

# The Role of Carbon Dioxide Removal in Climate Change Intervention

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**Countries represented:** US, China, Canada, Saudi Arabia, South Korea, India, Thailand, Iran, and Italy

# To Prevent 2 ° C Warming ...

Between 2000-2050 if cumulative emissions are less than:

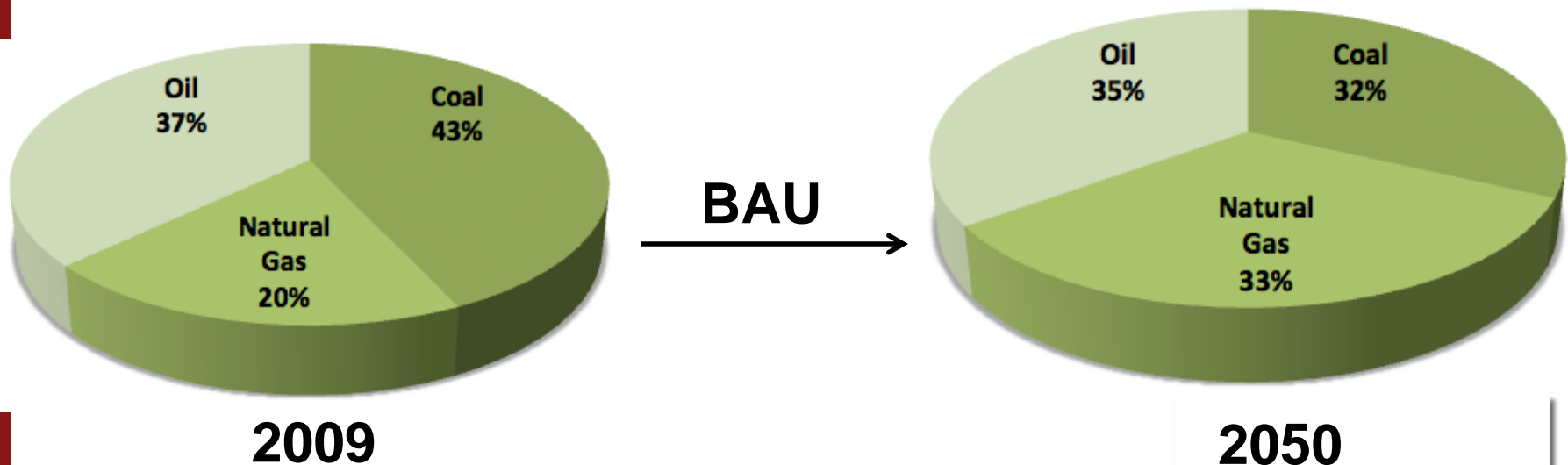
- 1,000 Gt → 25% probability global warming beyond 2 ° C
- 1,440 Gt → 50% probability global warming beyond 2 °

**Ref:** Allen et al., Nature, 2009

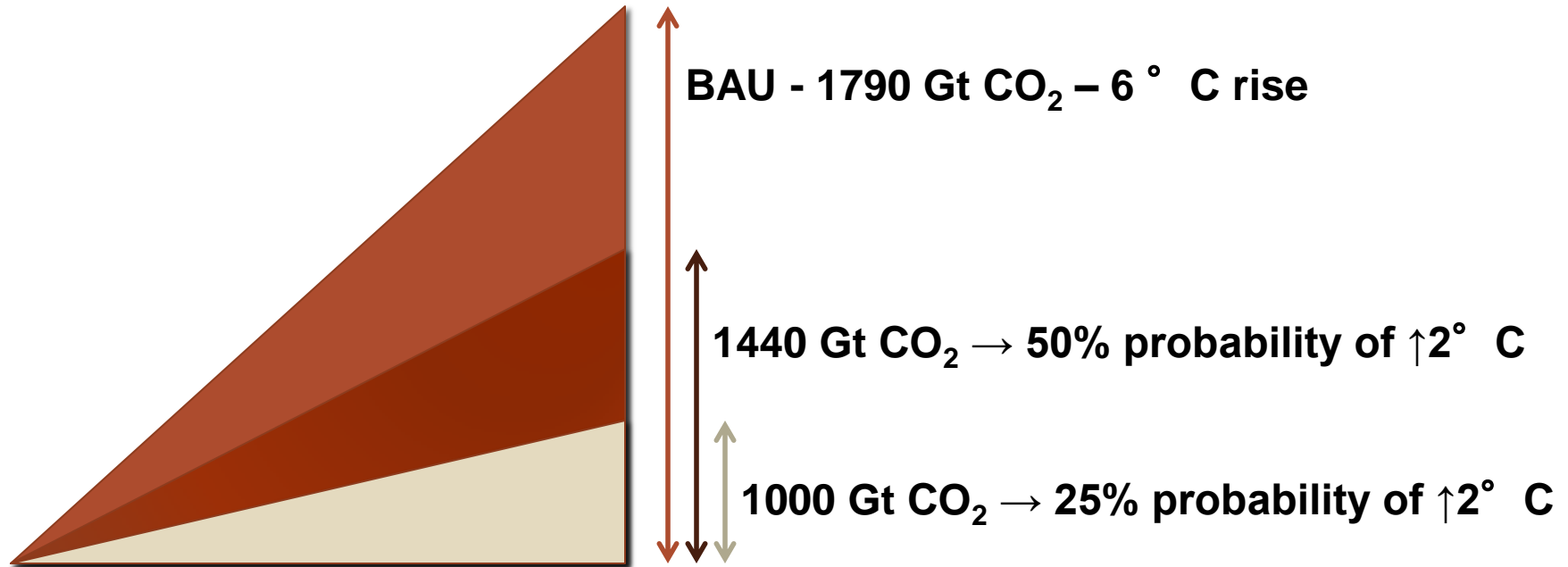
Where we're projected to go (BAU):

- Assuming annual increases:
  - › Coal – 0.3%
  - › Oil – 0.9%
  - › Natural Gas – 2.3%
- **≈ 31 Gt CO<sub>2</sub> emitted in 2011**
- **≈ 44 Gt CO<sub>2</sub> projected in 2050**
- **1790 cum. Gt CO<sub>2</sub> in 2050!**

**Ref:** BP Statistical Rev. of World Energy, 2012



# Can the Impact of CCS be Expanded?

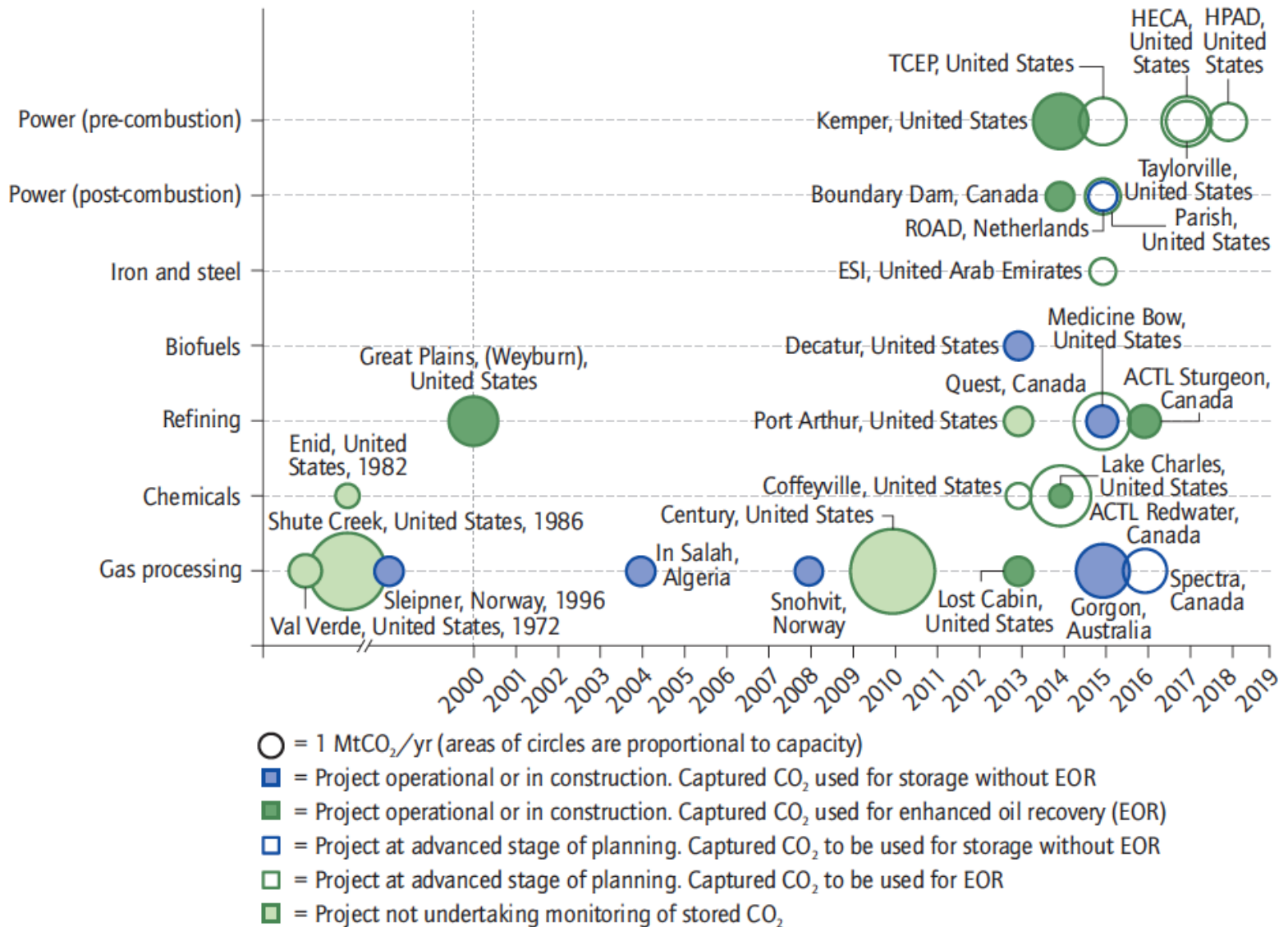


Scenario	Cumulative GtCO <sub>2</sub>
Replace Coal w/ NG	1512
90% Capture (Point Source Electric Sector)	1288
90% Capture (Point Source Electric Sector) + 50% Transport (on-board capture; EV; DAC)	1083

# CCS Progress to Date

- 4 large-scale CCS projects have carried out monitoring sufficient to ensure injected CO<sub>2</sub> is permanently sequestered
- Combined, ~50 MtCO<sub>2</sub> has been stored
- 9 additional projects under construction + ~13 MtCO<sub>2</sub>/yr and expected to be operational by 2016
- 2 possible demonstration projects at iron and steel plants and one at coal-to-chemicals/liquids – advanced stages of planning
- CO<sub>2</sub> pipeline transport is a mature technology w/ more than 3700 miles of pipelines in the U.S.
- CCS may be the primary large-scale option for emissions reductions from the industrial sector, e.g., cement, iron and steel, chemicals and refining, which represent ~20% of total global emissions
- CO<sub>2</sub> emissions from current systems under construction as of 2011 (e.g., power plants, industrial facilities, etc.) will total ~550 GtCO<sub>2</sub> through 2035

# Large-Scale CCS Projects





# ... but what if we fail to make progress?

## *Back-up Plans: Carbon Dioxide Removal (CDR) and Albedo Modification*

Separate CDR approaches into two categories:

- Combined CCS – Land Management and Accelerated Weathering

### **Potential Limitations**

- › Land Management - Irreversible land changes from deforestation and decreased biodiversity
- › Accelerated Weathering (ocean) – rate and capacity of CDR the can ocean handle
- › Mineral Carbonation (land) – scale of the available market for aggregate produced
- Carbon Capture + Storage – BECS and DACS (Bioenergy with Carbon Capture and Storage; Direct Air Capture with Storage)

### **Potential Limitations**

- › Bioenergy – storage of 18 GtCO<sub>2</sub>/yr requires ~ 1,000 million acres of arable land (Azar, 2010), while there's ~ 1380 million acres available worldwide
- › Direct Air Capture – land requirements for fueling process with non-carbonized energy (e.g., solar, wind)
- › Storage – quality of reservoir, maximum injection rate and capacity per reservoir, source location

# COMMITTEE ON GEOENGINEERING CLIMATE: TECHNICAL EVALUATION AND DISCUSSION OF IMPACTS

DOE, NASA, NOAA, U.S. intelligence community, and National Academy of Sciences supported this study

## **Technical assessment** of two classes of climate intervention technologies

- Removing carbon dioxide from the atmosphere
- Reducing sunlight absorbed by Earth in order to cool planet's surface
  - Afternoon Session Chaired by Marcia McNutt

## What is currently known

- Science - risks and consequences
- Viability for implementation

## Identify future research needed



# COMMITTEE ON GEOENGINEERING CLIMATE: TECHNICAL EVALUATION AND DISCUSSION OF IMPACTS

**Marcia K. McNutt (Chair)**

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University of Chicago

**Philip J. Rasch**

Pacific Northwest National Laboratory

**Lynn M. Russell**

Scripps Institution of Oceanography

**John T. Snow**

University of Oklahoma

**David W. Titley**

Penn State University

**Jennifer Wilcox**

Stanford University

- The Committee held four meetings and interacted with dozens of scientists
- Reports were reviewed by 16 outside experts

# THERE IS NO SUBSTITUTE FOR MITIGATION AND ADAPTATION

## Recommendation 1:

Efforts to address climate change should continue to focus most heavily on

- mitigating greenhouse gas emissions
- in combination with adapting to the impacts of climate change

because these approaches

- do not present poorly defined and poorly quantified risks and
- are at a greater state of technological readiness

# CARBON DIOXIDE REMOVAL READY FOR INCREASED RESEARCH AND DEVELOPMENT

## Recommendation 2:

The Committee recommends research and development investment to

- improve methods of carbon dioxide removal and disposal at scales that matter

in particular to

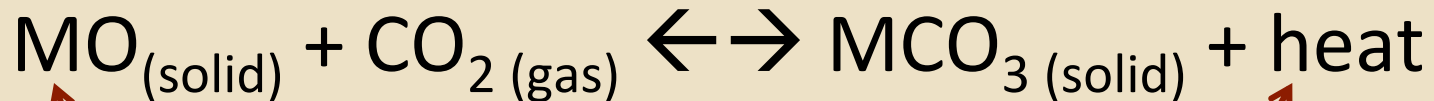
- minimize energy and materials consumption
- identify and quantify risks
- lower costs, and
- develop reliable sequestration and monitoring

# MINERAL CARBONATION - OVERVIEW

Mineral carbonation has been proposed for the removal of CO<sub>2</sub> from the atmosphere

Mineral carbonation converts gaseous CO<sub>2</sub> into solid mineral matter

- Reactions are analogous to silicate weathering (responsible for CO<sub>2</sub> uptake on geologic time scales)
- Mineralization products are stable carbonate rocks



M = divalent cation  
(e.g., Ca<sup>2+</sup> or Mg<sup>2+</sup>)

CaO → CaCO<sub>3</sub> = 179 kJ/mol  
MgO → MgCO<sub>3</sub> = 117 kJ/mol

# MINERAL CARBONATION – ALKALINITY SOURCES

A range of alkalinity sources can be used as reactants

- Naturally abundant silicate minerals
  - olivine
  - serpentine
- Industrial byproducts
  - coal fly ash (FA)
  - cement kiln dust (CKD)
  - steel slag (SS)



Magnesite after olivine<sup>1</sup>



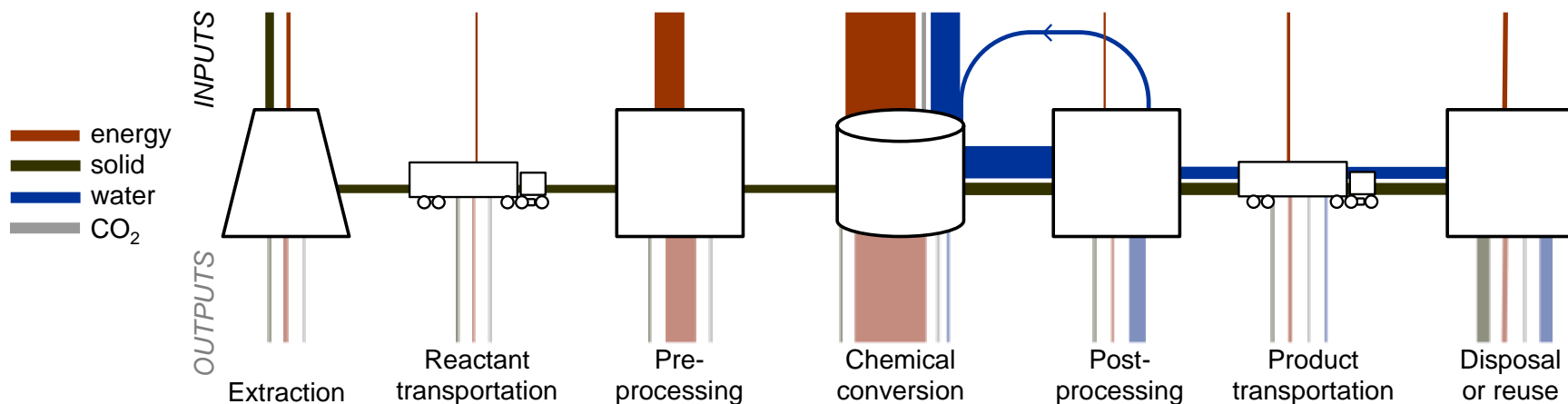
Fly ash disposal site<sup>2</sup>

<sup>1</sup><http://geologicalintroduction.baffl.co.uk>

<sup>2</sup><http://carbonwaters.org/2010/12/a-debate-over-fly-ash-disposal/>

# LIFE CYCLE ASSESSMENT

## *Olivine – 155 °C case*



### Inputs

Energy (GJ)	188	52	846	3,185	8	150	223
Solid material (t)	1,944	1,924	1,866	1,848	2,819	2,791	2,707
Water (t)	0	0	0	6,659	7,317	2,791	2,707
Recycled water (t)	0	0	0	731	0	0	0
Carbon dioxide (t)	0	0	0	1,000	0	0	0

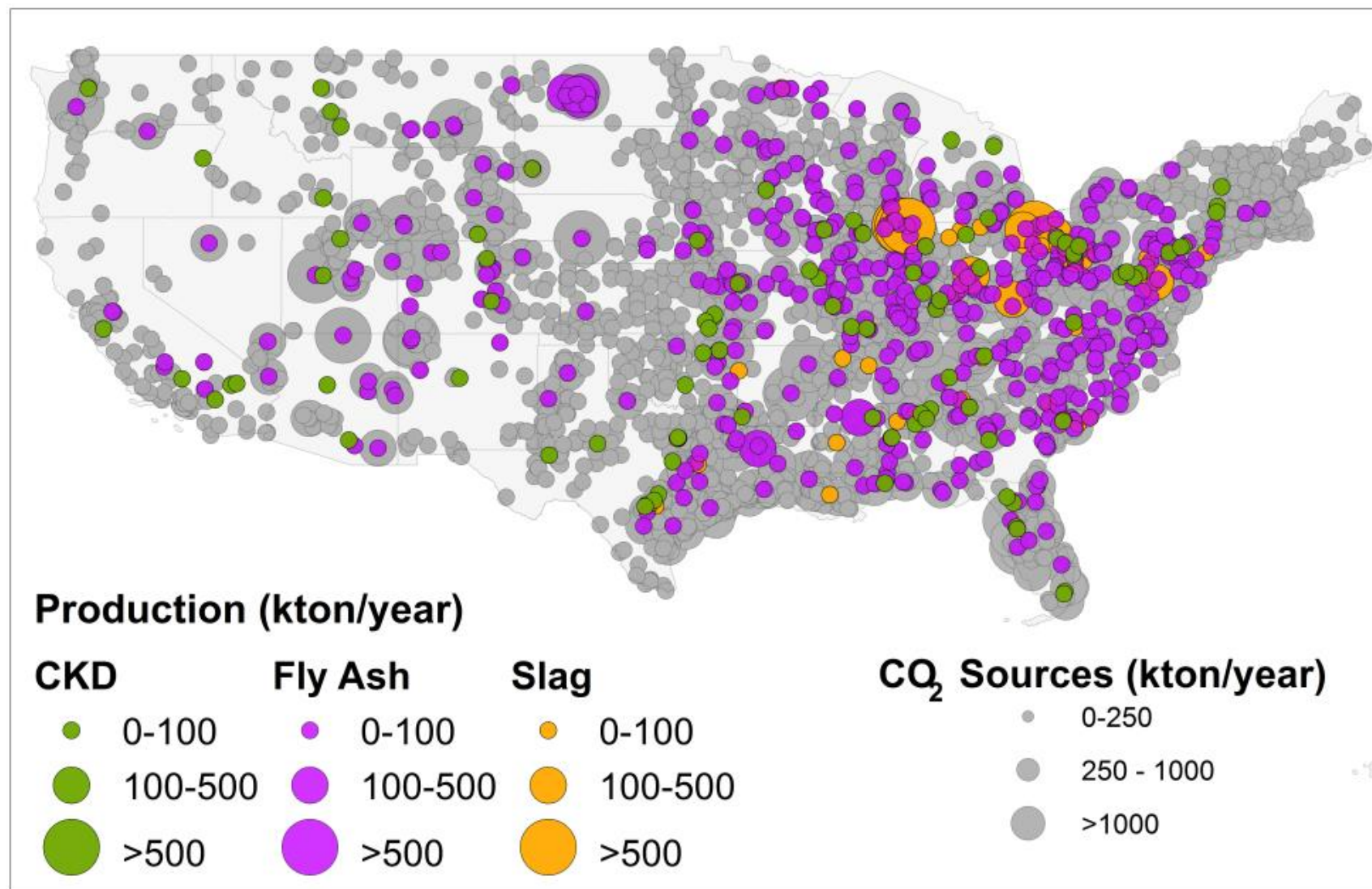
### Outputs

Solid material (t)	1,924	1,866	1,848	2,819	2,791	2,707	2,707
Water (t)	0	0	0	7,317	2,791	2,707	2,707
Water for recycle (t)	0	0	0	0	731	0	0
Waste material (t)	19	58	19	102	3,822	168	0
Waste energy (GJ)	188	52	846	3,185	8	150	223
CO <sub>2</sub> emissions (t)	11	3	62	166	1	10	13

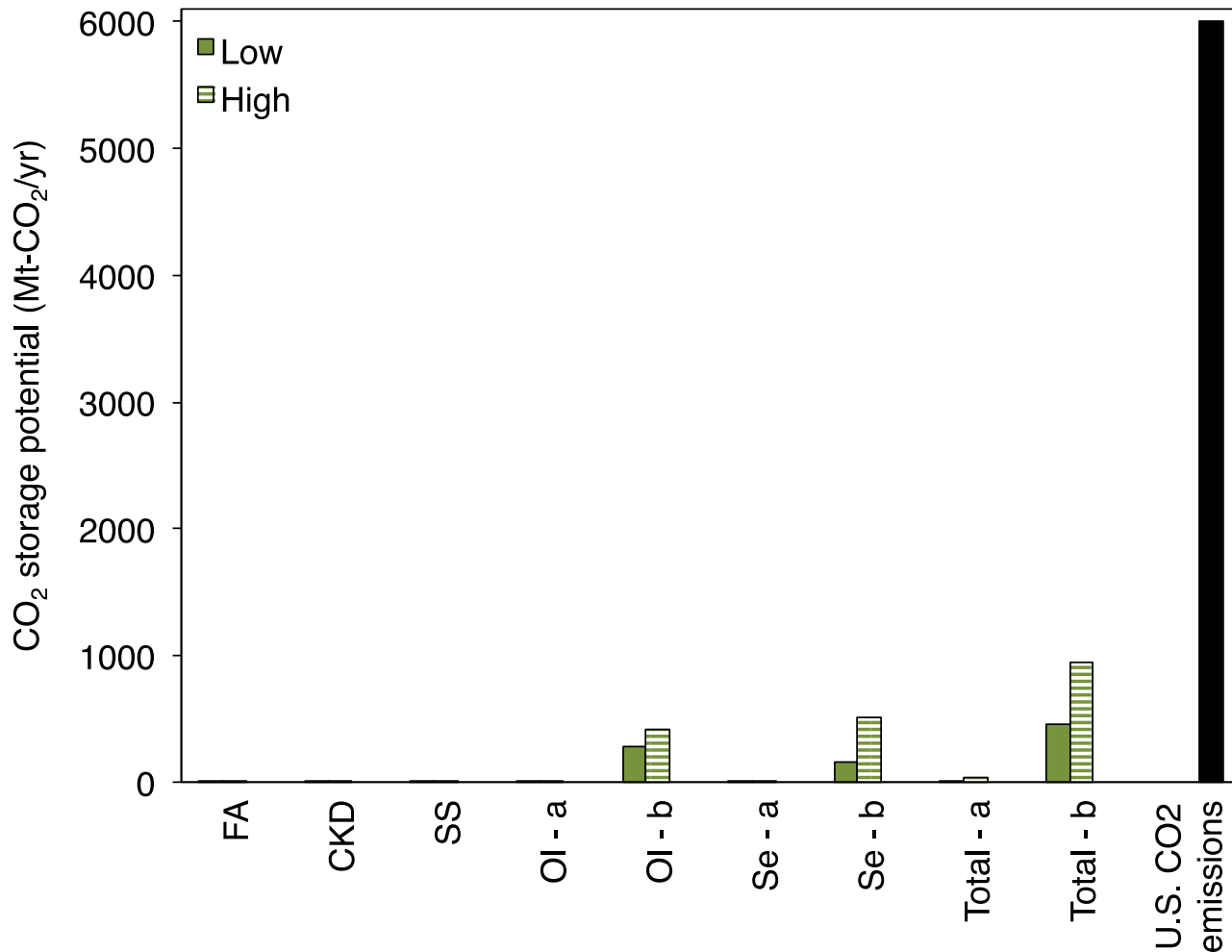




# INDUSTRIAL ALKALINITY PRODUCTION AND CO<sub>2</sub>



# SEQUESTRATION POTENTIAL OF MINERAL CARBONATION



- low mitigation potential for industrial alkalinity sources
- for natural alkalinity sources, mitigation potential depends on assumed production rate

# DIRECT AIR CAPTURE AND SEQUESTRATION (DACS)

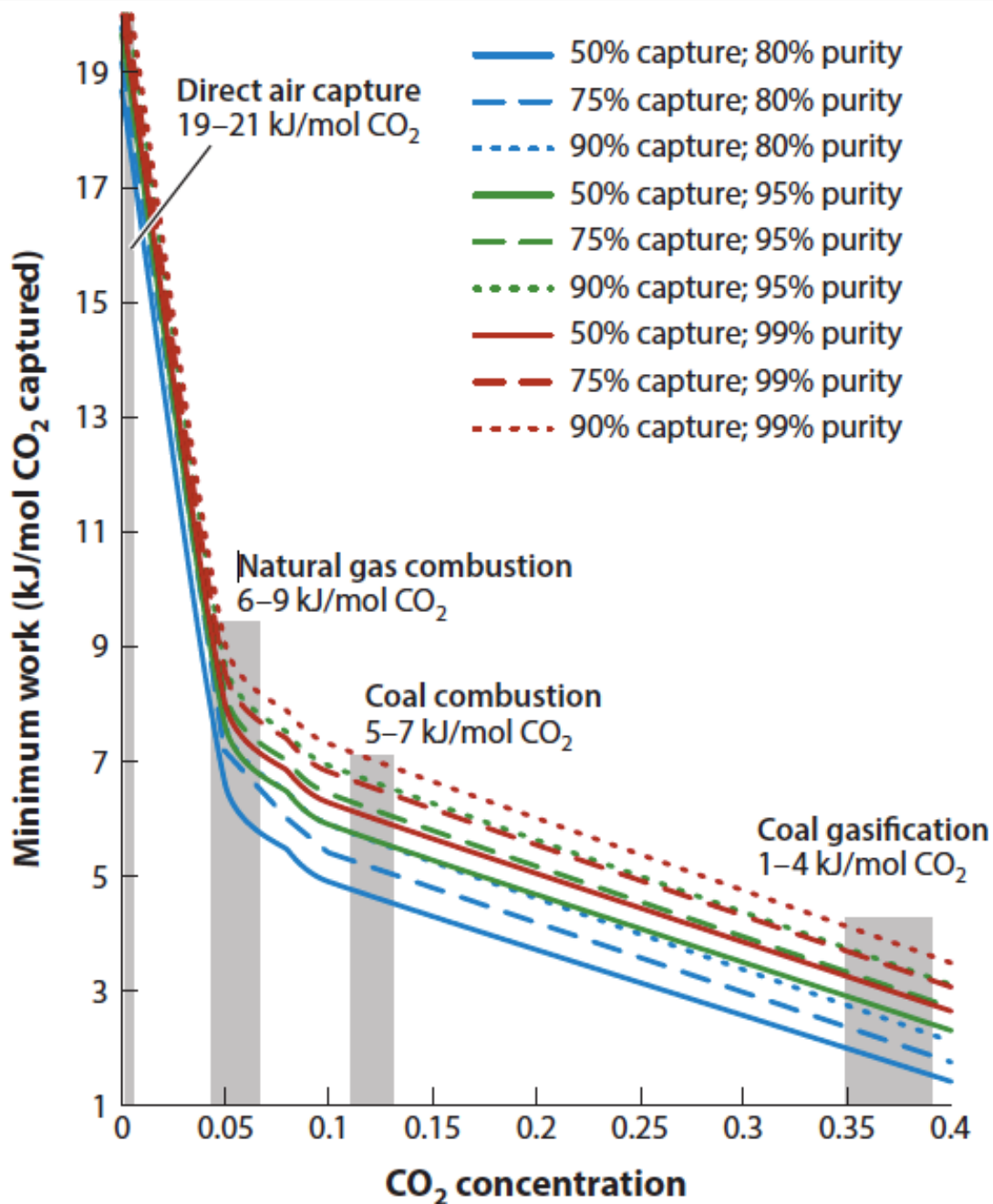
Chemical scrubbing processes capture carbon dioxide directly from the atmosphere

- Demonstration-scale projects are in progress
- Further development needed to reduce costs



# CAPTURE

## Minimum Work



**TABLE 2.2** Summary of the potential impacts of various CDR strategies. Amounts of CO<sub>2</sub> included in table are estimates of the theoretical or potentially feasible amounts, with the exception of those noted as the amounts required to keep global warming to less than 2°C (2DS). These estimates are provided mostly to only one significant figure to indicate possible scales of deployment and costs as estimated in published literature. Real world values could differ substantially from these estimates.

CDR Method		Rate of Capture or Sequestration [GtCO <sub>2</sub> /yr]	Cumulative CDR to 2100 [GtCO <sub>2</sub> ]	Cost [\$/tCO <sub>2</sub> ]	Limitations
Combined Capture and Sequestration	Land Management				<ul style="list-style-type: none"> <li>• Irreversible land changes from deforestation/past land uses</li> <li>• Decreased biodiversity</li> <li>• Competition for land for agricultural production</li> </ul>
	Afforestation/ Reforestation	2-5 <sup>a</sup>	100 <sup>b</sup>	1-100 <sup>c</sup>	
	Accelerated Weathering:				
	Land	2 (U.S. only)	~100 (U.S. only)	20-1,000 <sup>e</sup>	<ul style="list-style-type: none"> <li>• Land—available cheap alkalinity and aggregate markets for product</li> <li>• Ocean—available cheap alkalinity</li> </ul>
	Ocean	1 <sup>d</sup>	~ 100	50-100 <sup>ef</sup>	
Ocean Iron Fertilization		1-4 <sup>g</sup>	90-300	500 <sup>h</sup>	<ul style="list-style-type: none"> <li>• Environmental consequences and potential co-benefits</li> <li>• Uncertainty in net carbon sequestration</li> </ul>
Capture	Bioenergy with Capture	15-18 <sup>i</sup> (Theoretical)	100-1,000 <sup>j</sup>	~100 <sup>k</sup>	<ul style="list-style-type: none"> <li>• Sequestration of 18 GtCO<sub>2</sub>/yr requires ~ 1,000 million acres of arable land (1,530 mill. acres available worldwide<sup>l</sup>; actual amount of arable land available for bioenergy production will likely be significantly less because much of arable land area is required for food production)</li> </ul>
	Direct Air Capture	10 <sup>m</sup> (U.S. only)	~1,000 (U.S. only)	400-1,000 <sup>n</sup>	<ul style="list-style-type: none"> <li>• Land available for solar ~ 100,000,000 acres of BLM land in Southwest United States<sup>o</sup></li> </ul>

# Combined Capture and Sequestration

CDR Method	Rate of Capture or Sequestration [GtCO <sub>2</sub> /yr]	Cumulative CDR to 2100 [GtCO <sub>2</sub> ]	Cost [\$/tCO <sub>2</sub> ]	Limitations
Land Management				
Afforestation/ Reforestation	2-5 <sup>a</sup>	100 <sup>b</sup>	1-100 <sup>c</sup>	<ul style="list-style-type: none"> <li>• Irreversible land changes from deforestation/past land uses</li> <li>• Decreased biodiversity</li> <li>• Competition for land for agricultural production</li> </ul>
Accelerated Weathering:				
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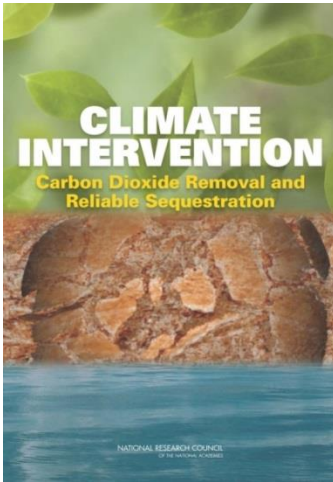
# Sequestration

CDR Method	Rate of Capture or Sequestration [GtCO <sub>2</sub> /yr]	Cumulative CDR to 2100 [GtCO <sub>2</sub> ]	Cost [\$/tCO <sub>2</sub> ]	Limitations
Geologic	1-20 <sup>p</sup> (2DS)	800 <sup>p</sup> (2DS)	10-20 <sup>q</sup>	<ul style="list-style-type: none"> <li>Permeability of formation, number of wells, and overall size of the sequestration reservoir</li> </ul>
Ocean (molecular CO <sub>2</sub> )	?	2,000 to 10,000 <sup>r</sup>	10-20 <sup>r</sup>	<ul style="list-style-type: none"> <li>Environmental consequences associated with ocean acidification</li> </ul>
Ocean (CO <sub>2</sub> neutralized with added alkalinity)	? <sup>s</sup>	? <sup>s</sup>	10-100 <sup>r</sup>	<ul style="list-style-type: none"> <li>Availability of alkaline minerals</li> </ul>

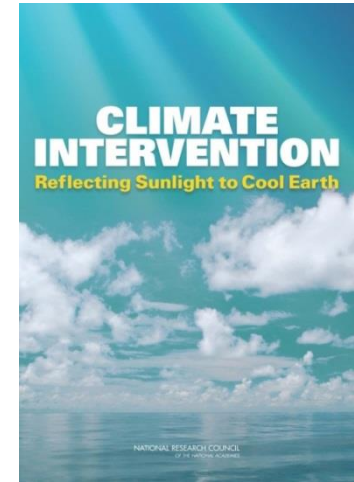
# RESEARCH OPPORTUNITIES FOR CDR

- Assess and improve strategies for performing and monitoring geologic sequestration
- Explore strategies that increase the ocean's ability to store carbon without causing adverse effects
- Continued research on combining biomass energy with carbon dioxide capture and sequestration including exploration of approaches that do not form and sequester concentrated CO<sub>2</sub>
- Solicit, foster, and develop approaches for scrubbing carbon dioxide from the atmosphere that hold the potential to bring costs and energetics into a potentially feasible range
- Land use management techniques that promote carbon sequestration
- Accelerated weathering as a CO<sub>2</sub> removal/sequestration approach that would allow conversion to stable, storable, or useful carbonates and bicarbonates

# ACKNOWLEDGMENTS



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Committee  
Reviewers  
NRC Staff  
Numerous colleagues consulted  
during study



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- Information about upcoming events, such as webinar Feb 26
- Briefing slides and archived public release webcast

# Questions?



Clean Energy Conversions Website: <http://cec-lab.stanford.edu>



# CO<sub>2</sub> Utilization

- Most of the “CCS” projects involve utilization (i.e., EOR) rather than permanent storage of CO<sub>2</sub>
- ~80 Mt – 120 MtCO<sub>2</sub> sold commercially each year for various applications (e.g., chemical solvents, coffee decaffeination, fertilizer, carbonated beverages, etc.)
- CO<sub>2</sub> demand for refrigerants and solvents << 1 MtCO<sub>2</sub>/yr, while beverage industry ~8 MtCO<sub>2</sub>/yr
- Largest user is EOR ~70 MtCO<sub>2</sub>/yr, mostly from natural sources
- Many utilization processes return CO<sub>2</sub> into the atmosphere

# Current EOR: Primary Use of CO<sub>2</sub> in US

Location of EOR / CO <sub>2</sub> Storage	CO <sub>2</sub> Sources by Type and Location	CO <sub>2</sub> Supply (MMcfd)*	
		Natural	Anthropogenic
Texas-Utah-New Mexico-Oklahoma	Natural CO <sub>2</sub> (Colorado-New Mexico)	1,730	335
New Mexico-Oklahoma	Gas Processing Plants (W. Texas)		
Colorado-Wyoming	Gas Processing Plants (Wyoming)	-	340
Mississippi/Louisiana	Natural CO <sub>2</sub> (Mississippi)	1,100	-
Michigan	Ammonia Plant (Michigan)	-	15
Oklahoma	Fertilizer Plant (Oklahoma)	-	30
Saskatchewan	Coal Gasification Plant (North Dakota)	-	150
<b>TOTAL (MMcfd)</b>		<b>2,830</b>	<b>870</b>
<b>TOTAL (million mt/yr)**</b>		<b>55</b>	<b>17</b>

Note the scale: ~ 72 Mt CO<sub>2</sub>/yr

# Future EOR in the US

Basin/Area	Technically Recoverable Oil (Billion Barrels)		Economically Recoverable Oil** (Billion Barrels)		Economic CO <sub>2</sub> Demand/Storage** (Million Metric Tons)	
	SOA	"Next Generation"	SOA**	"Next** Generation"	SOA**	"Next Generation"
<b>1. Miscible CO<sub>2</sub>-EOR</b>						
Lower-48 Onshore	55.7	104.4	24.3	60.3	8,940	17,230
Alaska	5.8	8.8	2.6	5.7	1,490	2,330
Offshore GOM	-	6.0	-	0.9	-	260
<b>Sub-Total</b>	<b>61.5</b>	<b>119.1</b>	<b>26.9</b>	<b>67.0</b>	<b>10,430</b>	<b>19,820</b>
<b>2. New Miscible CO<sub>2</sub>-EOR</b>	n/a	1.2	n/a	0.2	-	110
<b>3. Residual Oil Zones</b>	n/a	16.3	n/a	***	-	***
<b>Total</b>	<b>61.5</b>	<b>136.6</b>	<b>26.9</b>	<b>67.2</b>	<b>10,430</b>	<b>19,930</b>

~ 10-20 Gt CO<sub>2</sub>

**EOR → advancements in CO<sub>2</sub> separation technologies and decreased cost**