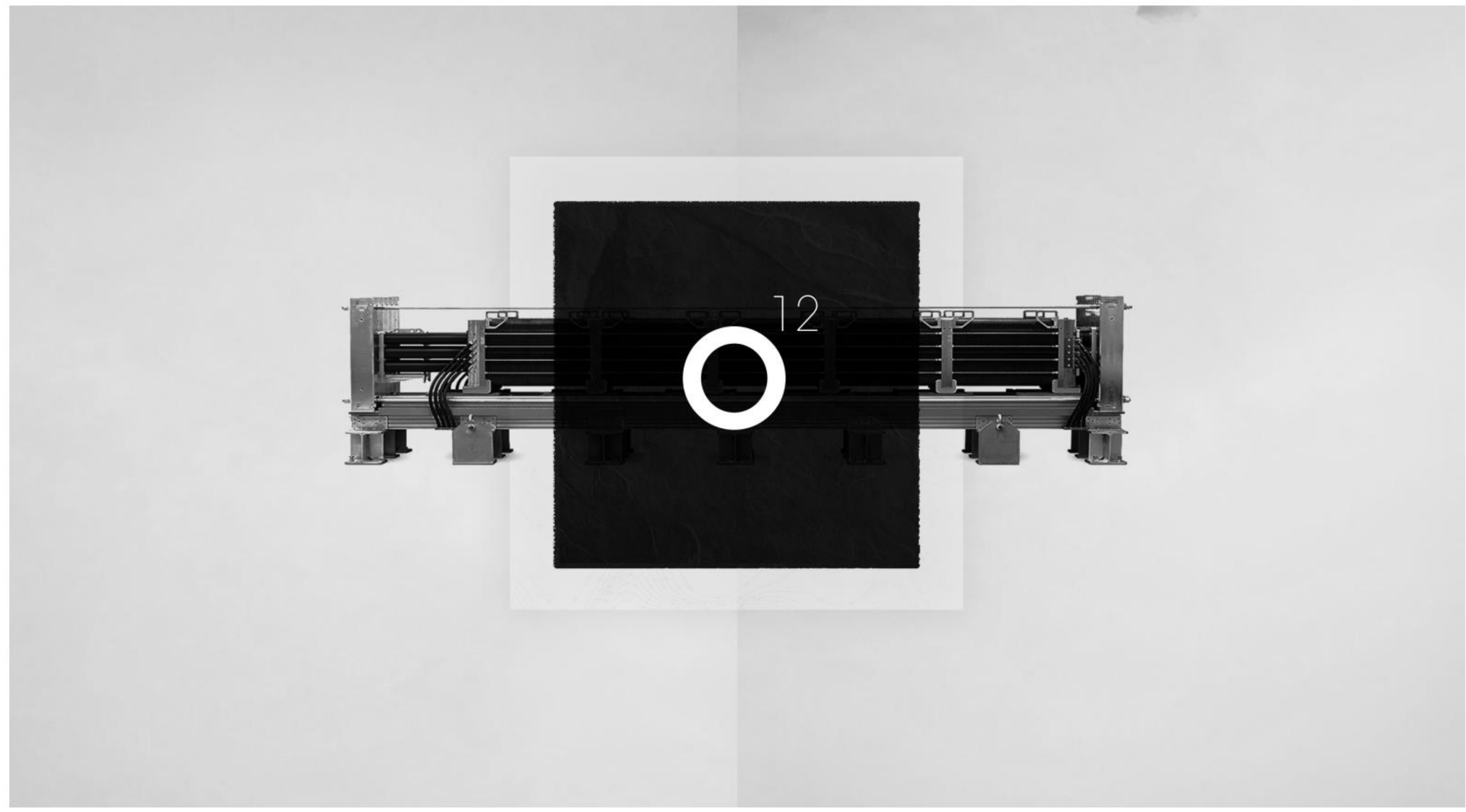
Early Stage investors	cyclotronroad TomKatCenter FOR SUSTAINABLE ENERGY STANFORD UNIVERSITY

Crossing the Chasm: Remaining Capital Lite

Leverage Existing Manufacturing Facilities

Power dense core component

Leverage project financing



Partner with existing manufacturing producers to build CO_2 conversion systems

Early R&D focus on increasing production density and robustness

20-year input contract + 20-year output contract