Opportunities for Advanced Manufacturing and Materials in Improving Carbon Capture Technology

NSF Workshop on Advanced Manufacturing for Industrial Decarbonization

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Net-Zero 2050: U.S. Economy-WideDeep Decarbonization Scenario Analysis

www.lowcarbonLCRI.com/netzero

Decarbonization Pathways Enabled by Innovation

Decarbonization

~10-15 years

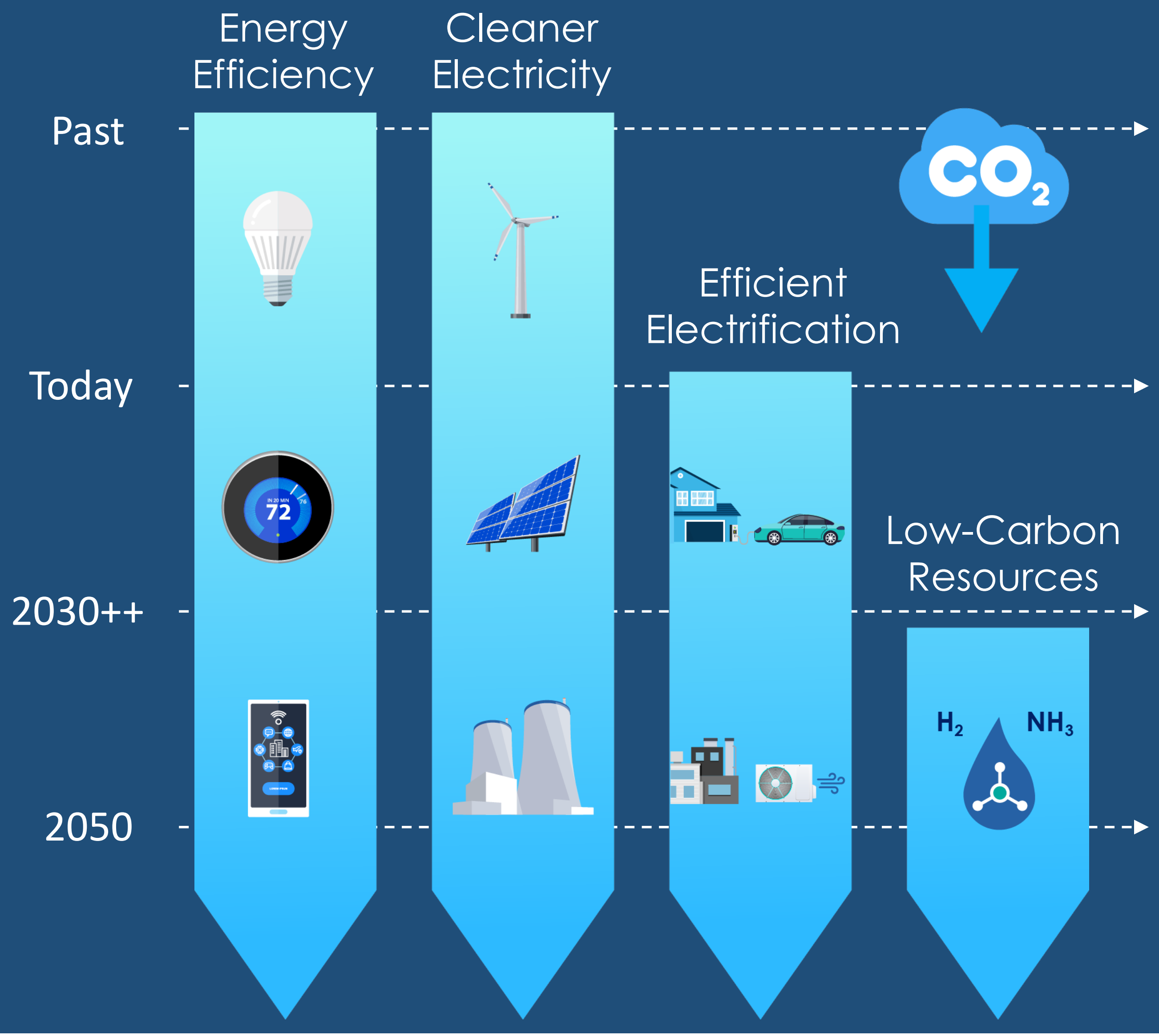
Accelerate economy-wide, low-carbon solutions

- Electric sector decarbonization
- Transmission and grid flexibility: storage, demand, EVs
- Efficient electrification

~15-30 years

Achieve a net-zero clean energy system

- Ubiquitous clean electricity: renewables, advanced nuclear, CCUS
- Negative-emission technologies
- Low-carbon resources: hydrogen and related, low-carbon fuels, biofuels, and biogas



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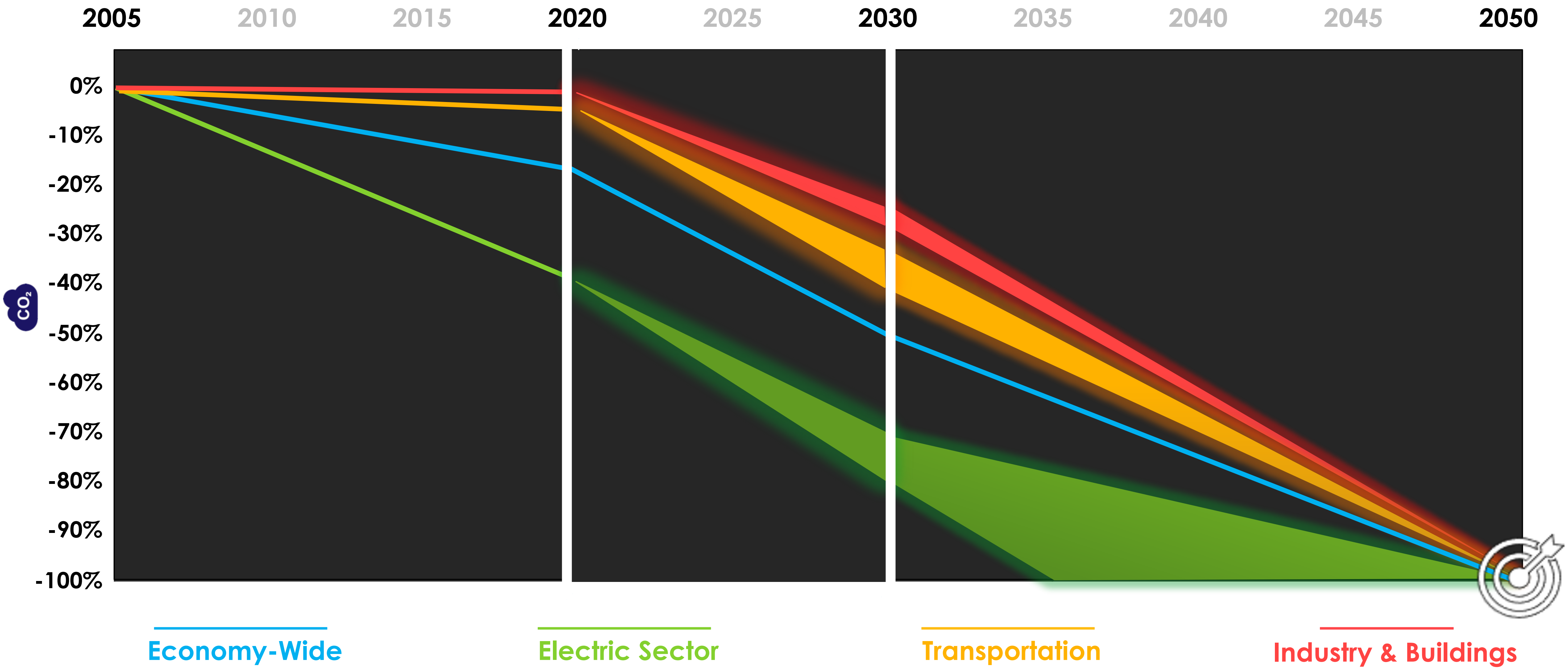
Pathway to Net-Zero

more technology needed

BEYOND THIS DECADE



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COAL

GAS



BIOMASS

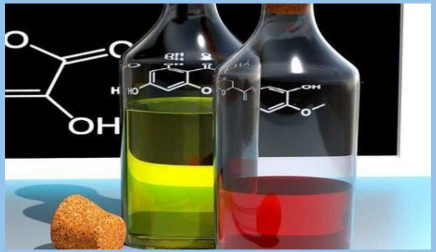

CONCRETE

STEEL



PETRO CHEMICAL


HYDROGEN

SYNTHETIC FUELS



DAC

Carbon Capture Utilization and Storage (CCUS) is a Cross-Cutting Solution

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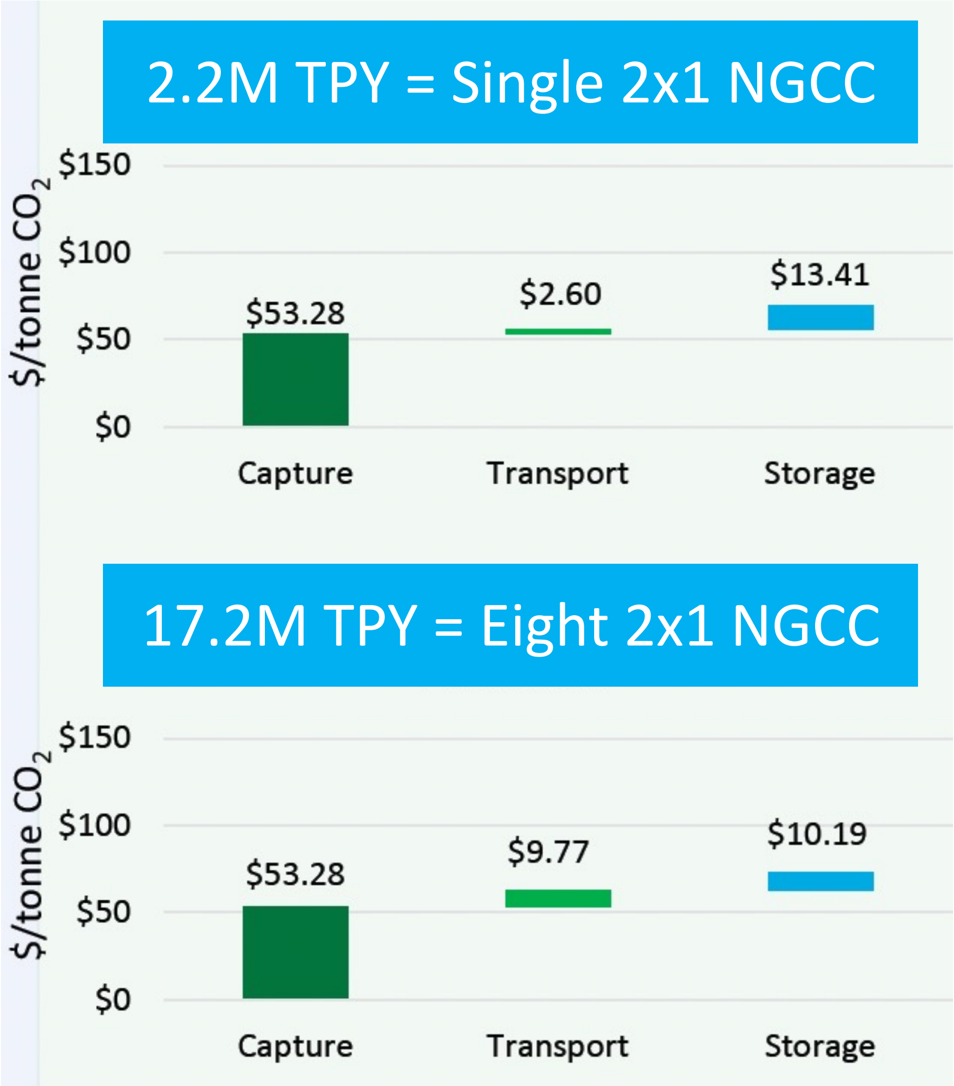
Capture costs dominate cost of CCUS

CCUS Requires:

- Capture System
- Transport (piping)
- Storage (or Utilization)

Example of cost estimate (\$/tonne CO_2) for a CCS system (500 mile pipeline) for a prototypical Natural Gas Combined Cycle (NGCC) power Plant



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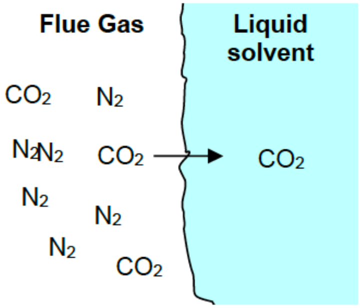
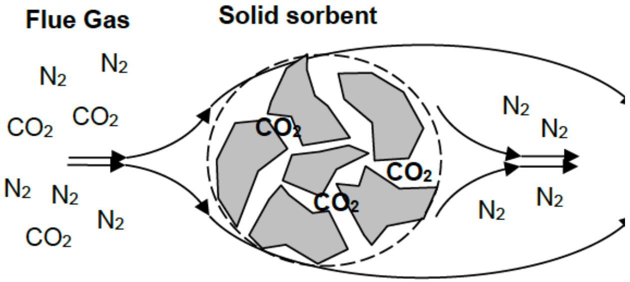
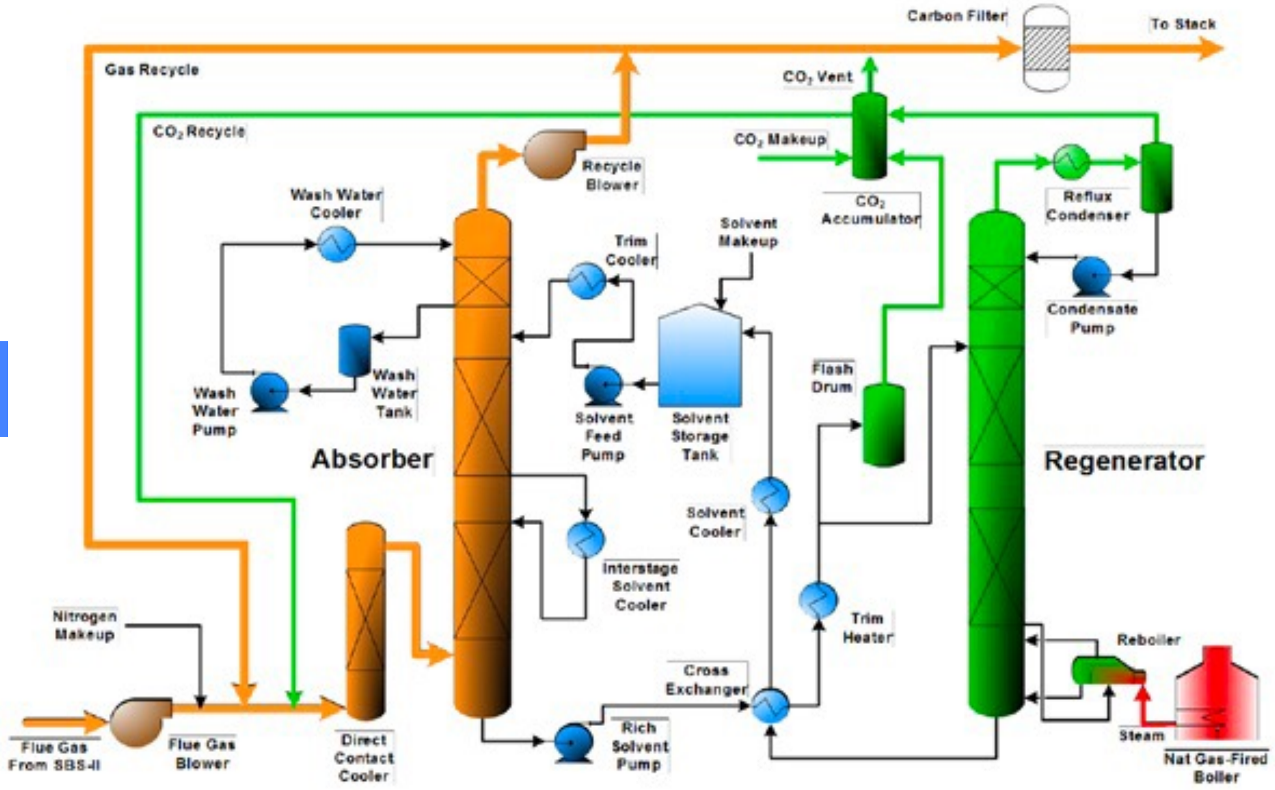
Typical Capture Processes for Stationary Sources

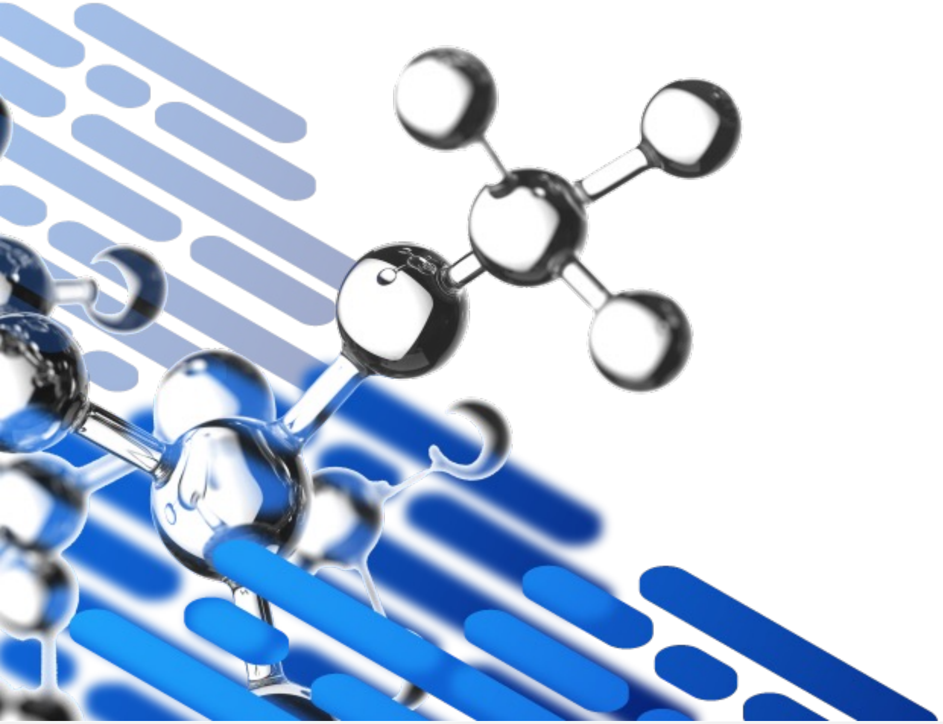


Absorption



Adsorption





Example of a typical Amine (Absorption-based) Carbon Capture System

EPRI 3002022091

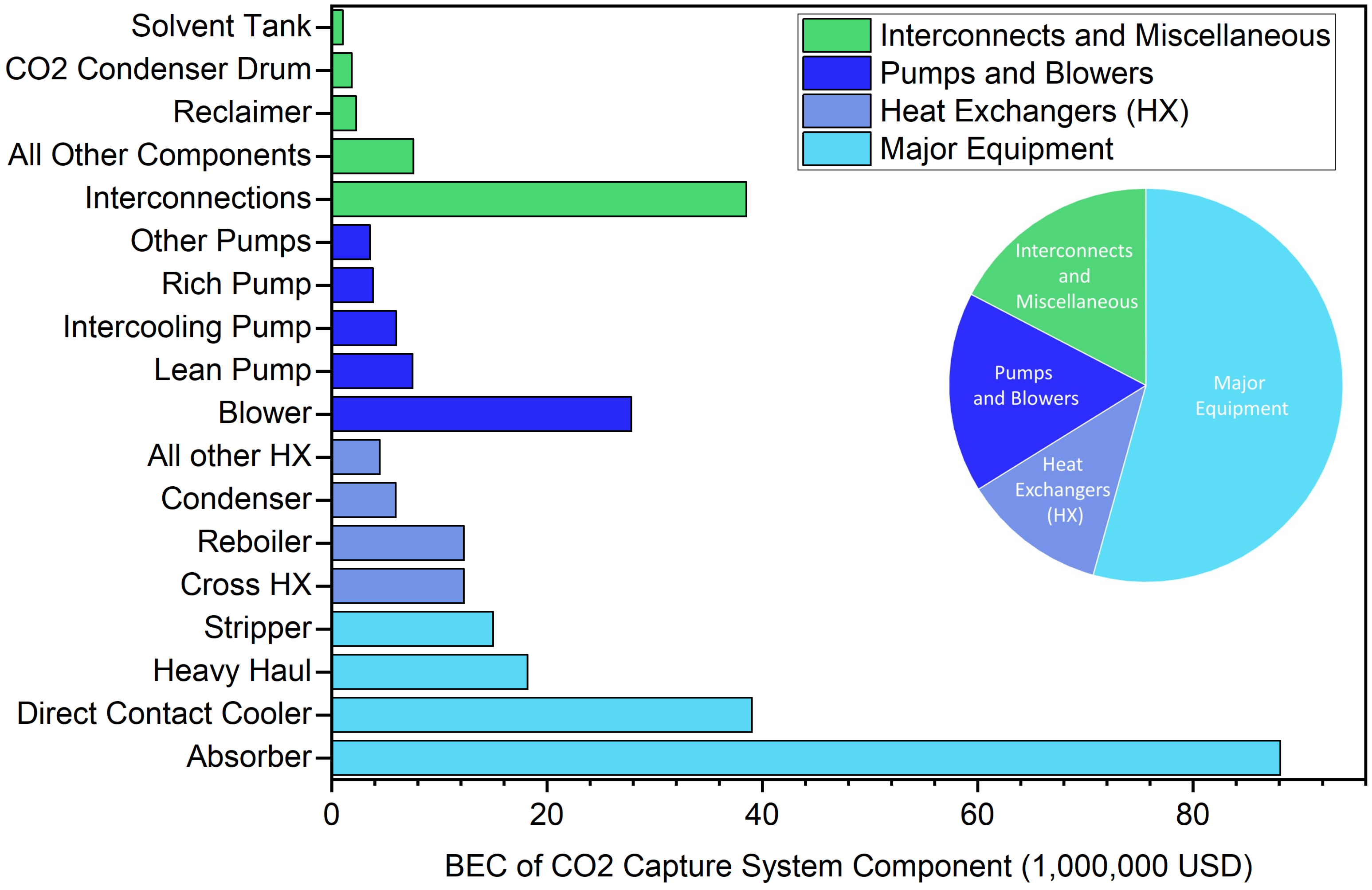
Capital costs for CCUS

Key potential areas for cost reduction

- Absorber
- Heat Exchangers
- Pumps
- Piping (interconnections)

Where could Advanced Manufacturing (AM) and Materials Impact Capital Costs?

EPRI CAPEX Cost Model for Bare Erected Cost (BEC) Carbon Capture Systems (NGCC Plant with 90% capture based on DOE/NETL Reference Case 31B)



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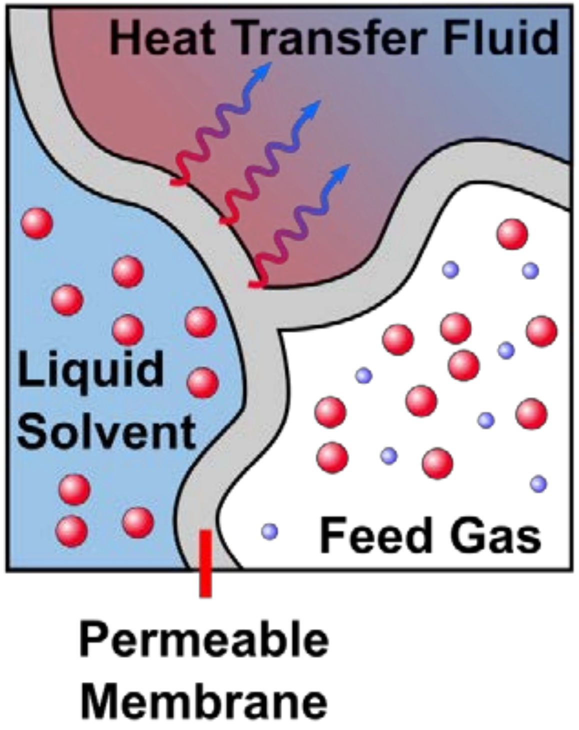
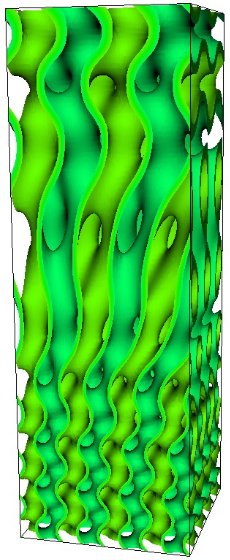
Opportunities & Challenges for AM in Carbon Capture Systems

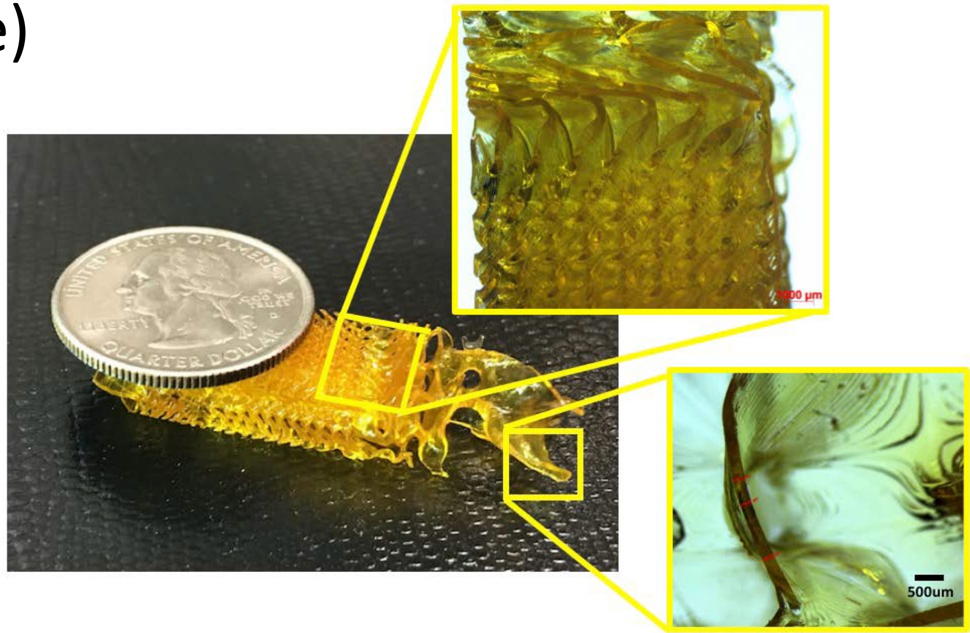
AM Produced Structures for improved heat and mass transfer





- Potential uses for hierarchical gyroids
  - Intercooled absorber packings
  - Gas/solvent membranes
  - Sorbent scaffold (possible with heat exchange)

CO_2-permeable silicone gyroids (LLNL)

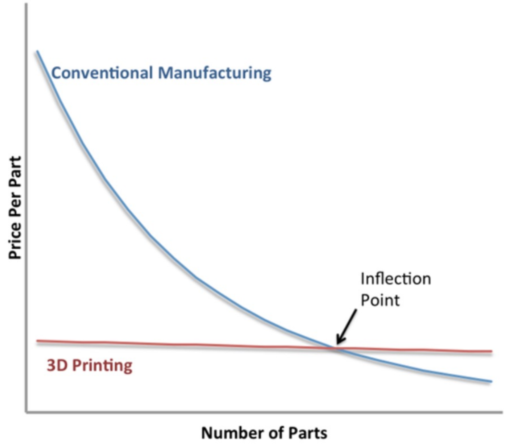


Stolaroff, "FEW0225: High-Efficiency, integrated reactors for sorbents, solvents, and membranes using additive manufacturing" NETL Carbon Capture Technology Review, August 13, 2018

How do we select proper materials and scale these concepts for real-world applications?

Innovations in unstructured packing

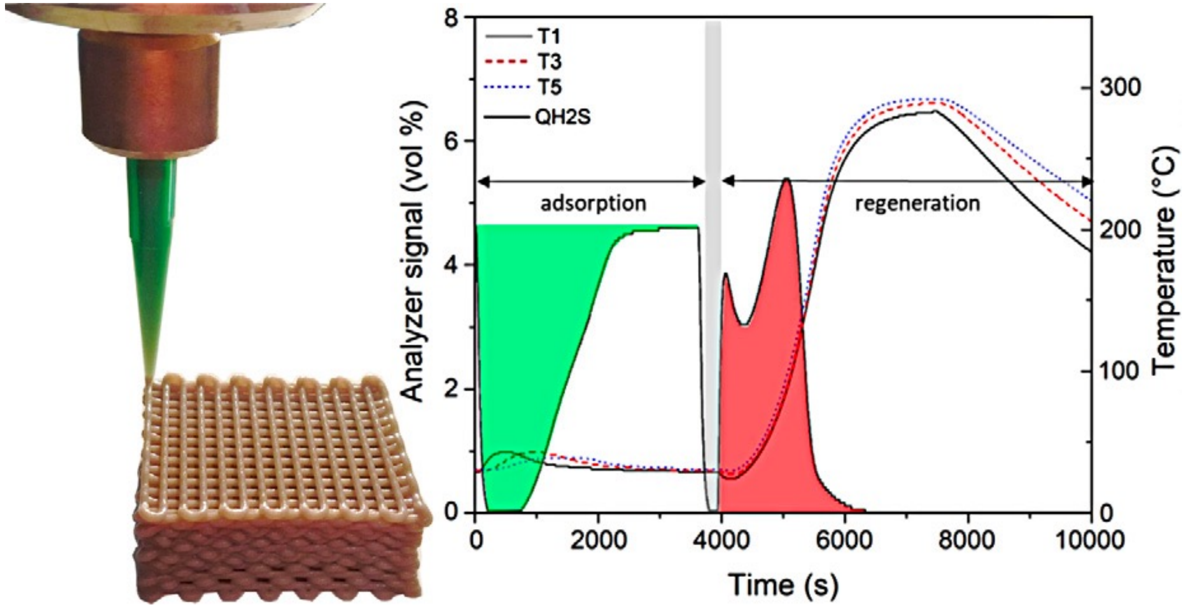
- Low-cost plastic 3-D printing allows for exploring innovative designs
- AM is good for testing new concepts but production may favor other approaches



Bara et. al. Nanomaterials and Energy, Vol. 2, 31/07/2013

Meaningful performance benefits?

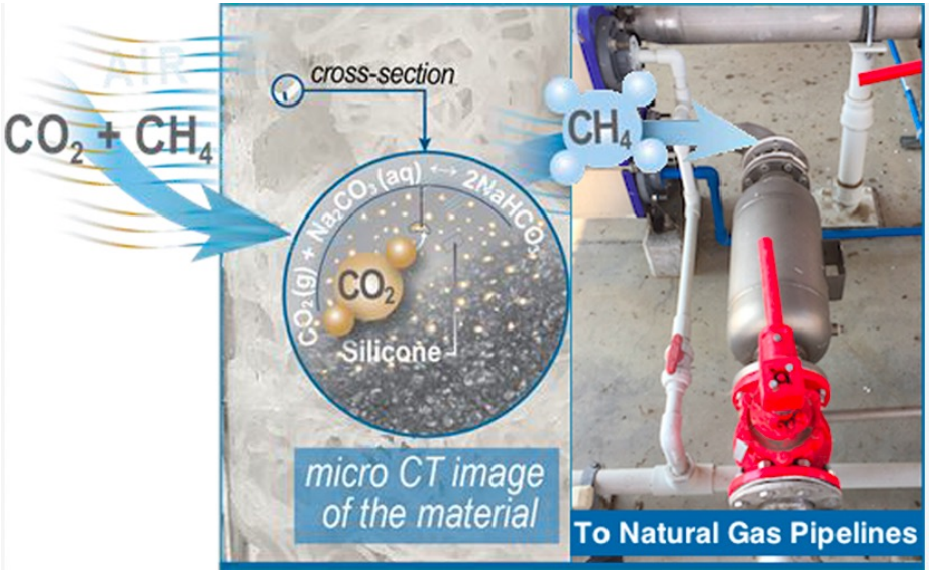
3-D Printed adsorbents



3-D printed packed beds compared to spherical adsorbents (sour gas removal), same sorbent:

- (+) 3-D printed beds improved adsorption and desorption rates
- (-) Typical spherical packing had higher adsorption capacity

Middelkoop et al. "3D printed versus spherical adsorbents for gas sweetening,' *Chemical Engineering Journal*, https://doi.org/10.1016/j.cej.2018.09.130.



3-D printed composite sorbents for CO_2 removal from Biogas

- (+) selective CO2 removal resulting in CH4 >99%
- (+) lower capital costs compared to pressure swing adsorption, water scrubbing, or cryogenic separation
- (+) regeneration at low pressures and temperature
- (-) larger beds required

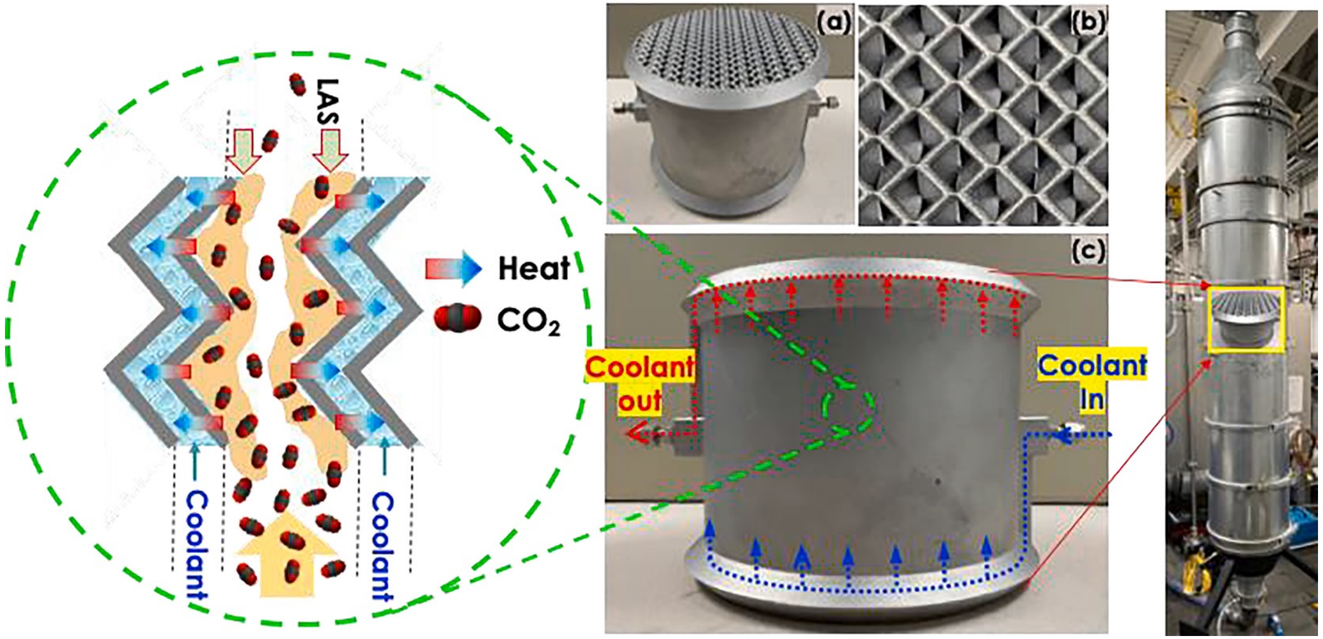
Murialdo et. al. *Environmental Science & Technology* **2020** *54* (11), 6900-6907
DOI: 10.1021/acs.est.0c01755

Lab scale results suggest potential advantages of 3-D printed packing materials to improve performance, but cost and scale-up have not been explored

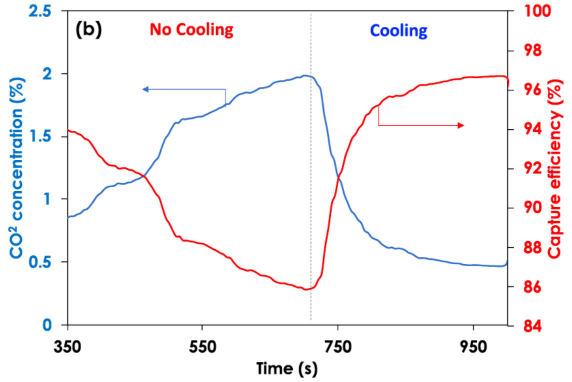
Integrated heat exchange

- Integrating heat exchange into the absorber tower can improve process efficiency and lower absorber height
- AM being explored to allow for optimization of both heat and mass transfer
  - Novel geometries, corrugated surfaces, gyroid, etc.

3-D Printed column packing structure with built-in heat exchange (ORNL)



Jang et. al. "Process intensification of CO2 capture by low-aqueous solvent, Chemical Engineering Journal, Volume 426, 2021, https://doi.org/10.1016/j.cej.2021.131240.



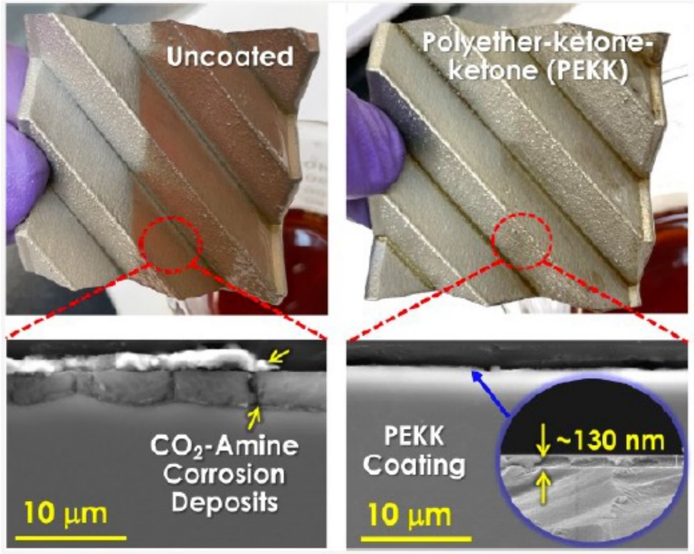
Large lab-scale test show promising improvements and potential to integrate into existing designs as 'stage' in the structured packing arrangement

Materials selection for AM – Cost and Environmental Compatibility

- Materials selection for AM for CCUS
  - Structural integrity
  - Performance

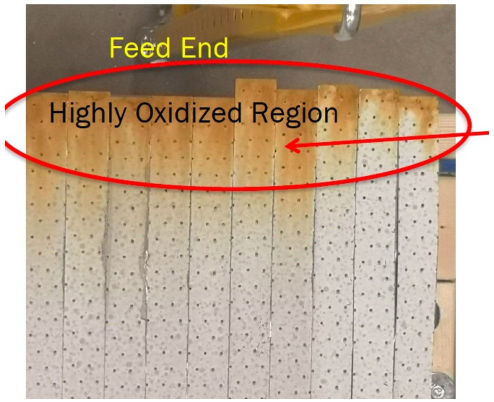
  Vs….
  - Cost, cost, cost
  - Corrosion
- Metallics versus non-metallics
- AM method is important

Little public data available on component degradation in pilot/commercial scale carbon capture systems



Jang et. al, Ind. Eng. Chem. Res. 2021, 60, 17036-17044

Aqueous corrosion in 3-D printed aluminum packing device, PEEK coating provided protection



Odom & Hovington, ”Advanced Structured Adsorbent Architectures for Transformative Carbone Dioxide Capture Performance.” Presentation, Aug. 18, 2022. DE-FE0031732

Bench-scale testing of advanced structured segmented beds (not AM) showing oxidation after amine experimental run

www.netl.doe.gov/research/coal/carbon-capture

3-D printed plastic absorber packing with integral cooling

Recent Review Article

Nanomaterials 2020, 10, 2198; doi:10.3390/nano10112198

nanomaterials

MDPI

Review

A Review on New 3-D Printed Materials' Geometries for Catalysis and Adsorption: Paradigms from Reforming Reactions and CO_2 Capture

Ahmad Soliman [1,2], Nahla AlAmoodi [2,3], Georgios N. Karanikolos [2,3], Charalabos C. Doumanidis [4] and Kyriaki Polychronopoulou [1,2,*]

Little available research

… As comparatively little research has been performed in this area at the crossroads of mechanical and chemical engineering...

Research Needed: Manufacturing & Materials

…According to recent studies, 3D printing technologies have been utilized in enhancing the heat, mass transfer, adsorption capacity and surface area in CO2 adsorption and separation applications and catalytic reactions. However, intense work is needed in the field to address further challenges in dealing with the materials and metrological features of the structures involved.

Potential

…Although few studies have been performed, the promise is there for future research to decrease carbon emissions and footprint.

Heat Exchangers (HXs)

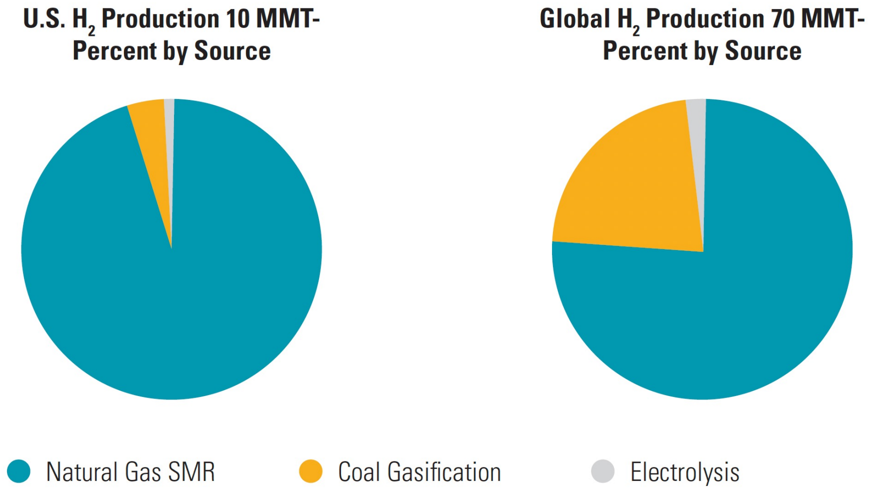
- Shell & Tube
- Plate & Frame
- Compact (Printed Circuit, Plate & Fin)
- Additively Manufactured

Capital Cost	Performance	Size/Mass
Lowest	Lowest	Highest
↓	↓	↑
Highest	Highest	Lowest

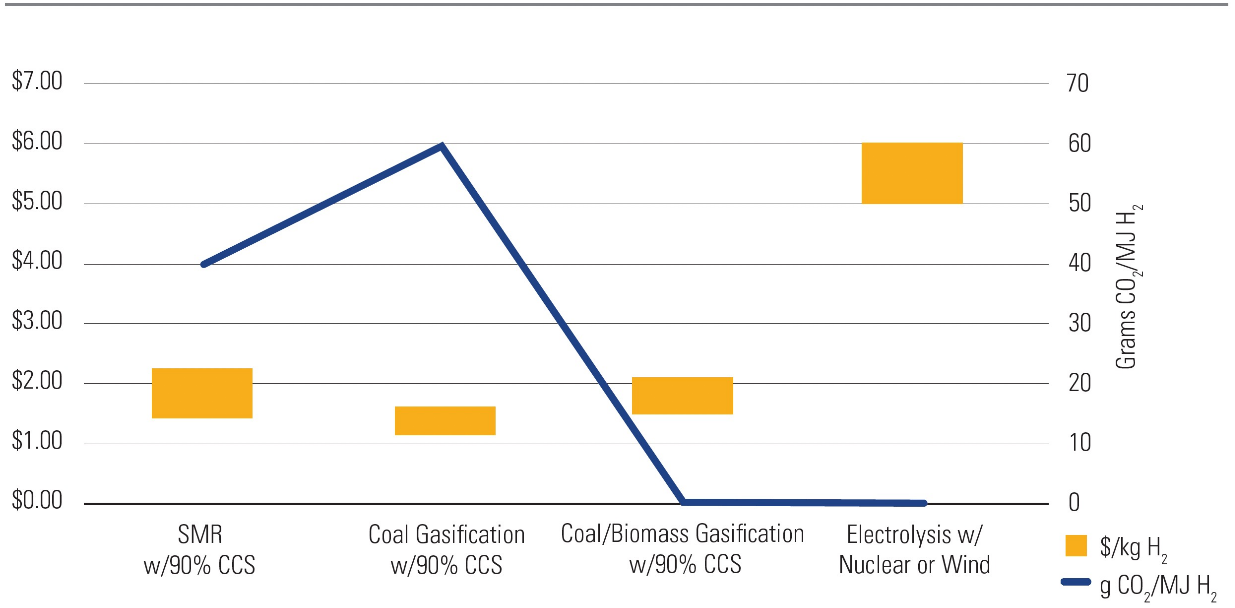
Example: Plate & Frame HX for Carbon Capture System (source: Alfa Laval)

Many options to improve performance of HXs compared to traditional shell and tube, but will they reduce cost? – most AM produced HXs are small & expensive today

CCS for Steam Methane Reformation (SMRs), aka 'Blue Hydrogen Production'



Majority of World's Hydrogen Produced by Natural Gas SMRs



Source: U.S. DOE "Hydrogen Strategy: Enabling a Low-Carbon Economy" July 2020

SMRs + CCS projected to produce hydrogen as costs less than electrolysis from clean electricity

Other processes also being evaluated, size and scale matter for AM, higher efficiency and modular (smaller) designs may open up additional opportunities

What about Direct Air Capture (DAC)?

- Energy intense smaller DAC systems may benefit from AM where the added cost of AM can be offset by improvements in overall process efficiency
- Possible components:
  - Air Contactors / Mechanical filters (equivalent to a structured packing)
    - Desire for low pressure drop (reduce fan load) and high surface area
  - Highly efficient heat exchangers
  - Chillers/distiller for gas clean-up
  - Small fans or pumps

Mechanical filter for DAC designed for 3-D printing (lattice structure)

Forbes: https://www.forbes.com/sites/jimvinoski/2022/06/22/aircapture-and-3d-systems-partner-to-make-decarbonizing-our-atmosphere-profitable/?sh=918881c34ea8

Modular designs in some DAC systems may be amenable to AM

Conclusions

- The applicability of AM for CCUS systems is in its infancy with only a limited number of studies being conducted
- For large-scale CCUS, capital cost reduction is the key opportunity, but the applicability of AM has yet to be exploited
- Research on AM to improve heat and mass transfer is generally at the lab/bench scale today:
  - Integrating heat exchange with structured packing appears to be a promising approach
  - Structured packed beds may also benefit from AM
- AM for heat exchangers (and pumps) is possible today, but not at the sizes envisaged for large CCS systems
- Materials compatibility (and cost of materials) has been largely avoided in the conversation, more exploration is needed as decreasing material costs could have large impacts in capital cost
- Smaller systems such as DAC (and potentially SMR+CCUS) which have a stronger business case for efficiency appear to present a nearer-term opportunity for AM

Lots of Challenges = Lots of Opportunities

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