Coal Utilization for Power and Chemicals in a Carbon-Constrained World

Pittsburgh Coal Conference

Dr. Raghubir Gupta, Senior Vice President – Energy Technology Division

September 8th, 2017

What is RTI International?

RTI is an independent, nonprofit institute that provides research, development, and technical services to government and commercial clients worldwide.

Our mission is to improve the human condition by turning knowledge into practice.

RTI International and Its Energy Technology Division

delivering **the promise of science** for global good

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1,102 Clients (fiscal year 2016)

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Syngas Processing	Natural Gas

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY | U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy BIOENERGY TECHNOLOGIES OFFICE | U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy ADVANCED MANUFACTURING OFFICE | arpa-e | EMISSIONS REDUCTION ALBERTA | GASSNOVA | CASALE | CLARIANT | BASF We create chemistry | SINTEF | HALDOR TOPSØE | VEOLIA | Masdar | THE LINDE GROUP | BERKELEY LAB | MIT | CLEMSON UNIVERSITY | NC STATE UNIVERSITY | STANFORD UNIVERSITY | Duke UNIVERSITY | UC RIVERSIDE

US Coal Landscape – Short-Term Energy Outlook – Slight Uptick for Coal

- **Coal Production and Exports**
  - **37 million short tons (MMst)** of coal were exported in the first five months of 2017
    - **60% higher** than coal exports over the same period last year
  - The increase in coal exports contributes to an expected increase in coal production

- **Electric Power Sector**
  - U.S. total utility-scale electricity generation from natural gas will drop in 2017 (34% to 31%) , while **coal will increase from 30% to 32%**
    - Result of higher natural gas prices, increased generation from renewables and coal, and lower electricity demand

- **Emissions**
  - **After declining 1.7% in 2016,** energy-related carbon dioxide (CO_2) emissions are projected to decrease 0.3% in 2017 and then to **increase 2.0% in 2018**

Coal Production

2017	2018
58 MMst Increase (8%)	10 MMst Increase (1%)

2018 Projected Utility-Scale Electricity Shares

Natural Gas	Coal
31%	32%

CO_2 Emissions

2017	2018
0.3% Decrease	2% Increase

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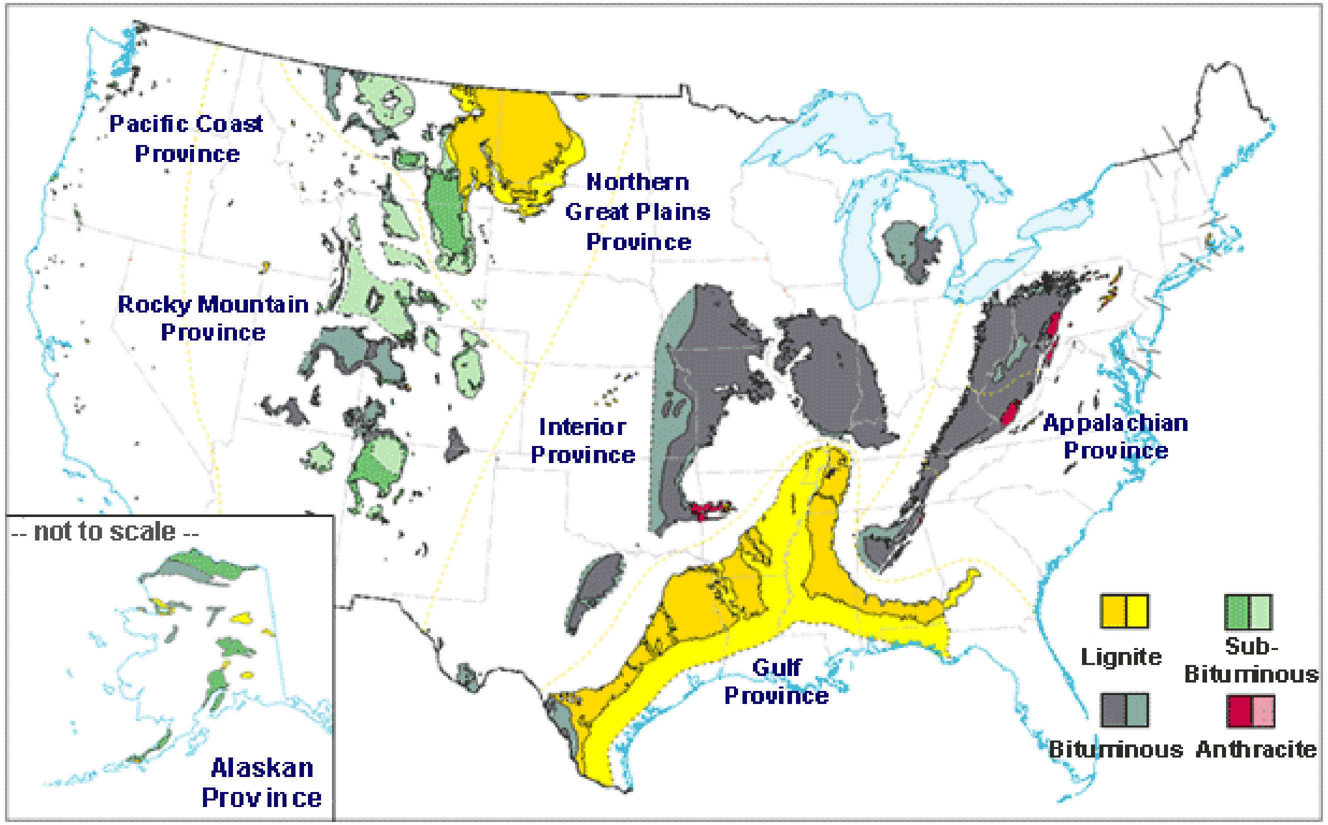
Source: U.S. Energy Information Administration (EIA), Short-Term Energy Outlook August 2017

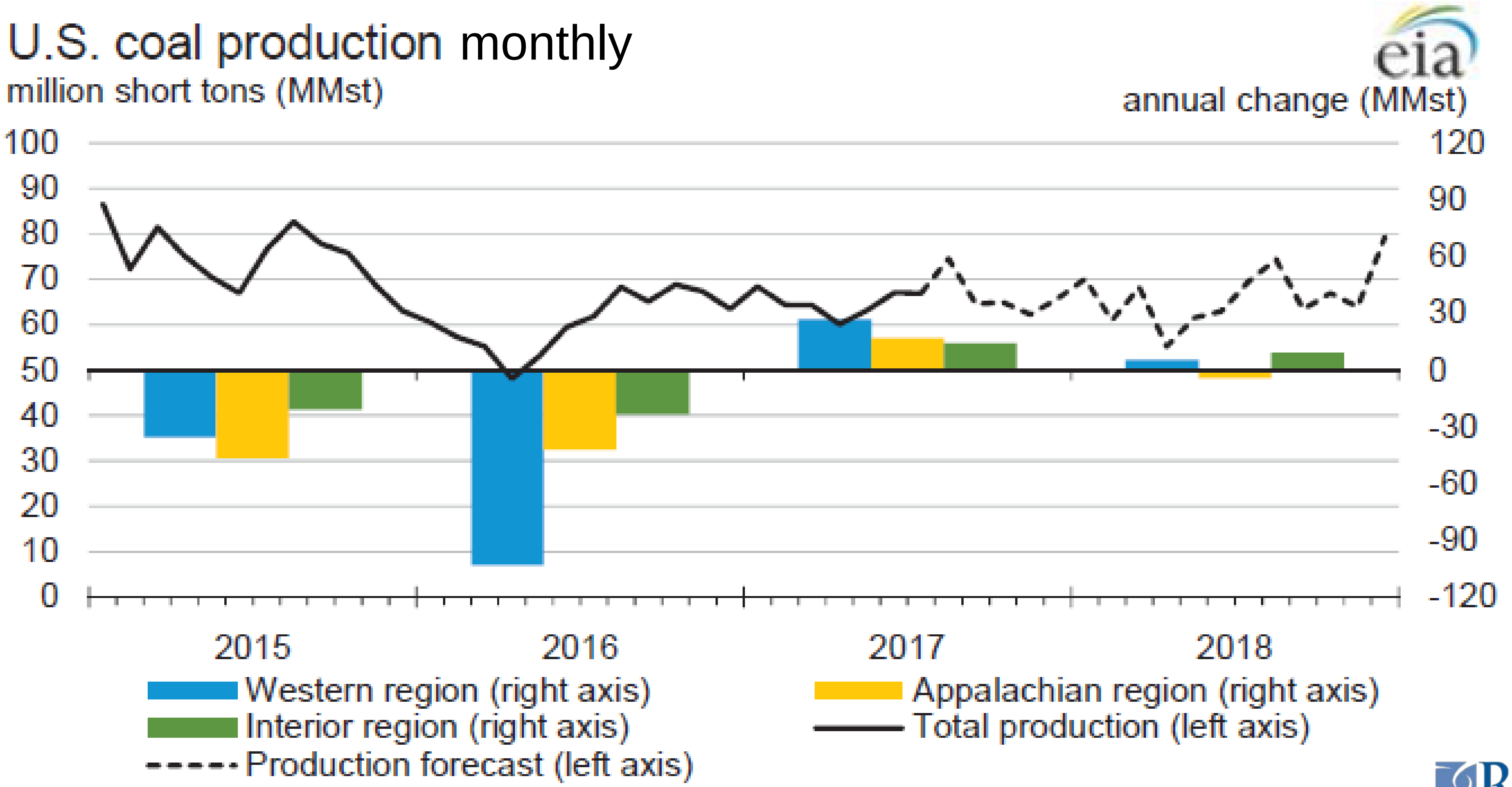
Low-Rank Coals Represent Half of all U.S. Demonstrated Coal Reserves



U.S. Coal Reserves by State and Type - 2014 (Billion Short Tons)		
State	U.S. Demonstrated Reserve Base (DRB)	% of Total DRB
Montana	118.73	24.82%
Illinois	103.78	21.69%
Wyoming	58.97	12.33%
West Virginia	30.88	6.45%
Kentucky	28.44	5.94%
Pennsylvania	26.46	5.53%
Ohio	22.90	4.79%
Colorado	15.74	3.29%
Texas	11.91	2.49%
New Mexico	11.83	2.47%
Indiana	8.98	1.88%
North Dakota	8.73	1.82%
Alaska	6.09	1.27%
Missouri	5.99	1.25%
Utah	5.02	1.05%

- These 15 states contain > 97% of total U.S. demonstrated coal reserves.
- Currently, ~40% of U.S. active/mined coal production reserves are PRB (sub-bit.) and ~10% are lignite.

Some Short-Term Improvement in Coal Production for All U.S. Regions



Source: Short-Term Energy Outlook, August 2017.

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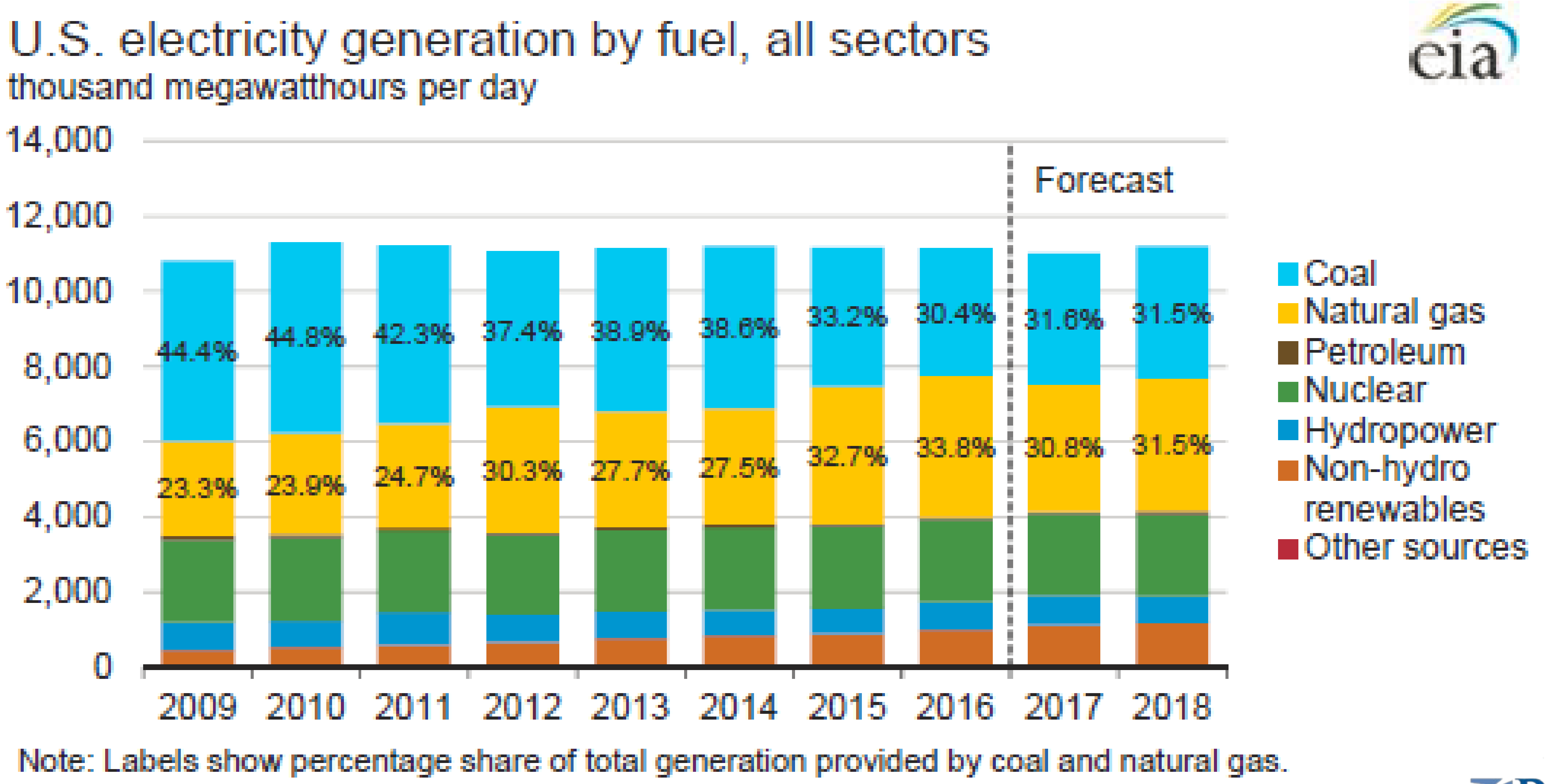
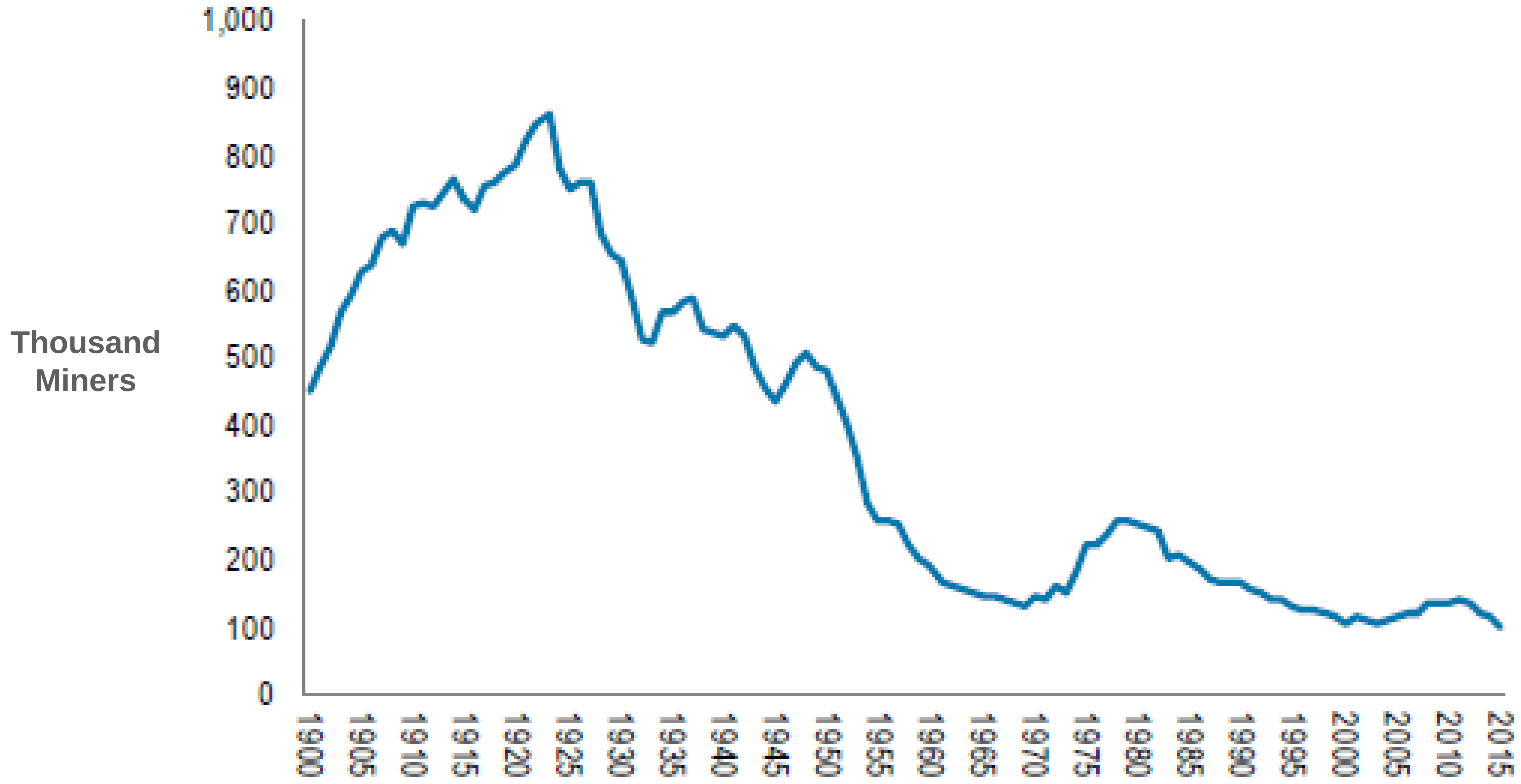
But the Trend has been for Decreasing Use of Coal for U.S. Power Generation



Source: Short-Term Energy Outlook, August 2017.

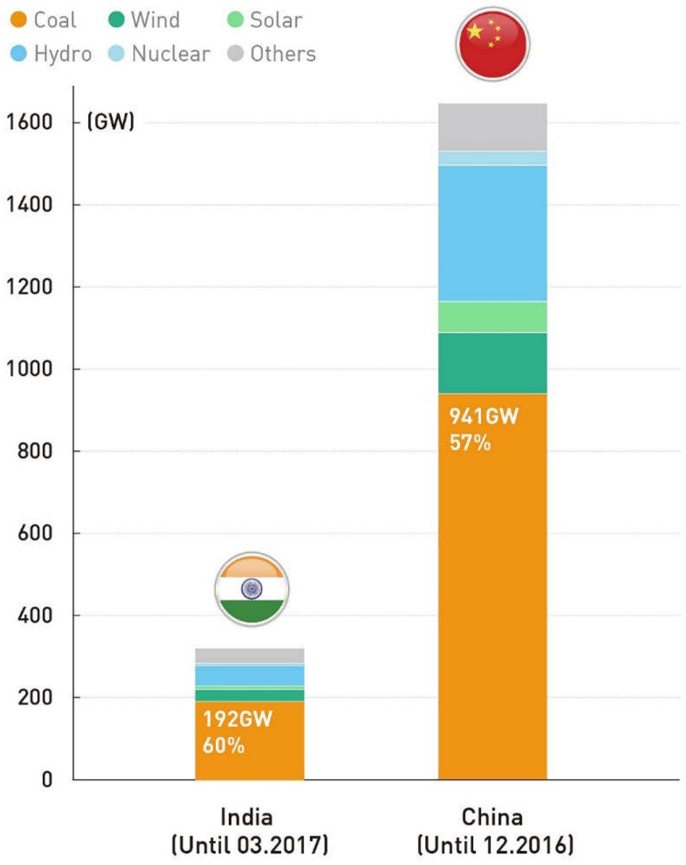
And U.S. Coal Mining Employment has been in General Decline Since 1980



Source: Mine Safety and Health Administration, includes office workers starting in 1973.

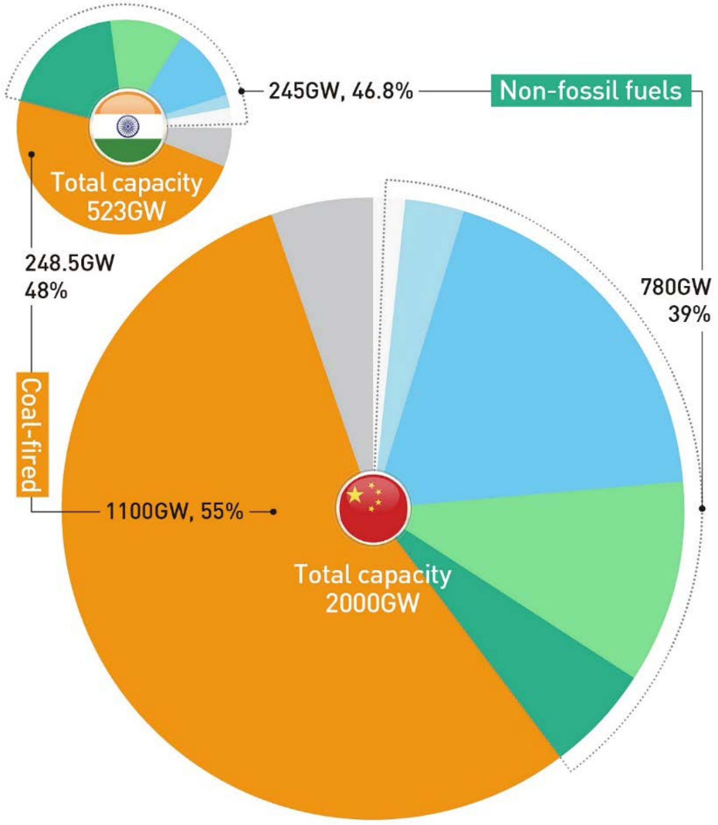
Coal Still Dominates in India and China…For Now

India and China's Total Installed Power Generation and the Structure



Projected Demand of Capacity Additions in India's National Electricity Plan

India and China's Electricity Generation Breakdown by End of 13th FYP



Note: India's 13thFYP ends in 2022, while China's 13th FYP ends in 2020

India estimates coal power's share falling from

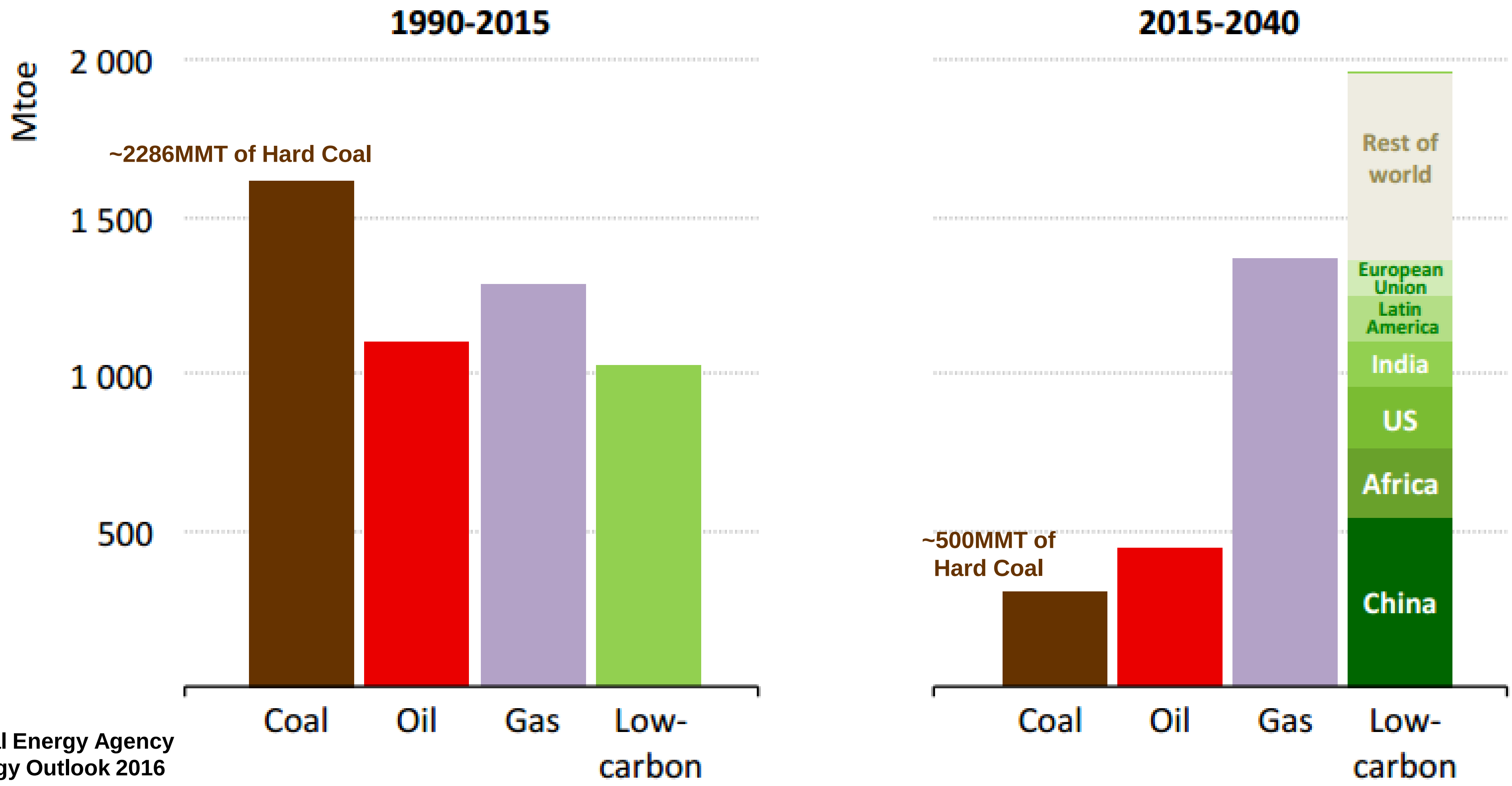
60% to 48%

by 2022

Source: Chinadialogue (Aug. 2017), Central Electricity Authority of India, National Bureau of Statistics of China, National Energy Administration of China

Long-Term Global Energy Demand Growth is Shifting to Low-Carbon Sources

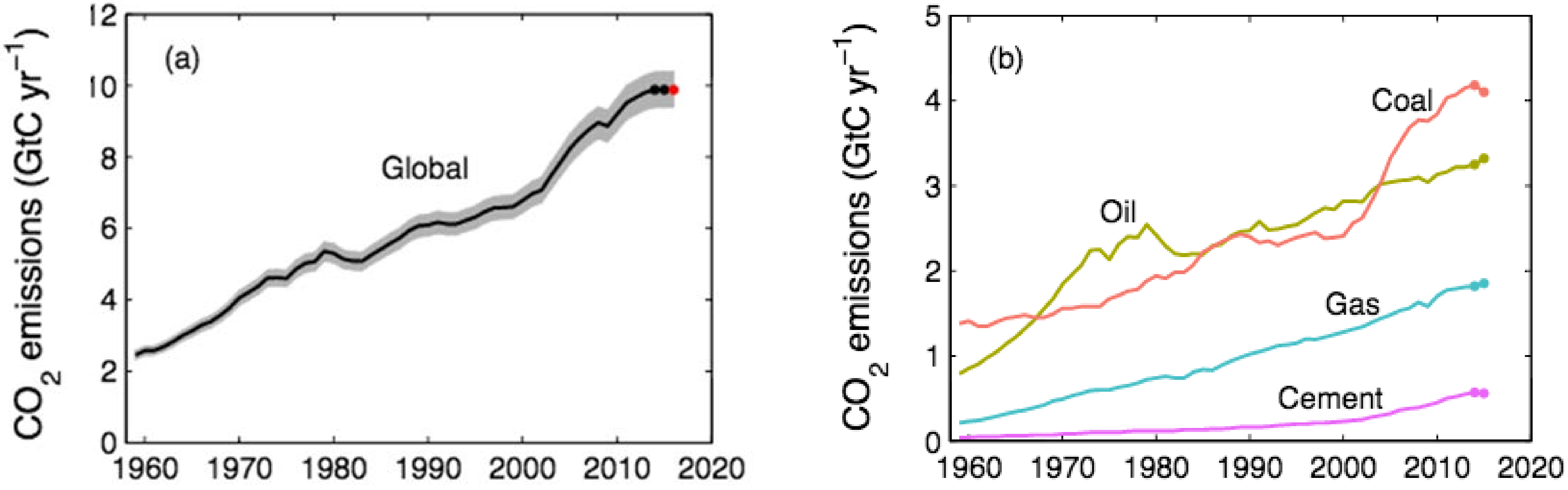
Change in primary global incremental energy demand growth



Source: International Energy Agency World Energy Outlook 2016

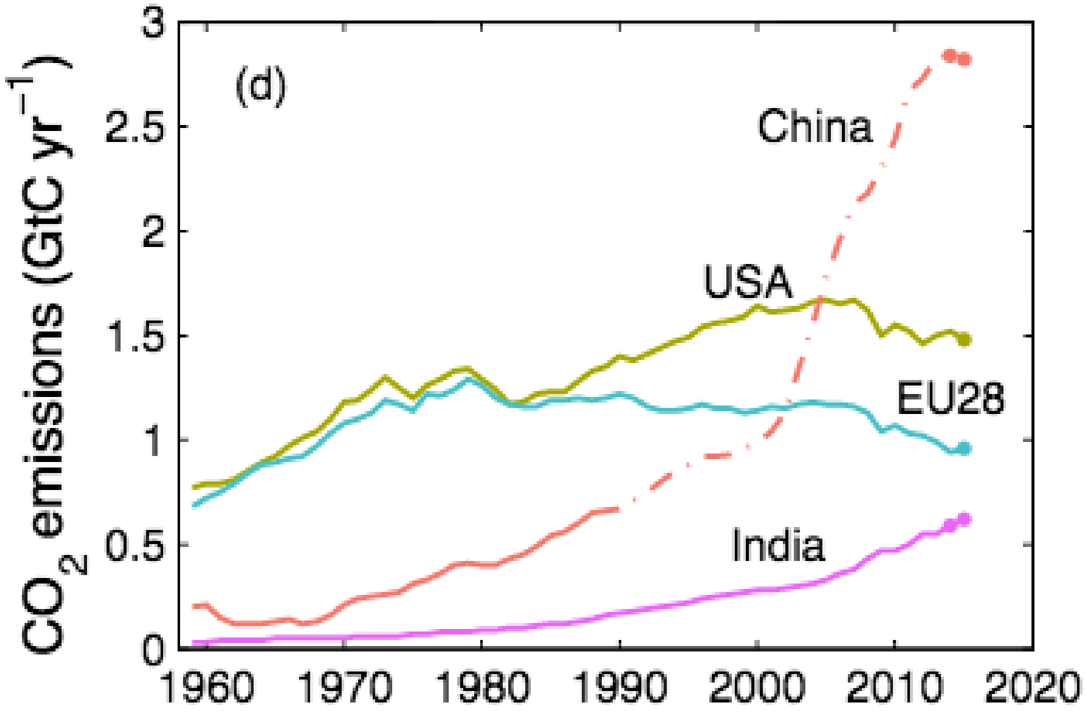
"Low-carbon fuels & technologies, mostly renewables, supply nearly half of the increase in energy demand to 2040"

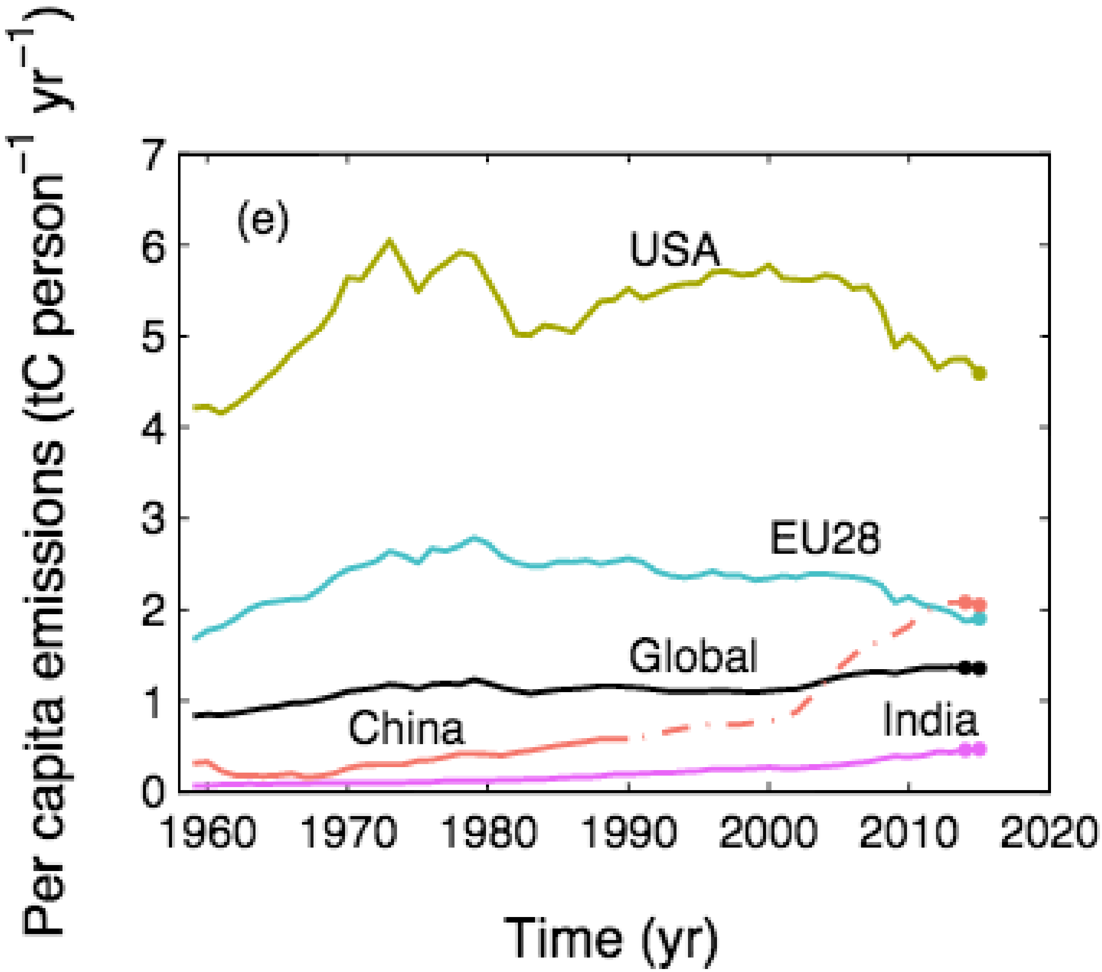
Global CO_2 Emissions from Fossil Fuel and Industry are Starting to Plateau



Source: Le Quéré, C. et al. (2016)

China and India CO_2 Emissions are Growing, While U.S. & Europe Decline – But Net Impact has Kept Global Per Capita Emissions Relatively Flat

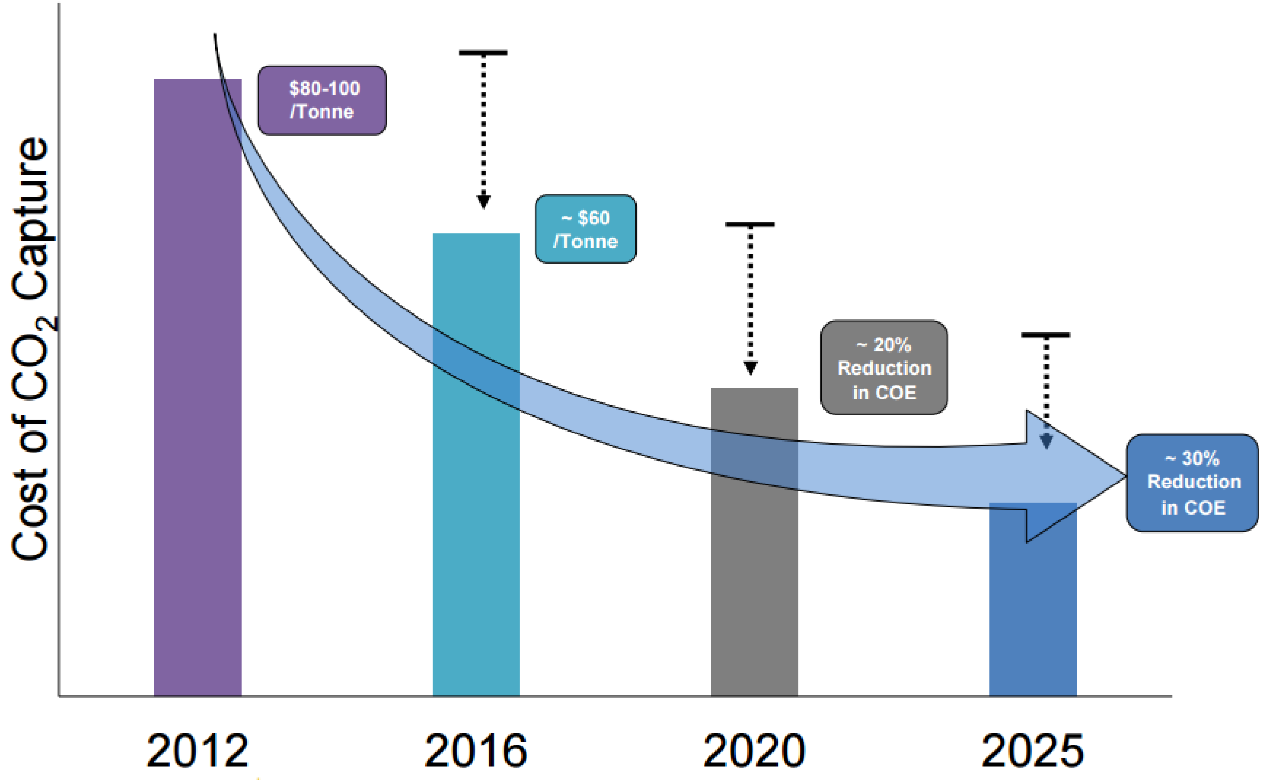




Source: Le Quéré, C. et al. (2016)

How Does Coal Survive in a Carbon-Constrained World?

- Long-term global concerns are expected to continue driving reduction of carbon emissions from use of coal
- To ensure coal remains competitive, coal-based process efficiencies must be increased and current carbon capture costs must be reduced



U.S. DOE Goals for Cost of CO_2 Capture

U.S. DEPARTMENT OF ENERGY Fossil Energy

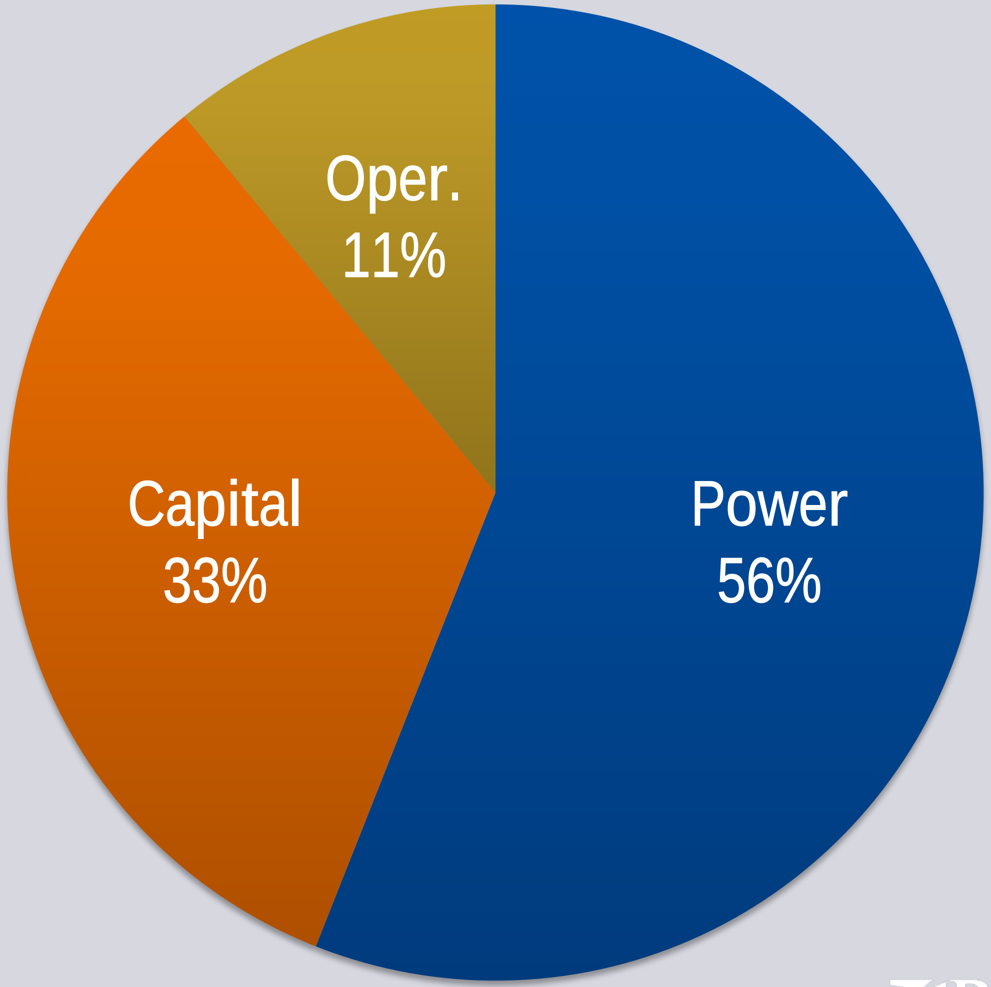
Source: US DOE-NETL

Pathway to Reducing the Cost of CO_2 Capture

Pathway to Reducing LCOE and Cost of CO_2 Avoided

- Primarily focus on reducing energy consumption – reboiler duty
- Reduce capital expenditures:
    - Simplify process arrangements
    - Cheaper materials of construction
- Limit operating cost increases

CO_2 Capture Cost Elements for Current Solvent Systems



[1] Rochelle, G. T. Amine Scrubbing for CO_2 Capture. *Science* **2009,** 325, 1652-1654.

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Examples of Current Large-Scale Carbon Capture and Storage Projects

SaskPower – Saskatchewan Canada

- **Company/Alliance**: SaskPower
- **Location:** Boundary Dam Power Plant, Saskatchewan, Canada
- **Source**: 115 MW coal-fired Unit #3 (retrofit)
- **Start Date**: October 2014 [world's 1st large-scale coal boiler carbon capture project]
- **Capture:** up to 1.3 Mt of CO_2/yr (up to 5,000 tpd @ 90% capture) for EOR with backup underground storage site [~1.5 Mt captured to date]
- **Capture Technology**: Post-combustion: Shell Cansolv amine process

Petra Nova Carbon Capture Project - Richmond, TX

- **Company/Alliance:** Petra Nova Holdings: a 50/50 partnership between NRG Energy and JX Nippon Oil & Gas Exploration Corp.
- **Location:** Unit 8, W.A. Parish plant, Thompsons, 60Km from Houston, Texas, USA
- **Source:** 240 MW slip stream from 610 MW coal-fired unit
- **Start Date:** January 2017 (ribbon-cutting April 13, 2017)
- **Capture:** 1.4 Mt of CO_2/yr (5,000 tpd at 90% capture) for EOR
- **Capture Technology**: Post-combustion: KM-CDR (KS-1 amine) absorption process developed by MHI and KEPCO

Sources: SaskPower, NRG Energy

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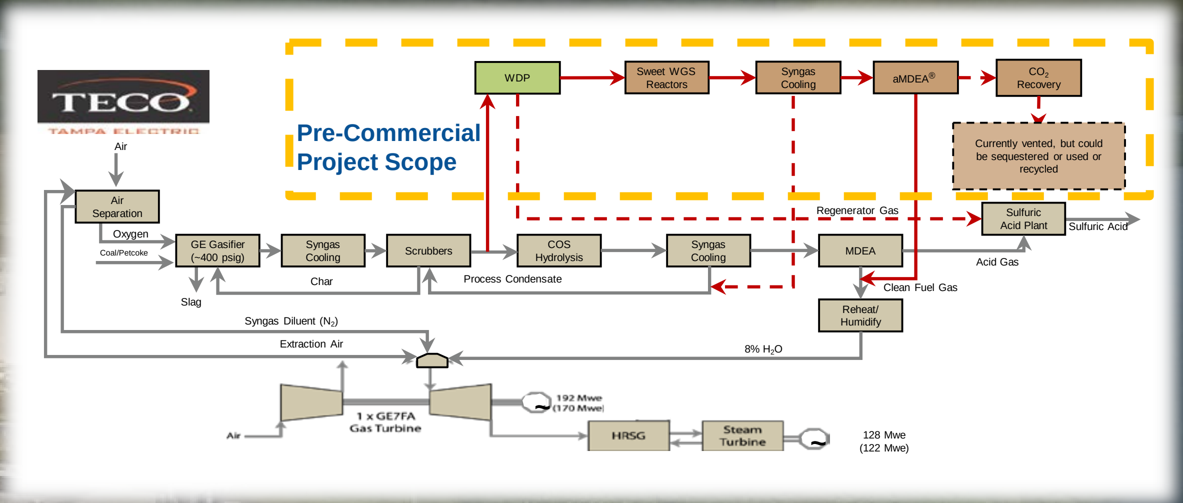
RTI - CO_2 Removal at Demonstration Scale at Tampa Electric Company



- **Demonstrated as one element of a 50-MW$_e$ demonstration of RTI's warm syngas desulfurization process (WDP)**
- **Designed, built, and operated an activated amine based CO_2 capture system**
- **Processed over 50,000 Nm^3/hr of syngas and produced about 1,000 ton/day of CO_2 which was captured at >99% efficiency**
- **Original plans were to sequester CO_2 in a saline aquifer, but permit issues drove the project to simply catch and release the CO_2**

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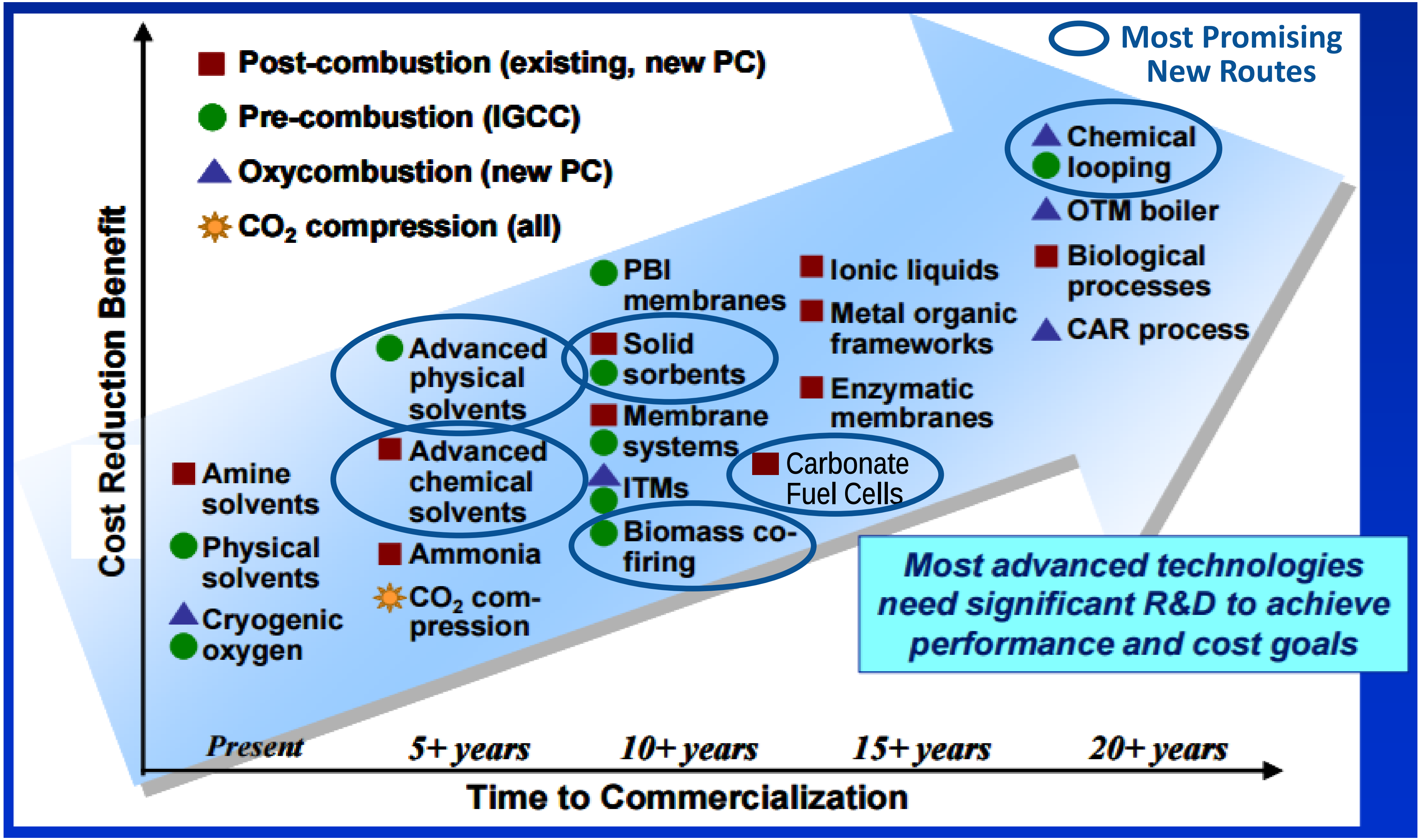
Numerous Advanced CO_2 Capture Technologies are Under Development



Source: US DOE-NETL

Innovative CO_2 Capture Technologies Being Developed at RTI

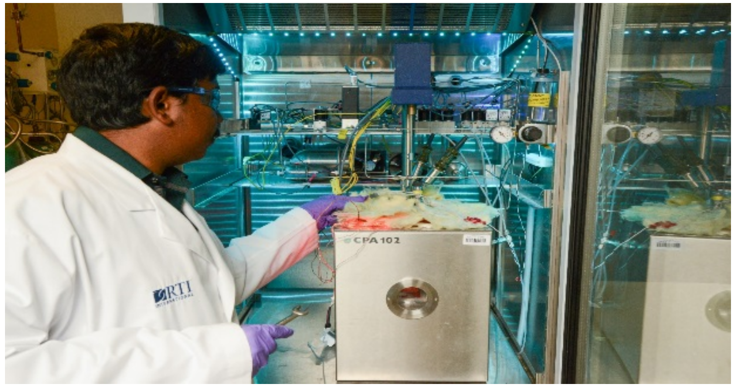
RTI is developing innovative solutions for capturing CO_2 from large industrial sources, such as fossil-fuel power, chemical and cement plants, at lower costs and energy penalties.

Technologies (pre- and post-combustion):

- Non-Aqueous Solvents
- Solid Sorbents
- Chemical Looping Systems
- Membranes
- Hybrid Systems

Benefits: Substantial improvements to the cost and energy demands of CO_2 capture and utilization compared to conventional technologies

- Regeneration energy reduced by as much as 40-50% (compared to MEA)
- Overall cost of electricity reduced ~10-12% for powergen (compared to a DOE baseline study)
- Capex of carbon capture block reduced by up to 50%



Source: Norcem

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RTI's Partnerships in CO_2 Capture & Utilization

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

arpa·e

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

ADVANCED MANUFACTURING OFFICE

Sorbent-Based

Masdar Institute, amec foster wheeler, PennState, CLARIANT

Warm Syngas Cleanup

TECO Tampa Electric, BASF The Chemical Company, EASTMAN, amec foster wheeler, CLARIANT, ch2m

Innovative Solvents

SINTEF, THE LINDE GROUP

CO_2 Capture - Cement Plants

NORCEM HEIDELBERGCEMENTGroup, GASSNOVA

CO_2 Utilization

EMISSIONS REDUCTION ALBERTA

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Solid Sorbent for CO_2 Capture

Solid sorbent-based CO_2 capture process that uses a supported, polymeric sorbent and a fluid-bed process arrangement for post-combustion applications

Technology Status

- Cumulative Bench-scale Prototype testing: 1,000+ circulation hours; 420+ CO_2 capture hours
- The sorbent is capable of rapid removal of CO_2 from the simulated flue gas
- Sustained 90% capture of the CO_2 in simulated flue gas stream is easily achieved
- Collected a wealth of performance data, identified how system performance varies due to process variables, and proved the reliable nature of bench-scale testing
- Additional tests conducted in U.S. and on-site at a Norcem cement plant in Norway

Impact

- Substantial reduction in cost of CO_2 capture
- ~ 40% energy reduction
- Reduction in CAPEX
- High CO_2 loading capacity
- Relatively low heat of absorption; no heat of vaporization penalty
- No evaporative emissions

RTI Solid Sorbent Based CO_2 Capture Technology Development

1st and 2nd Generation Sorbents

Initial Sorbent Discovery
2011 – 2015

- Demonstrated > 25% reduction in cost of CO_2 capture
- ~10 wt% CO_2 loading capacity
- Sorbent production scaled up to 1,000 kg

Masdar A MUBADALA COMPANY | PENNSTATE | amec foster wheeler

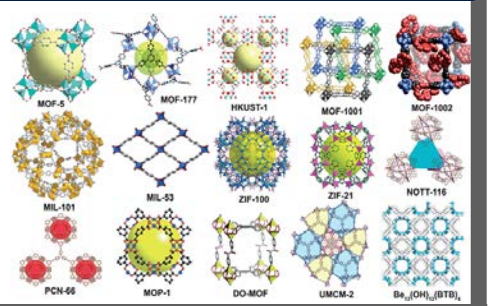
NORCEM Cement Plant Pilot Testing
2013 – 2016

- Demonstrated the technical and economic feasibility of RTI's solid sorbent CO_2 capture process in an operating cement plant
- Pilot unit captured >100 kg/day CO_2

NORCEM HEIDELBERGCEMENTGroup | GASSNOVA

3rd Generation Sorbents

3rd Generation Sorbent Development
2015 – 2017



- Metal organic framework and dendrimer based, fluidizable sorbents
- Higher CO_2 capacity and sorbent stability and attrition resistance
- Tunable pore sizes
- Exceptionally high surface areas
- Scalable manufacturing process

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Novel, Non-Aqueous Solvents for CO_2

CO_2 Capture Technology with substantially reduced energy consumption

Additional potential in other gas separation applications

Technology Status

- Cumulative DOE funding > $9 MM
- Successful cooperation between RTI, Linde, and SINTEF (Scandinavia's leading research organization)
  - Ongoing pilot testing in Norway at SINTEF
    - MEA baseline testing completed
    - Confirmed reported reboiler heat duty of 3.5-3.6 GJ/T-CO_2 for amine (MEA)
    - NAS drop-in (no modification) testing with coal-based flue gas reduced reboiler heat duty to 2.7 GJ/T-CO2, validating projections
    - Modifying unit now for NAS-optimized design
    - Expecting modifications to enable ~2.0 GJ/T-CO_2
- Pre-commercial demonstration (10 MW) planned at Technology Center Mongstad, Norway for FY18

Impact

- Doesn't absorb water like conventional amine systems
- Reduces regeneration energy penalty ~40-50% lower than MEA solvents (and better than state-of-the-art systems)
- Reduces the increase in cost of electricity associated with CO2 capture
- Substantially reduces capital costs for carbon capture

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Technology Roadmap: RTI Novel Non-Aqueous CO_2 Solvents (NAS)

Lab-Scale Development & Evaluation (2010-2013)

Solvent screening

Lab-scale evaluation of process

Large Bench-Scale System (RTI facility, 2014-2016)

Demonstration of key process features (≤ 2,000 kJ/kg CO_2)

Pilot Testing at Tiller Plant (Norway, 2016-2018)

Demonstration of all process components at pilot scale (~60 kWe)

Future Demonstration (2018+)

Pre-commercial Demonstration at Technology Centre Mongstad, Norway (~1-10 MWe)

Planning and pre-qualification ongoing (will test range of flue gases – coal, NG, etc.)

BASF The Chemical Company | arpa·e | National Energy Technology Laboratory | SINTEF | Linde | GASSNOVA | CO2 Technology Centre Mongstad

Applicability of RTI NAS for Gasification Syngas Carbon Capture

Since syngas is at pressure, we expect the NAS to work even better for syngas-based carbon dioxide capture than in the flue gas case, but they need to be coupled with upstream sulfur removal (such as RTI's warm gas desulfurization process).

- NAS is both a chemical solvent and a physical solvent.
- Therefore, it will behave as a chemical solvent and a physical solvent.
- At higher pressures, the overall absorption of CO_2 should be enhanced.

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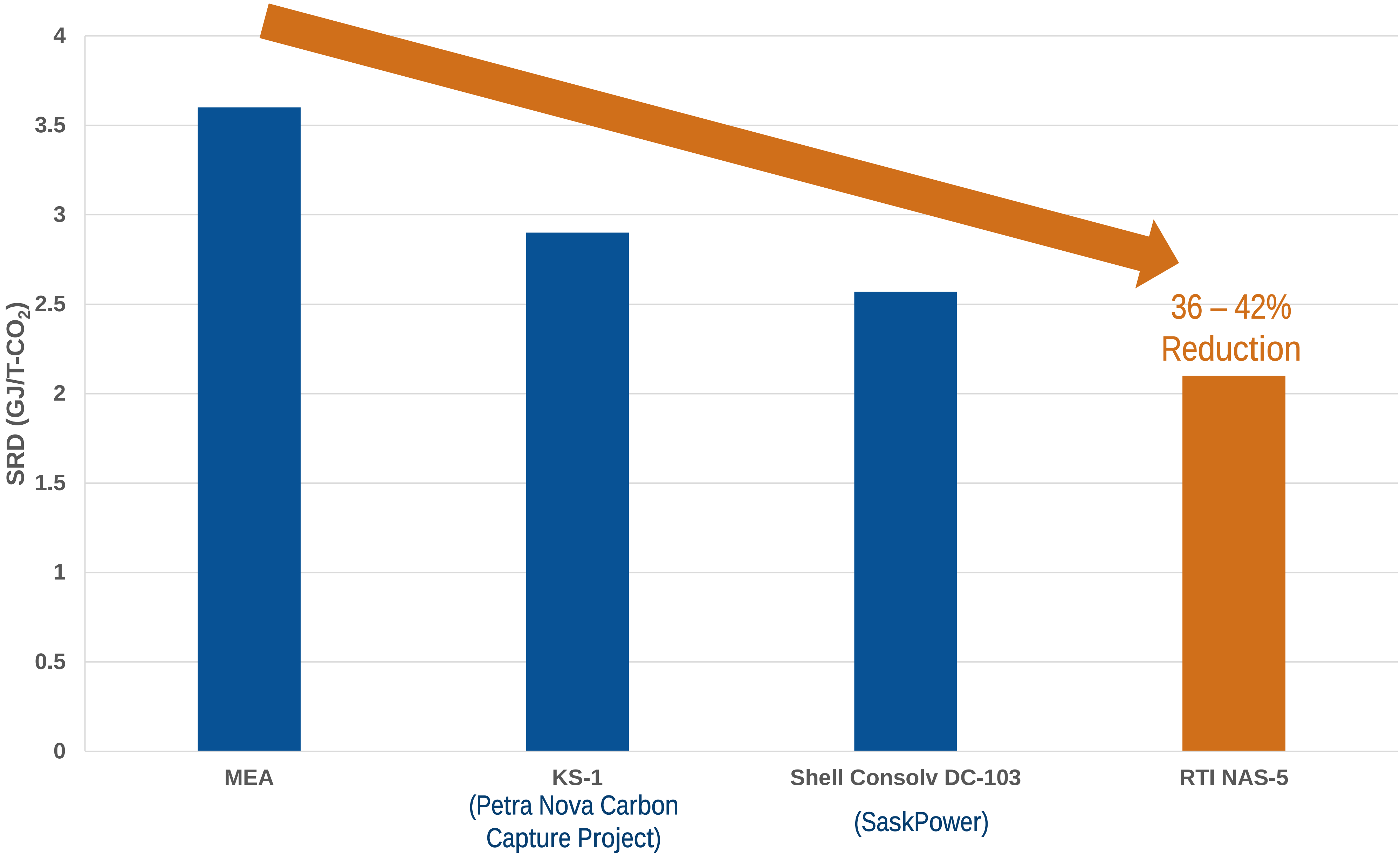
Advanced Technologies are Driving Down the Reboiler Duty Energy Penalty



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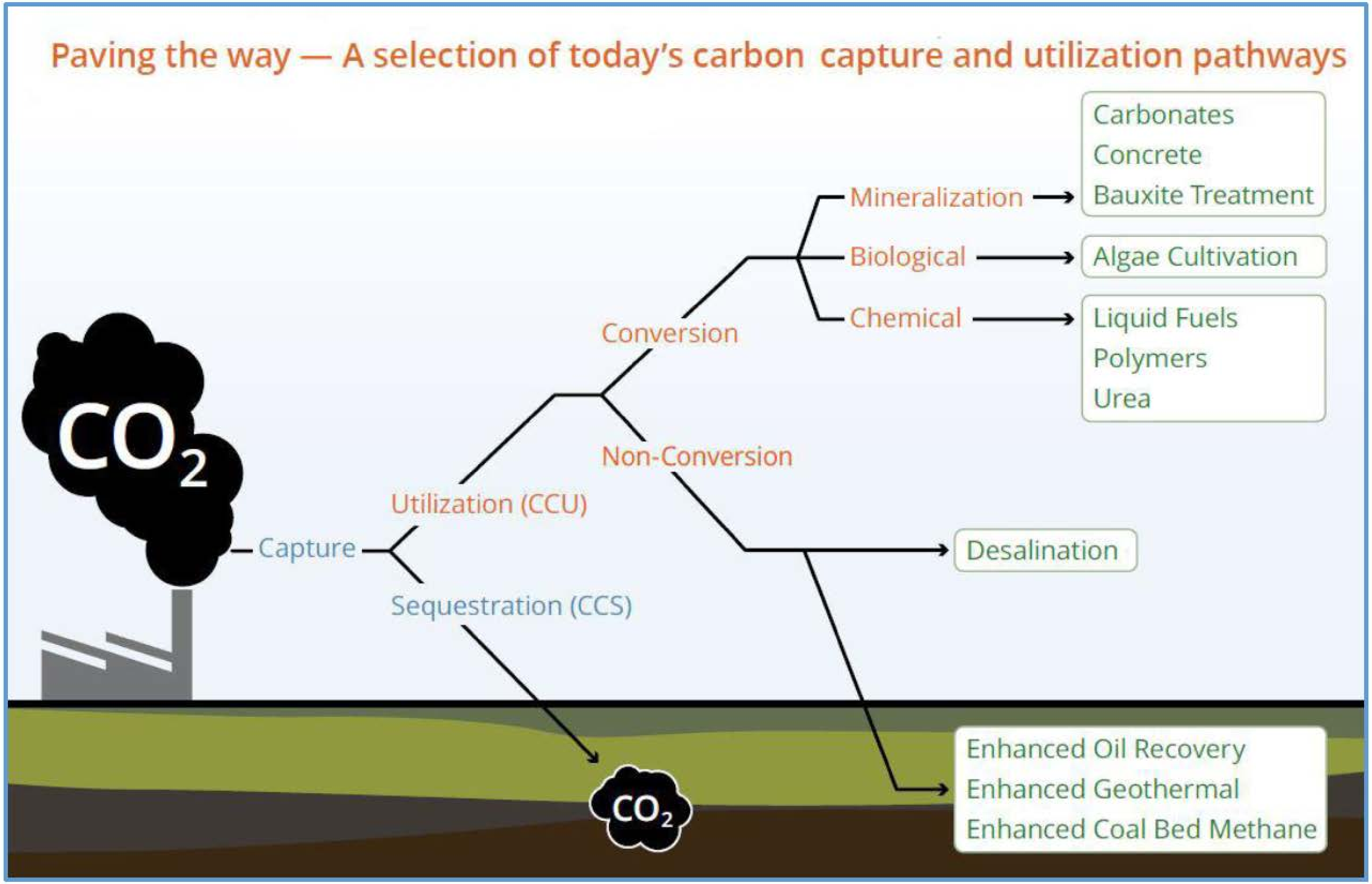
Carbon Capture and Utilization Pathways



Source: Global CCS Institute

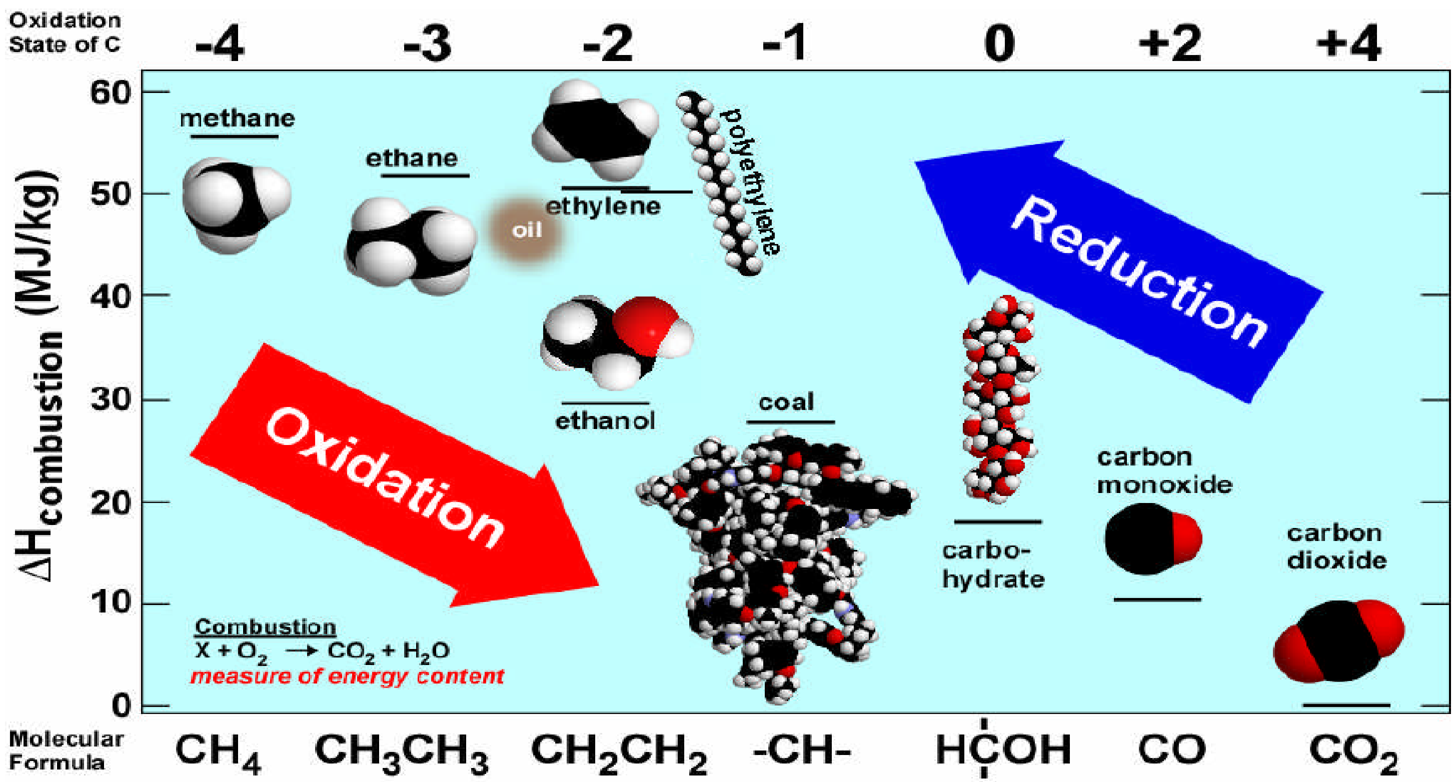
Challenges of CO_2 Reuse

Challenge

Identify low cost reducing agents that have a small CO_2 footprint

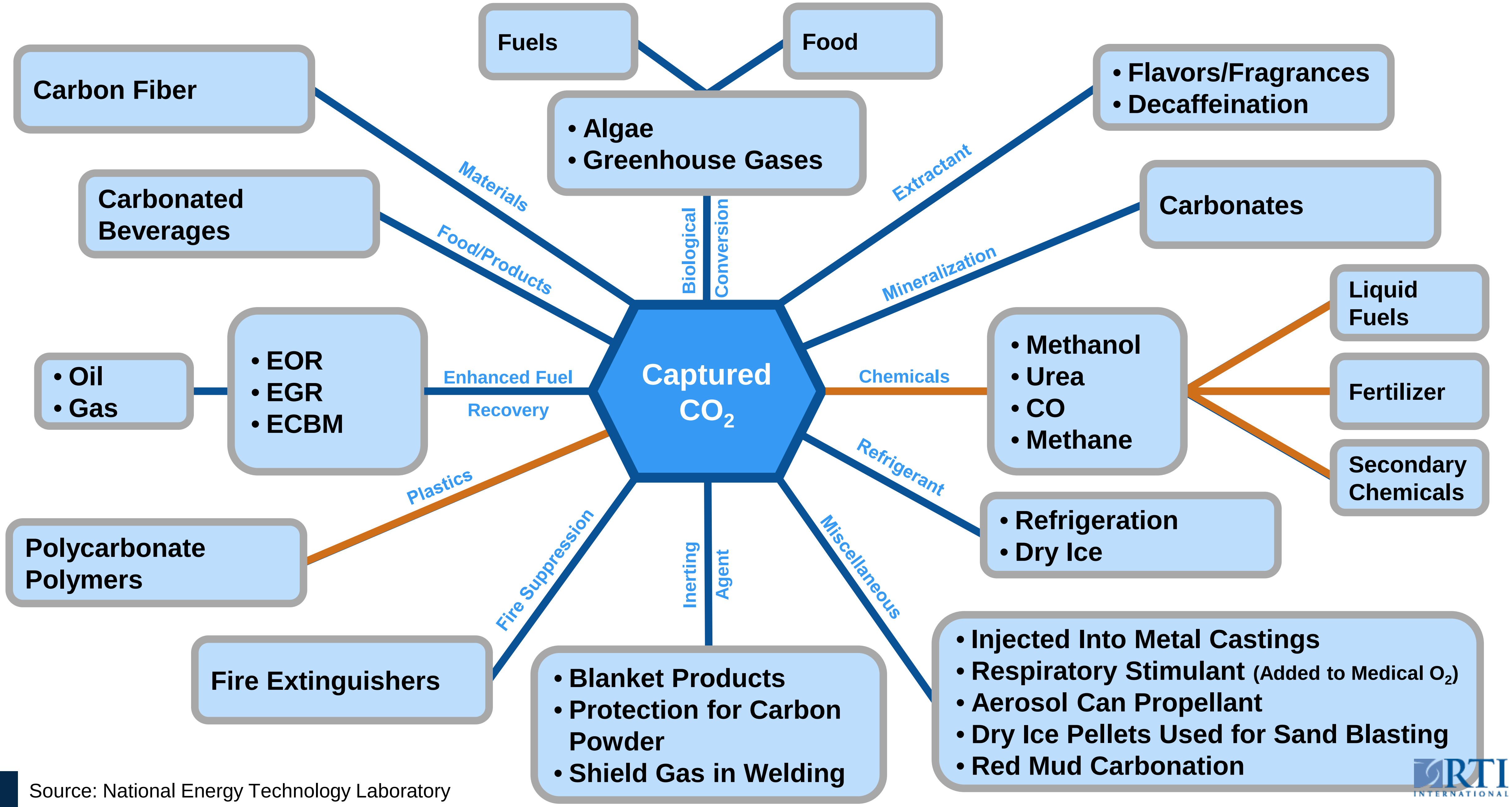
CO_2 Properties

- Most fully oxidized form of carbon
- Extremely chemically stable
- Conversion to useful products requires abundant reducing agents and energy



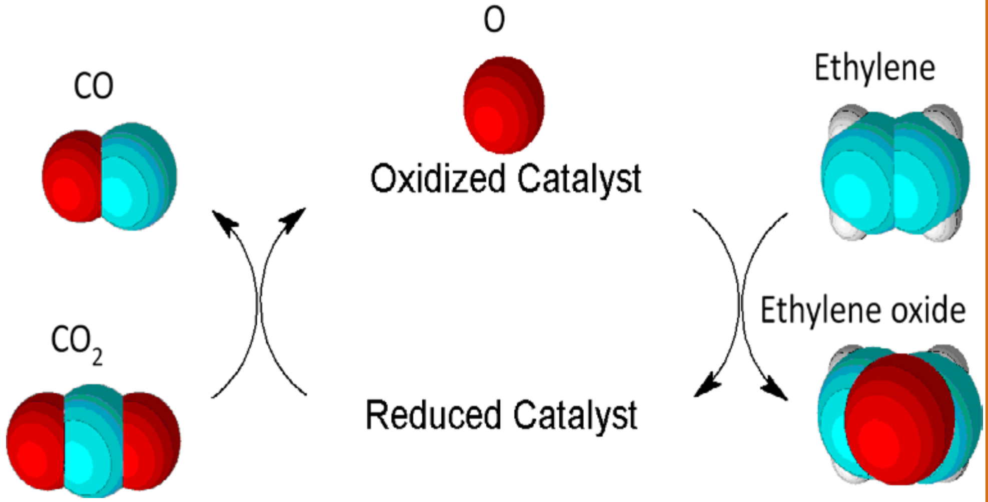
Source: Banholzer, 2008

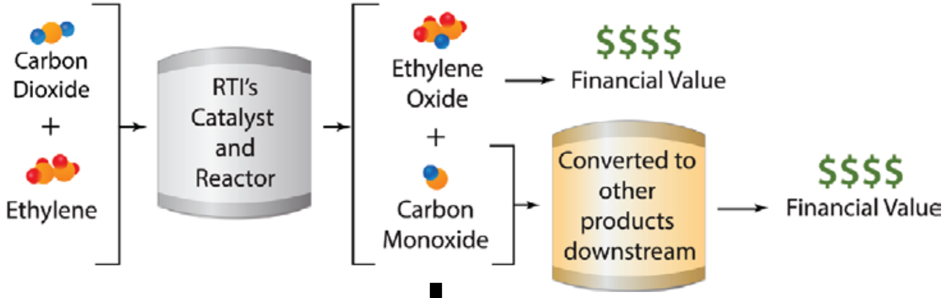
CO_2 Utilization – Broad Market Potential but Must be Economically Competitive

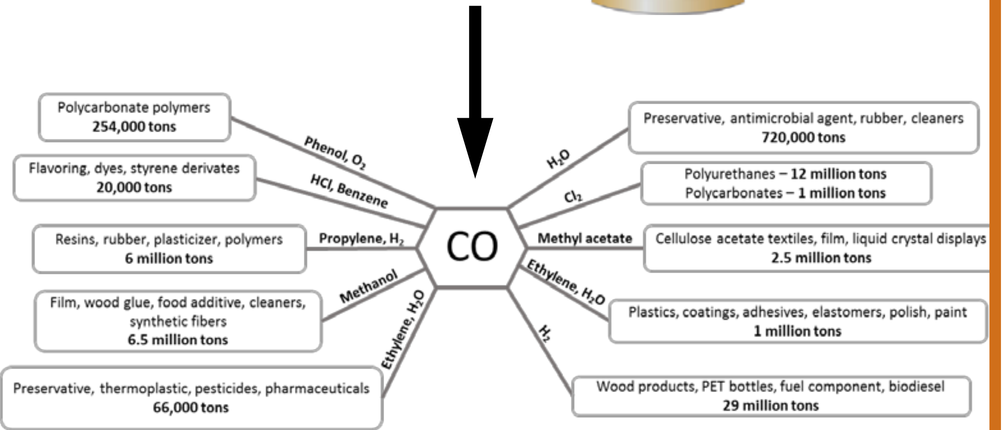


Source: National Energy Technology Laboratory

RTI CO_2 Utilization Technology Platform







Technology and Status

- Based on novel catalysts that can extract oxygen from CO_2, co-producing CO, while driving reactions such as dry methane reforming or oxidations.
- Utilizes CO_2 as a feedstock for large volume chemicals, e.g. ethylene oxide
- Initial catalyst formulations developed for Ethylene Oxide production
- Initial process design developed
- Techno-Economic potential confirmed
- Next steps:
  - Broaden to general targeted oxidation platform

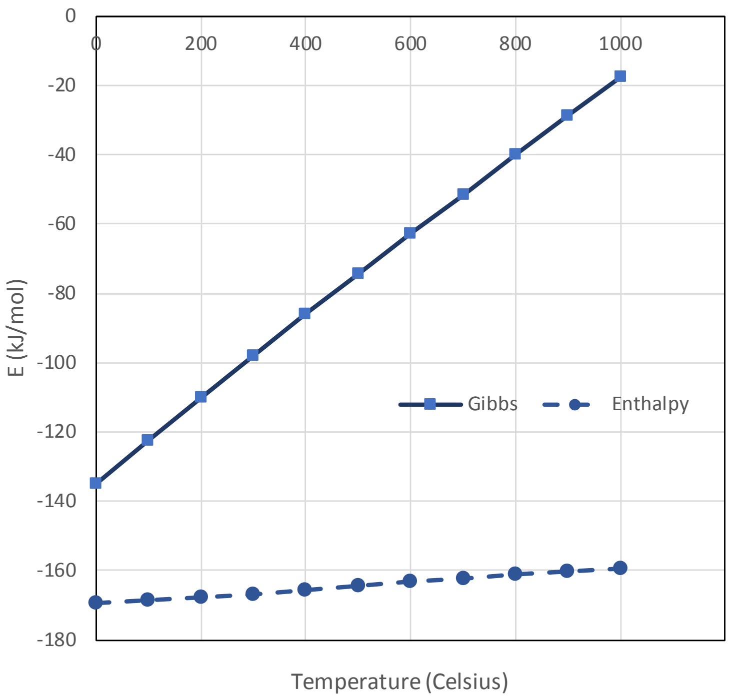
Impact

- Technology platform, expandable for variety of oxidative processes for large value applications
- Utilizing CO_2 as a feedstock for large volume chemicals with broad industrial interest
- Based on novel catalysts that can extract an oxygen (O) atom from CO_2, co-producing carbon monoxide (CO), while driving reactions such as dry methane reforming or oxidations such as ethylene to ethylene oxide (EtO)

CO_2 Utilization Technology Platforms

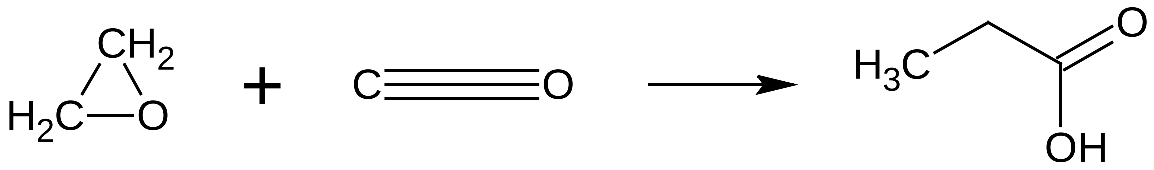
RTI has identified several potential CO_2 Utilization pathways that improve upon conventional routes with promising thermodynamics and supportive global markets.

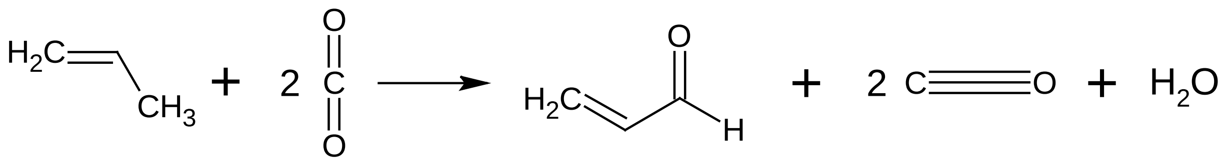
- Ethylene oxide
- Acrylic Acid
- Acrolein
- Acrylonitrile



Acryic Acid

Market demand was 5.75 MT in 2014 and is expected to reach 8.75 MT by 2022, growing at a CAGR of 5.6% from 2015 to 2022





Grand Challenge

Captured CO_2

from Small and Large Point Sources

+

Carbon Free Energy

→

Clean Products

Methane

Methanol

FT Products

Polymers

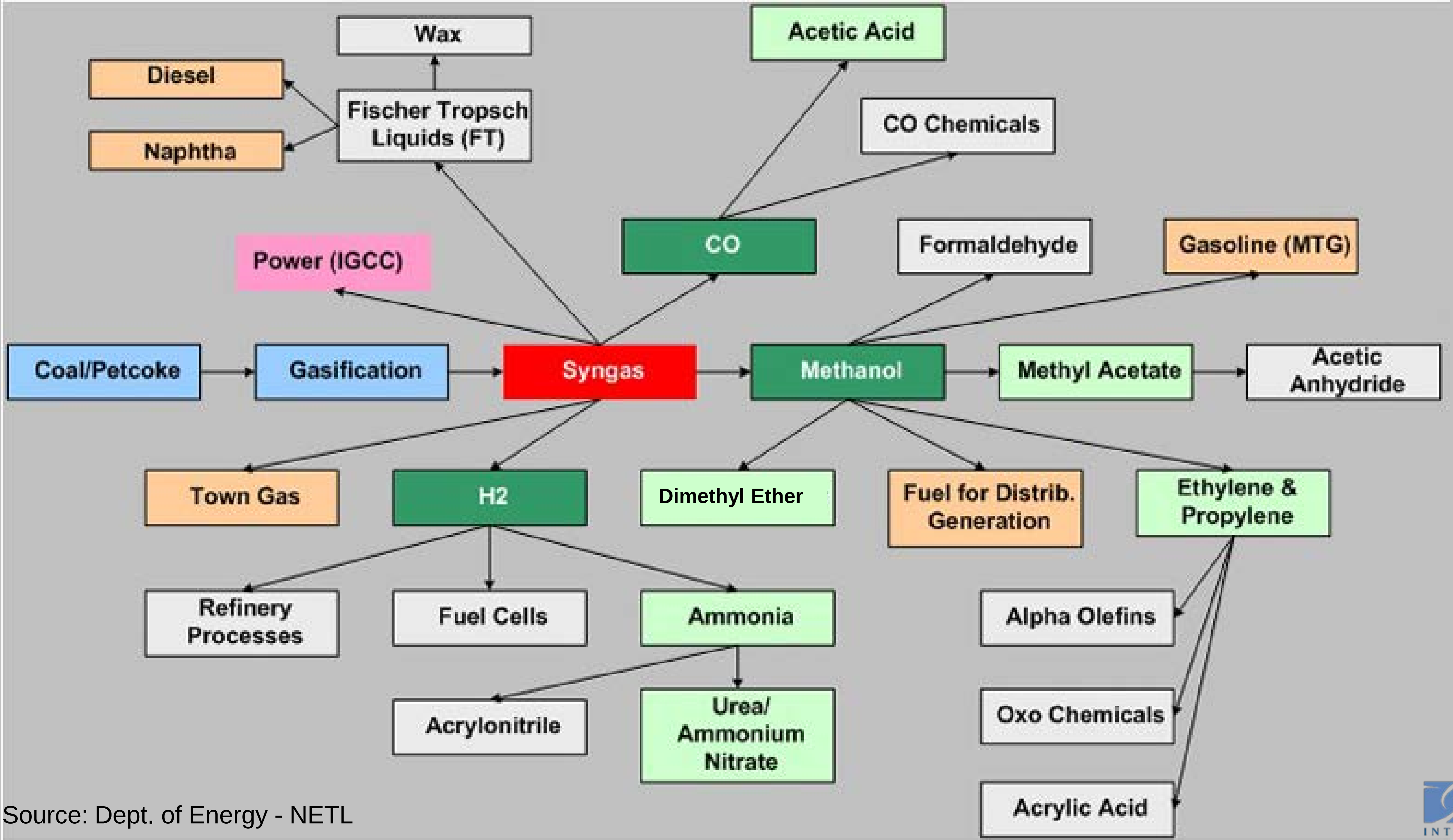
$H_2O \rightarrow H_2 + \frac{1}{2} O_2$

H_2 @ < $2/kg

$\Delta H = +50$ kWh/kg

If electricity is < 2¢/kWh, we can make something happen with CO_2

Coal to Chemicals: Low-Hanging Fruit for CO_2 Utilization



Source: Dept. of Energy - NETL

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Closing Thoughts

- Coal will continue as a key feedstock for world-wide energy, but long-term global concerns are still expected to drive the need to reduce carbon emissions from use of coal.
- Several large-scale carbon capture projects are now being demonstrated, but to keep coal use competitive, current carbon capture costs must be substantially reduced.
- Advanced technologies are being developed and demonstrated by RTI and others that offer hope for substantial cost reductions for low-carbon utilization of coal.
- Safe storage of CO_2 is being proven, but still faces legal and regulatory risks that need to be addressed through policy.
- Innovations in CO_2 utilization offer interesting technology and business options beyond CO_2 storage.
- Coal-to-chemicals offers low-hanging fruit for CO_2 utilization.

Source: Robert Nickelsberg/Getty Images

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RTI’s Energy Technology Team

Innovation focused R&D for solving **clients’ problems**

State of the art facilities and capabilities

Talented staff produce novel technologies from ideation to pilot-scale to commercial systems

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