Premium Carbon Capture Applications for ***Metal Organic Frameworks***

November 30, 2012

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Team experience in breakthrough technology and market analysis

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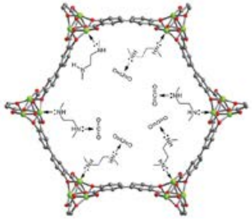
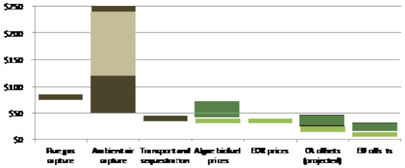
Improved approach to carbon capture, but how to monetize it?

The Opportunity: 30B tons CO_2 emitted per year



Technology: new chemistry, better performance

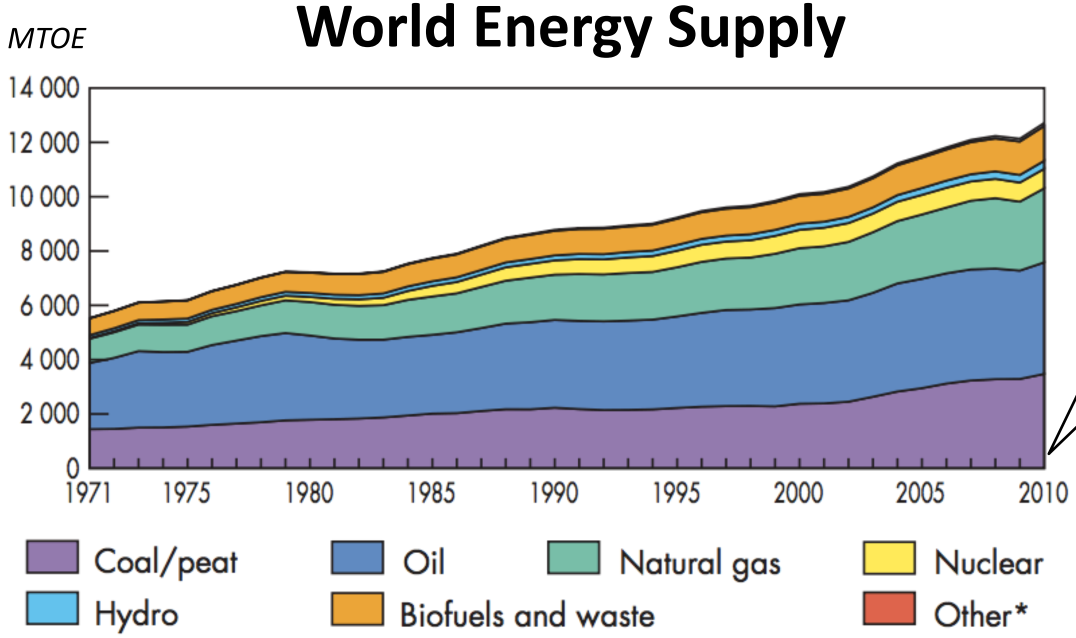


Carbon Economics: policy vs. industrial customers

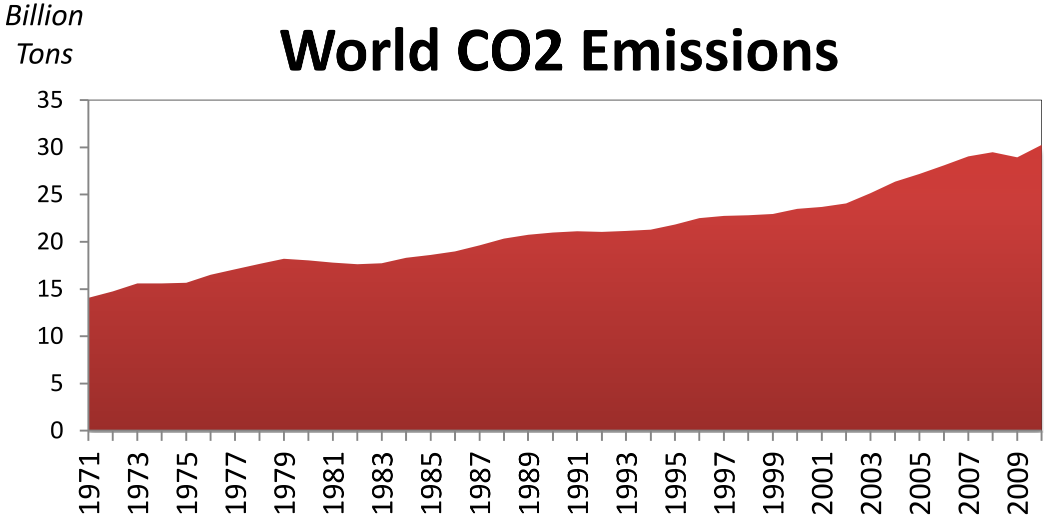
Applications: niche markets pay premium price

CO2 emissions almost too large to comprehend in real terms

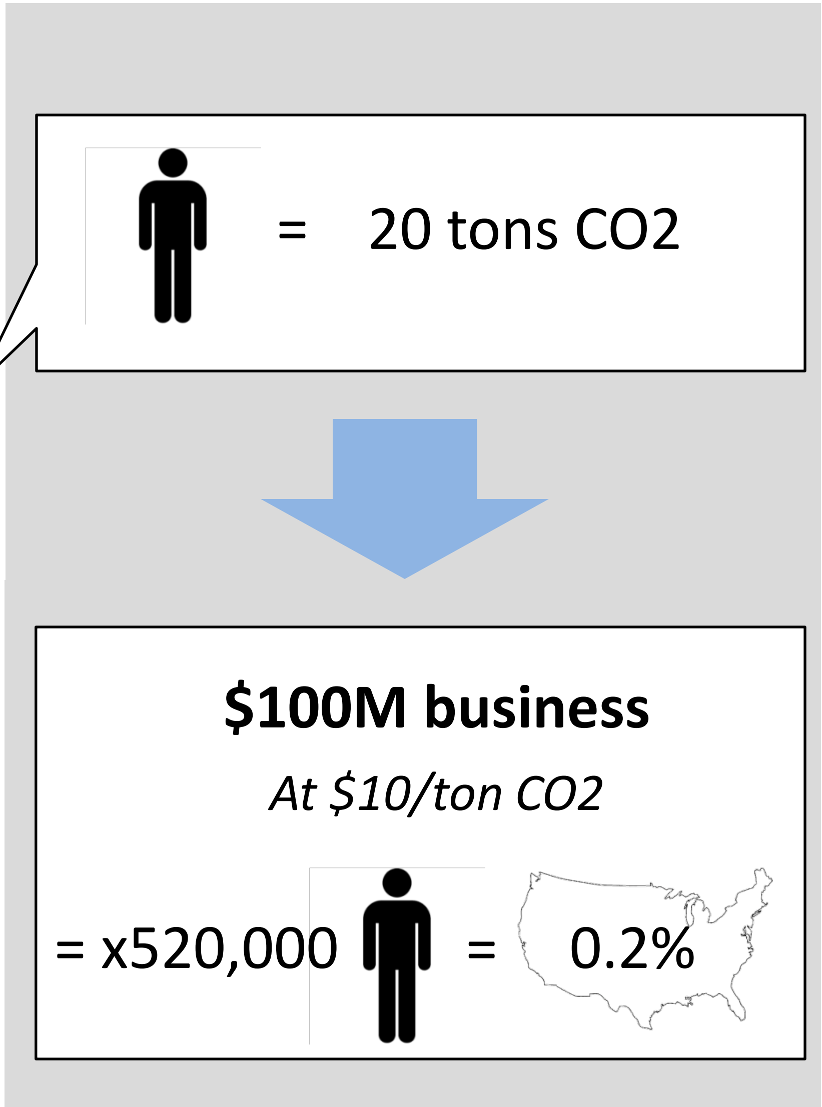
World Energy Supply



World CO2 Emissions



CO2 as a Market



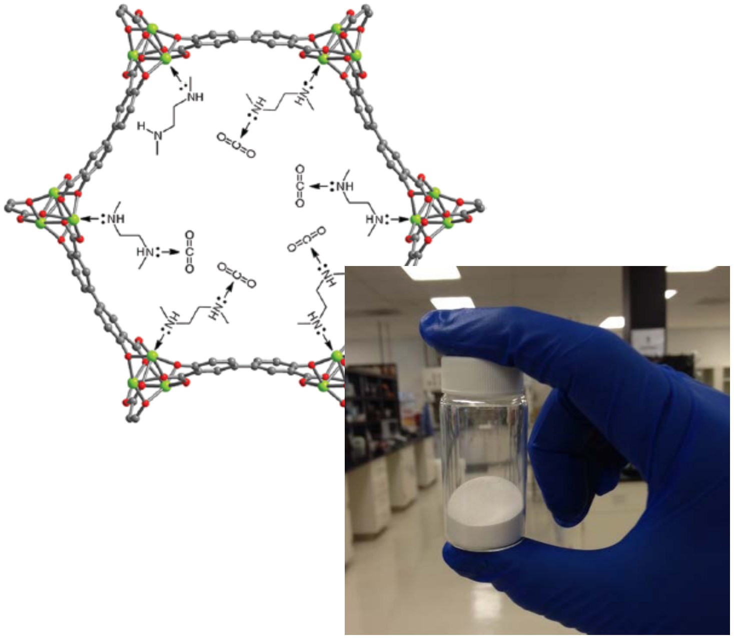
= 20 tons CO2

$100M business

At $10/ton CO2

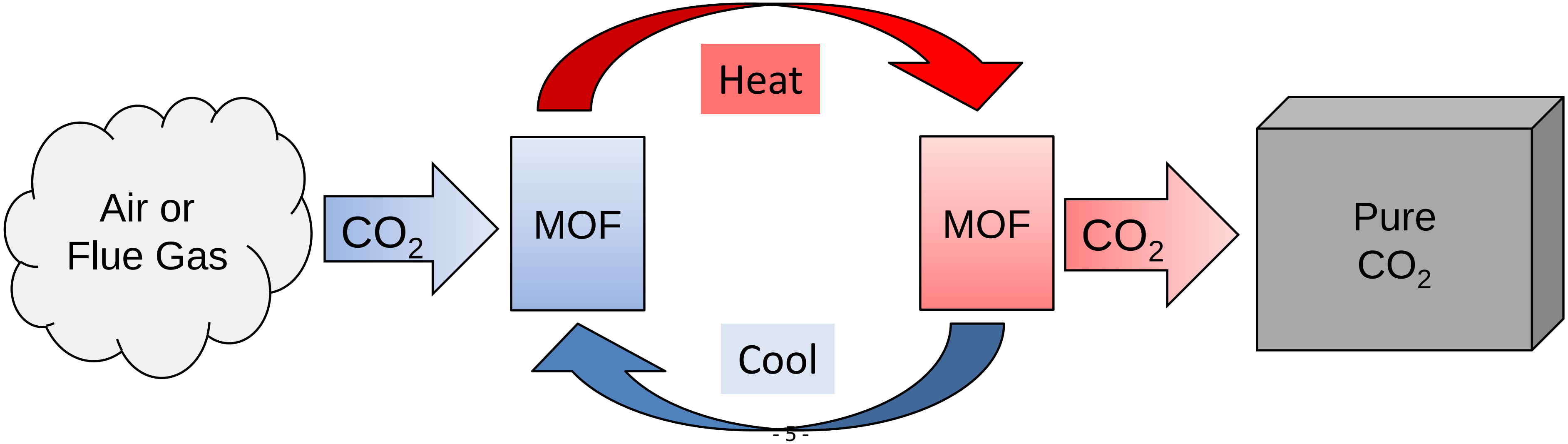
= x520,000 = 0.2%

Metal-organic frameworks (MOFs) have high CO_2 capacity



- Porous framework with tunable centers that add functionality
- Walls tuned to adsorb CO_2
- A lot of walls! (70 m^2/g)

= 10 x



Air or Flue Gas

CO_2

MOF

Heat

Cool

MOF

CO_2

Pure CO_2

Breakthrough MOF outperforms competing technologies

	Amines	Zeolites
Max. Capacity	<5.5%	16 wt%
Capacity from Air	--	1.4 wt%
Regeneration Temp	<100 °C	>135 °C
Energy input TSA	High	Low
Pressure Drop	Low	High

- Very **high capacity** from high surface area
  - Smaller volume MOF material, higher volume of carbon
- **High adsorption from low concentration**
  - Wider range of operating conditions and gas streams
- **Low heat capacity and ΔT** between capture and release
  - Less energy needed to heat and cool down the MOF
  - Energy = cost

MOFs as component of larger processes in diverse industries

Metal Organic Frameworks

Carbon Capture Applications


Policy-Driven Sequestration


Enhanced Oil Recovery (EOR)


Algae Biofuels

Existing Industrial Applications


Natural Gas Processing

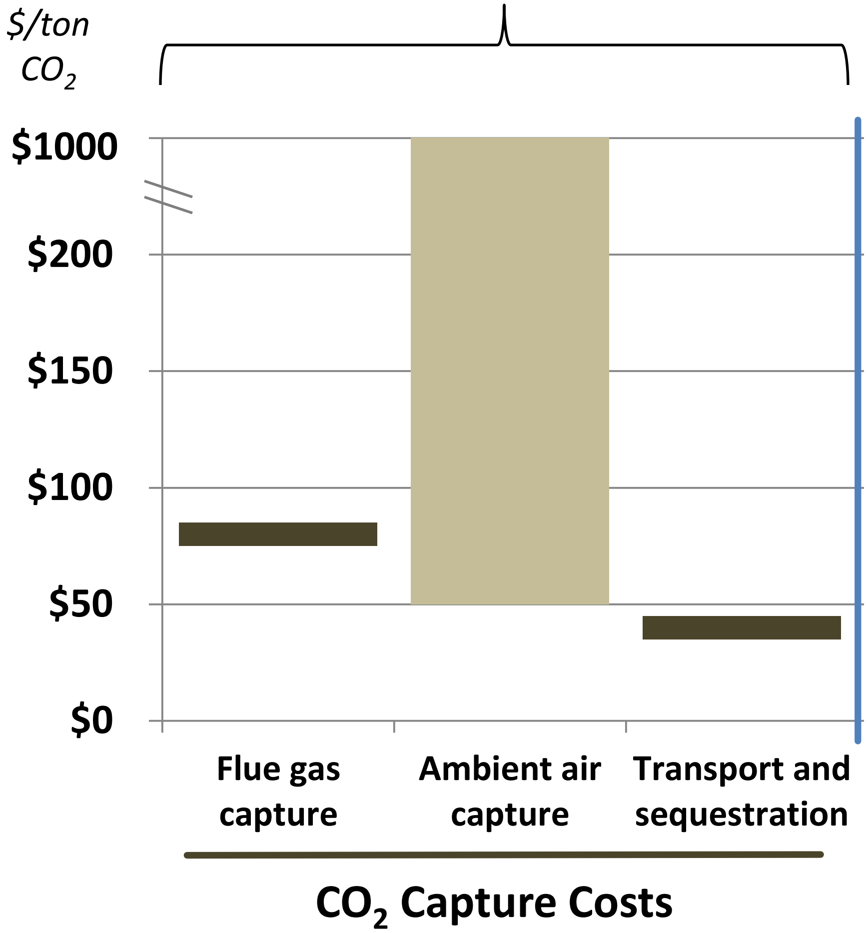

Cryogenic Air Distillation


CO_2 Scrubbing

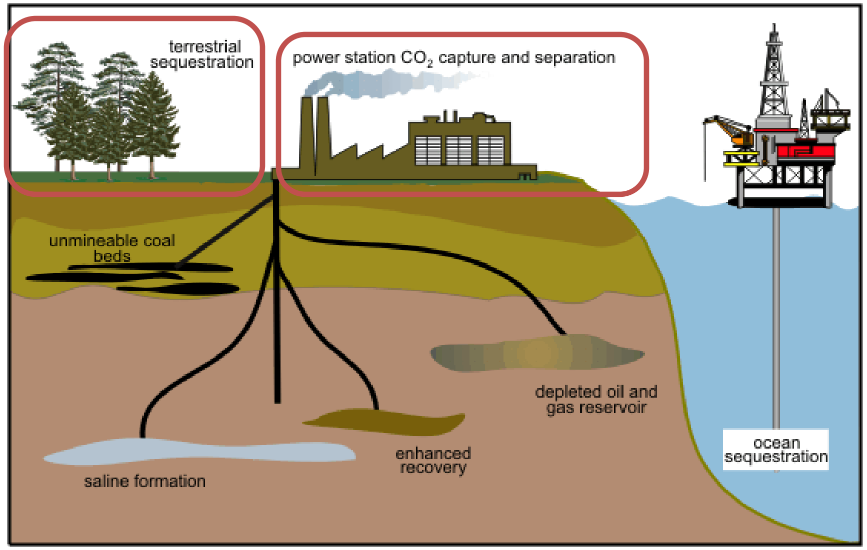

Alkaline Fuel Cells

Carbon economics driven by policy and technical constraints

Technical constraints contribute to high costs

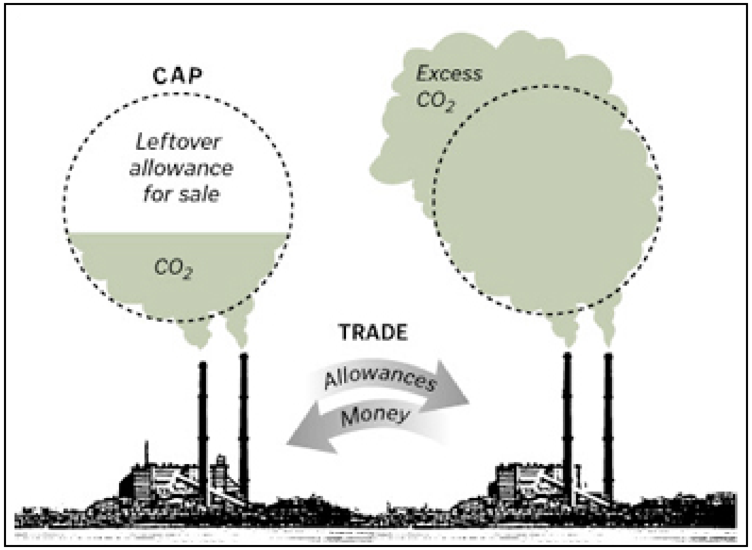


CCS: price on CO_2 depends on policy that penalizes emissions



Challenges for CCS

- ? Sequestration debated as reliable
- ? Limited policy leads to low CO2 price
- ? Low cost alternatives: reforestation



Opportunities for CCS

- ✓ Proven scientifically; no leakage
- ✓ Positive policy momentum worldwide
- ✓ MOF conserves valuable arable land

Near-term focus on niche applications for carbon capture

Metal Organic Frameworks

Carbon Capture Applications

Policy-Driven Sequestration

Enhanced Oil Recovery (EOR)

Algae Biofuels

Existing Industrial Applications

Natural Gas Processing

Cryogenic Air Distillation

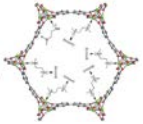
CO_2 Scrubbing

Alkaline Fuel Cells

Natural gas sweetening: numerous technologies available

→ Emerging technologies

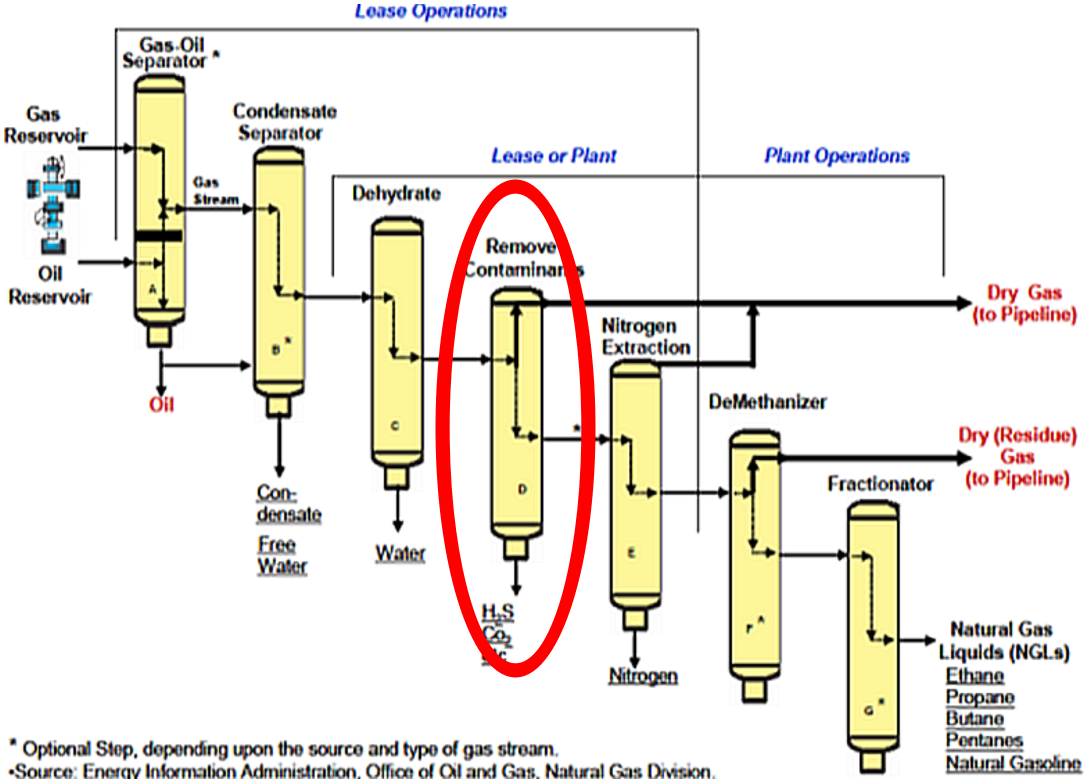
→ **Adsorbents: Used for low CO_2 gas**



Membranes < 10%

Amine Scrubbers ~ 90%

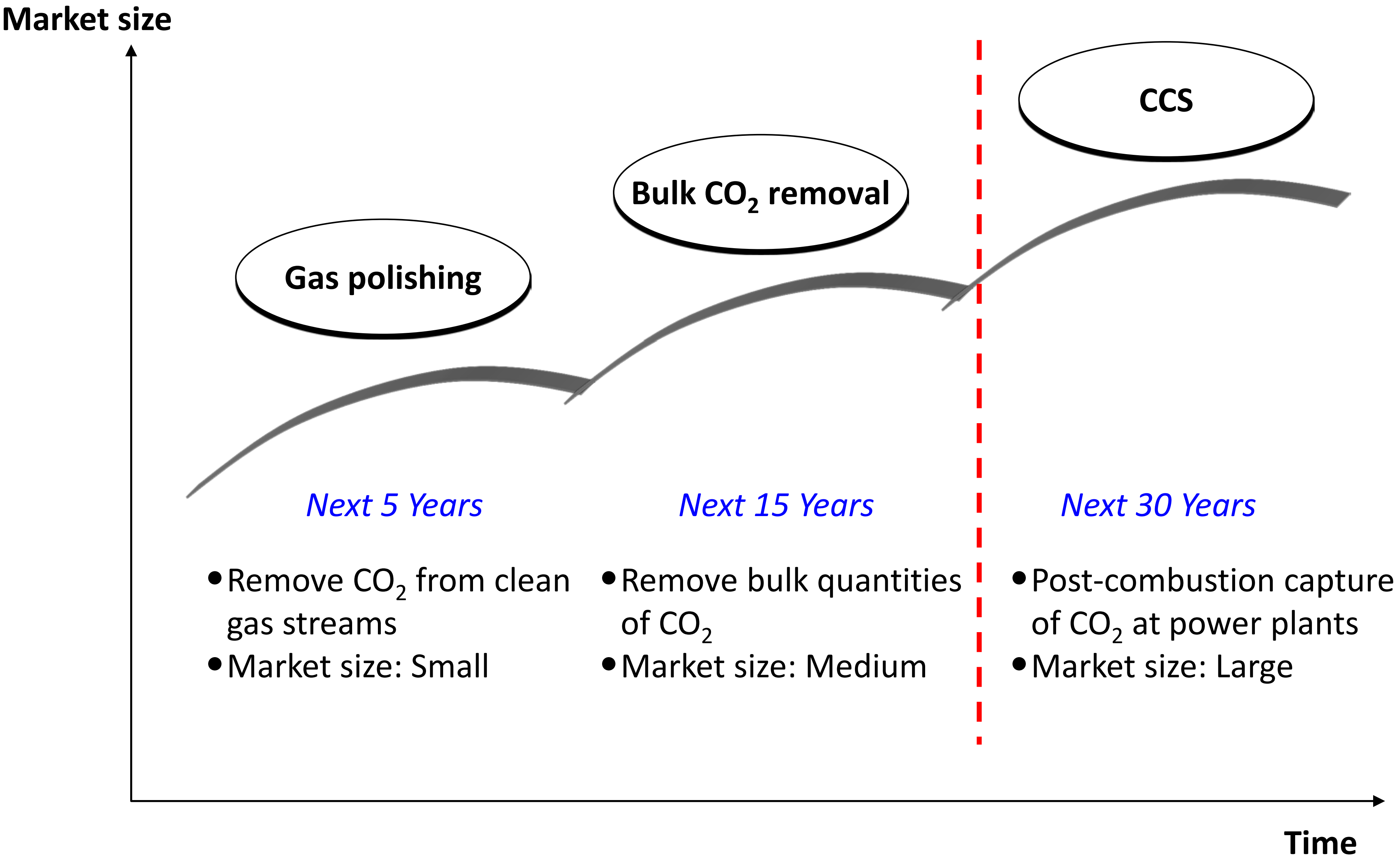
Used for bulk CO_2 removal



* Optional Step, depending upon the source and type of gas stream.

•Source: Energy Information Administration, Office of Oil and Gas, Natural Gas Division.

Natural gas sweetening: best pathway to prove the technology



Gas polishing

Next 5 Years

- Remove CO_2 from clean gas streams
- Market size: Small

Bulk CO_2 removal

Next 15 Years

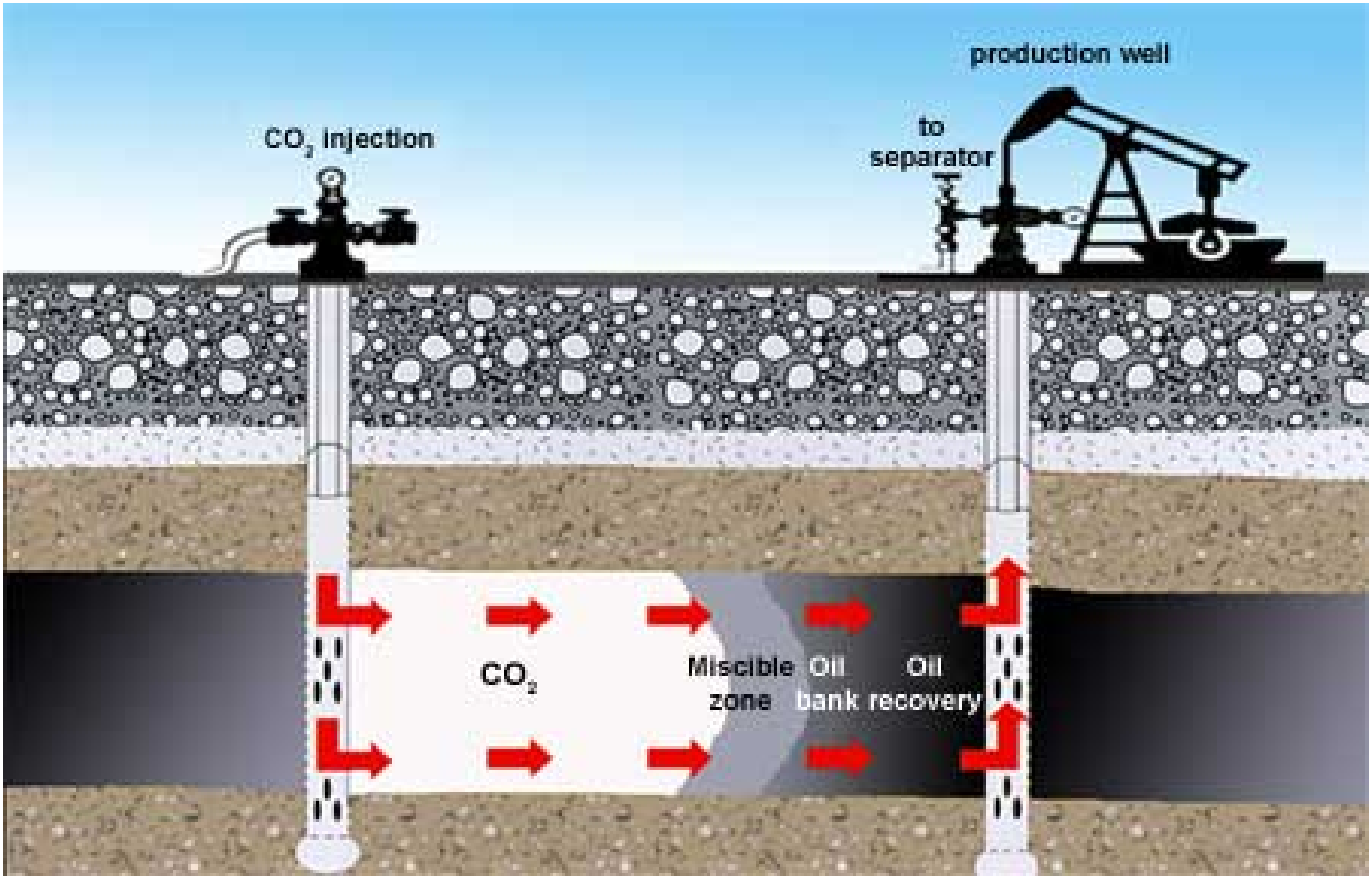
- Remove bulk quantities of CO_2
- Market size: Medium

CCS

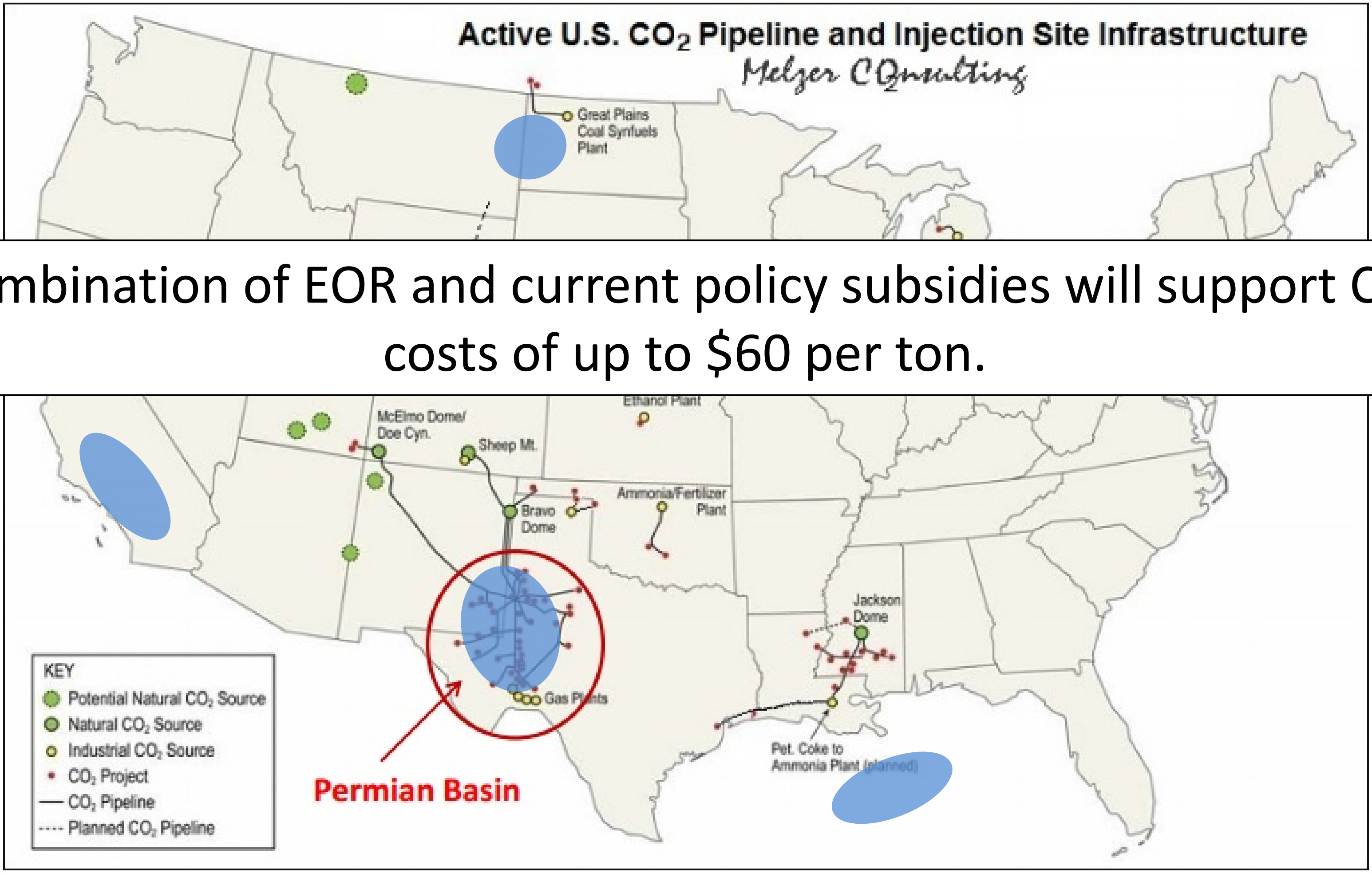
Next 30 Years

- Post-combustion capture of CO_2 at power plants
- Market size: Large

EOR: opportunity where CO_2 pipelines don't already exist



EOR: opportunity where CO_2 pipelines don't already exist



Combination of EOR and current policy subsidies will support CCS costs of up to $60 per ton.

Concentrations of the country's largest oil fields: ⬬

Algal biofuels: large customer base, but constrained by CO_2 pricing

Potential revenue from one customer	
Ethanol per acre (gallons)	7,000
Tons CO_2 per acre	40,000
# of acres	1,000
$s per ton CO_2	$40
Potential revenue	**$1,600,000**

- ✓ Optimal algae development is in US Southeast, not close to current CO_2 pipelines
- ? “Green” CO_2 for algae production needs a policy mandate
- ? Algae doesn’t need high purity CO_2 like EOR projects

Recommendation: niche applications until carbon policy matures

1 **License** with companies involved in natural gas sweetening

Dow®
BASF
UOP
A Honeywell Company

2 **License** with companies doing CCS with existing EOR and algae customers

kilimanjaro energy
globalthermostat

3 **Research** MOF’s capability to capture CO_2 from complex gas streams such as syn gas

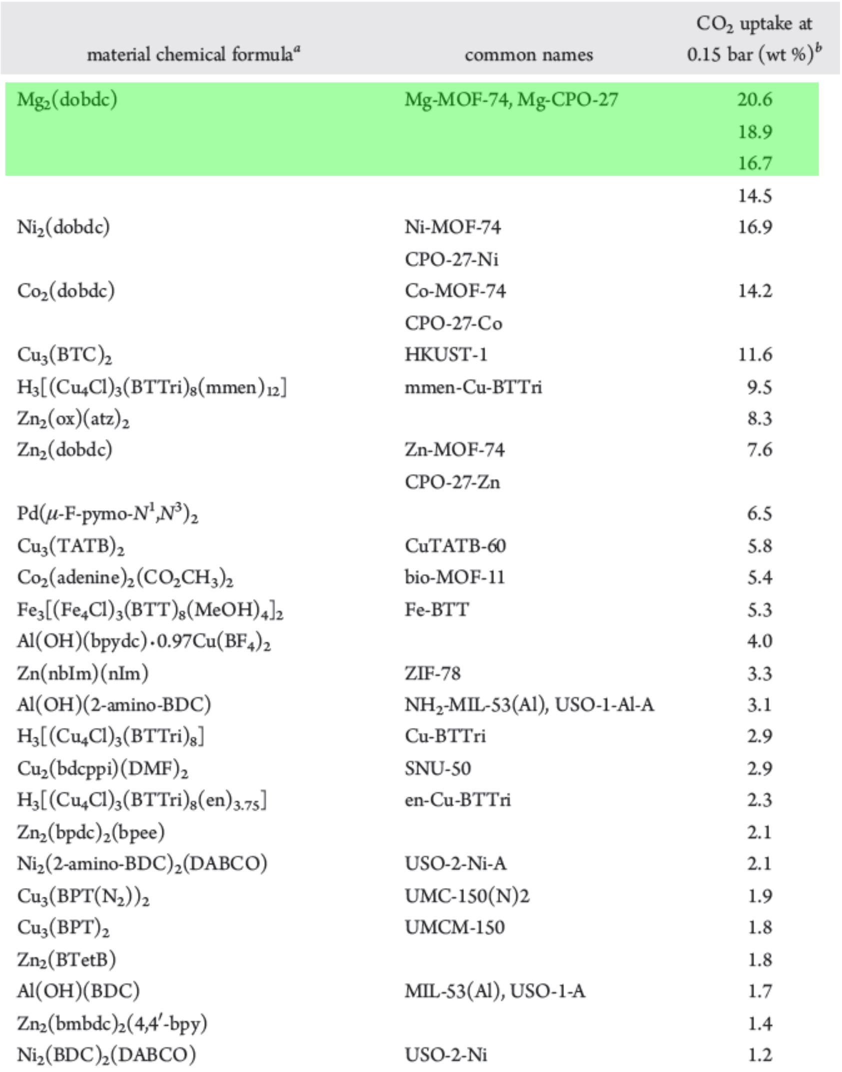
Thank You!

Appendix

MOFs can be used in industrial processes - anywhere CO_2 is unwanted

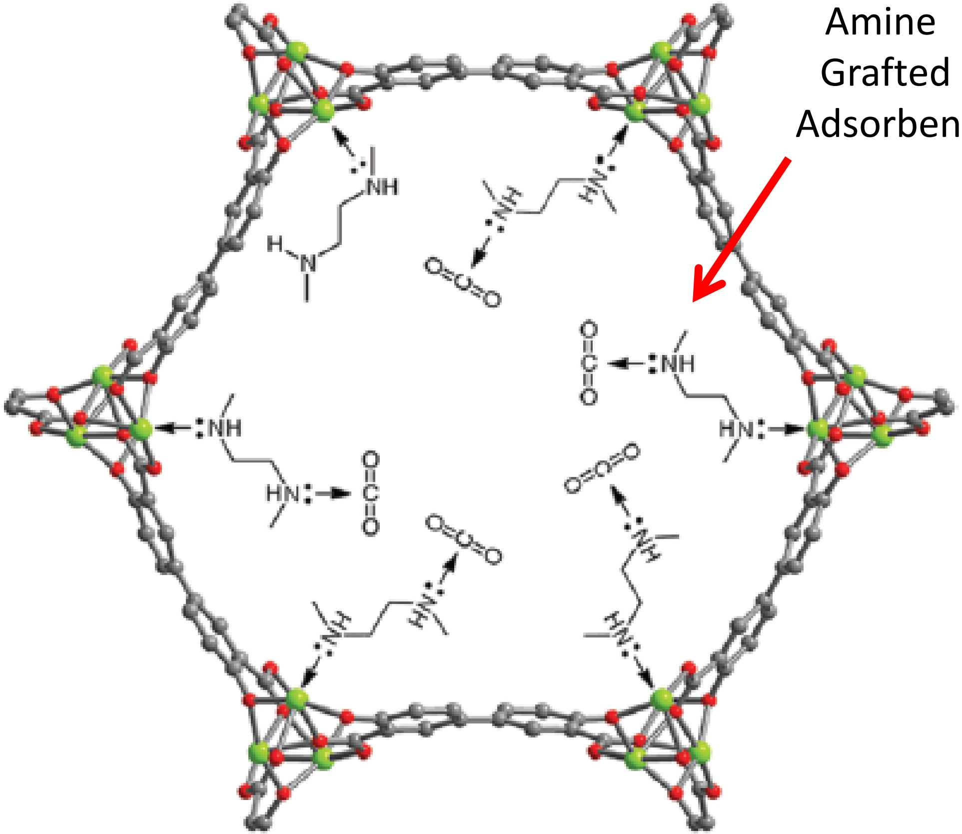
	Description	Obstacles
Gas treating	Removing CO_2 from natural gas before transportation	Not currently competitive for bulk CO_2 removal
Cryogenic distillation	Making pure streams of oxygen, nitrogen, and argon for industrial uses	MOFs unlikely to improve significantly on existing technology
CO_2 scrubbing	Removing CO_2 in spacecraft, submarines, and SCUBA gear	Very difficult market to enter and limited opportunities
Alkaline fuel cells	Preventing CO_2 contamination in AFCs, which powered Apollo space missions	Technology has largely been abandoned

Why is our MOF better?



material chemical formula[a]	common names	CO_2 uptake at 0.15 bar (wt %)[b]
Mg_2(dobdc)	Mg-MOF-74, Mg-CPO-27	20.6
		18.9
		16.7
		14.5
Ni_2(dobdc)	Ni-MOF-74	16.9
	CPO-27-Ni	
Co_2(dobdc)	Co-MOF-74	14.2
	CPO-27-Co	
$Cu_3(BTC)_2$	HKUST-1	11.6
$H_3[(Cu_4Cl)_3(BTTri)_8(mmen)_{12}]$	mmen-Cu-BTTri	9.5
$Zn_2(ox)(atz)_2$		8.3
Zn_2(dobdc)	Zn-MOF-74	7.6
	CPO-27-Zn	
$Pd(\mu\text{-F-pymo-}N^1,N^3)_2$		6.5
$Cu_3(TATB)_2$	CuTATB-60	5.8
$Co_2(adenine)_2(CO_2CH_3)_2$	bio-MOF-11	5.4
$Fe_3[(Fe_4Cl)_3(BTT)_8(MeOH)_4]_2$	Fe-BTT	5.3
$Al(OH)(bpydc)\cdot 0.97Cu(BF_4)_2$		4.0
Zn(nbIm)(nIm)	ZIF-78	3.3
Al(OH)(2-amino-BDC)	NH_2-MIL-53(Al), USO-1-Al-A	3.1
$H_3[(Cu_4Cl)_3(BTTri)_8]$	Cu-BTTri	2.9
$Cu_2(bdcppi)(DMF)_2$	SNU-50	2.9
$H_3[(Cu_4Cl)_3(BTTri)_8(en)_{3.75}]$	en-Cu-BTTri	2.3
$Zn_2(bpdc)_2(bpee)$		2.1
$Ni_2(2\text{-amino-BDC})_2(DABCO)$	USO-2-Ni-A	2.1
$Cu_3(BPT(N_2))_2$	UMC-150(N)2	1.9
$Cu_3(BPT)_2$	UMCM-150	1.8
$Zn_2(BTetB)$		1.8
Al(OH)(BDC)	MIL-53(Al), USO-1-A	1.7
$Zn_2(bmbdc)_2(4,4'\text{-bpy})$		1.4
$Ni_2(BDC)_2(DABCO)$	USO-2-Ni	1.2

- Highest capacity from dilute streams
- High stability under humid streams
- Potential to reversibly adsorb H_2S and water



Amine Grafted Adsorbent

Sumida et al. Chem. Rev. 2012, 112, 724-781