Advanced Technologies for CO_2 Capture & Utilization: Power & Industrial Applications

National Coal Council – 2017 Spring Meeting

David L. Denton, Senior Director, Business Development – Energy Technology Division

April 19, 2017

Source: Robert Nickelsberg/Getty Images

Energy Technologies at RTI International

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

RTI INTERNATIONAL

$885 M

FY2016 Revenue

3,064 Projects (fiscal year 2016)

1,102 Clients (fiscal year 2016)

5,032 Staff Members Worldwide

90 Languages

250 Degree Fields

105 Nationalities

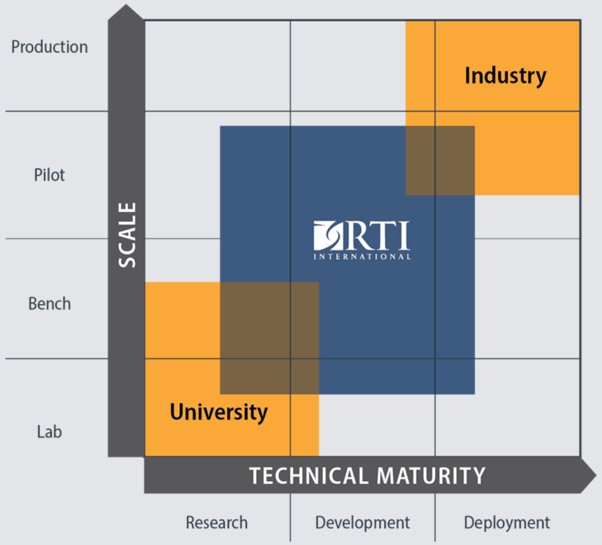
13 U.S. Offices

10 International Offices

ENERGY TECHNOLOGIES

Developing advanced process technologies for energy applications by partnering with industry leaders

Clean Coal / Syngas Processing	Industrial Water Treatment
Carbon Capture & Utilization / Gas Separations	Advanced Materials for Catalysis & Separations
Biomass Conversion	Natural Gas Extraction & Conversion



Focused on Applied Research (concept to demonstration) in Partnership with Government Agencies, Academia, and Industry

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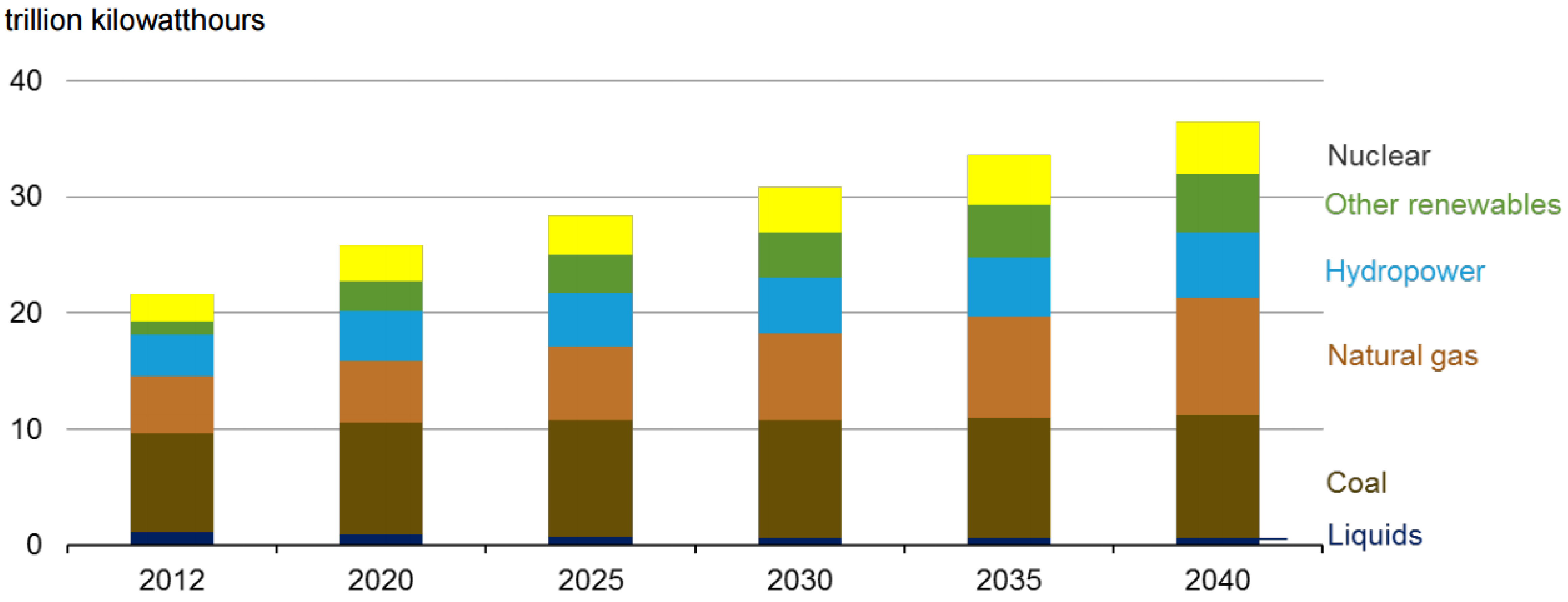
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy BIOENERGY TECHNOLOGIES OFFICE
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy ADVANCED MANUFACTURING OFFICE
arpa·e
EMISSIONS REDUCTION ALBERTA
GASSNOVA
CASALE
CLARIANT
BASF We create chemistry
SINTEF
HALDOR TOPSØE
VEOLIA
Masdar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

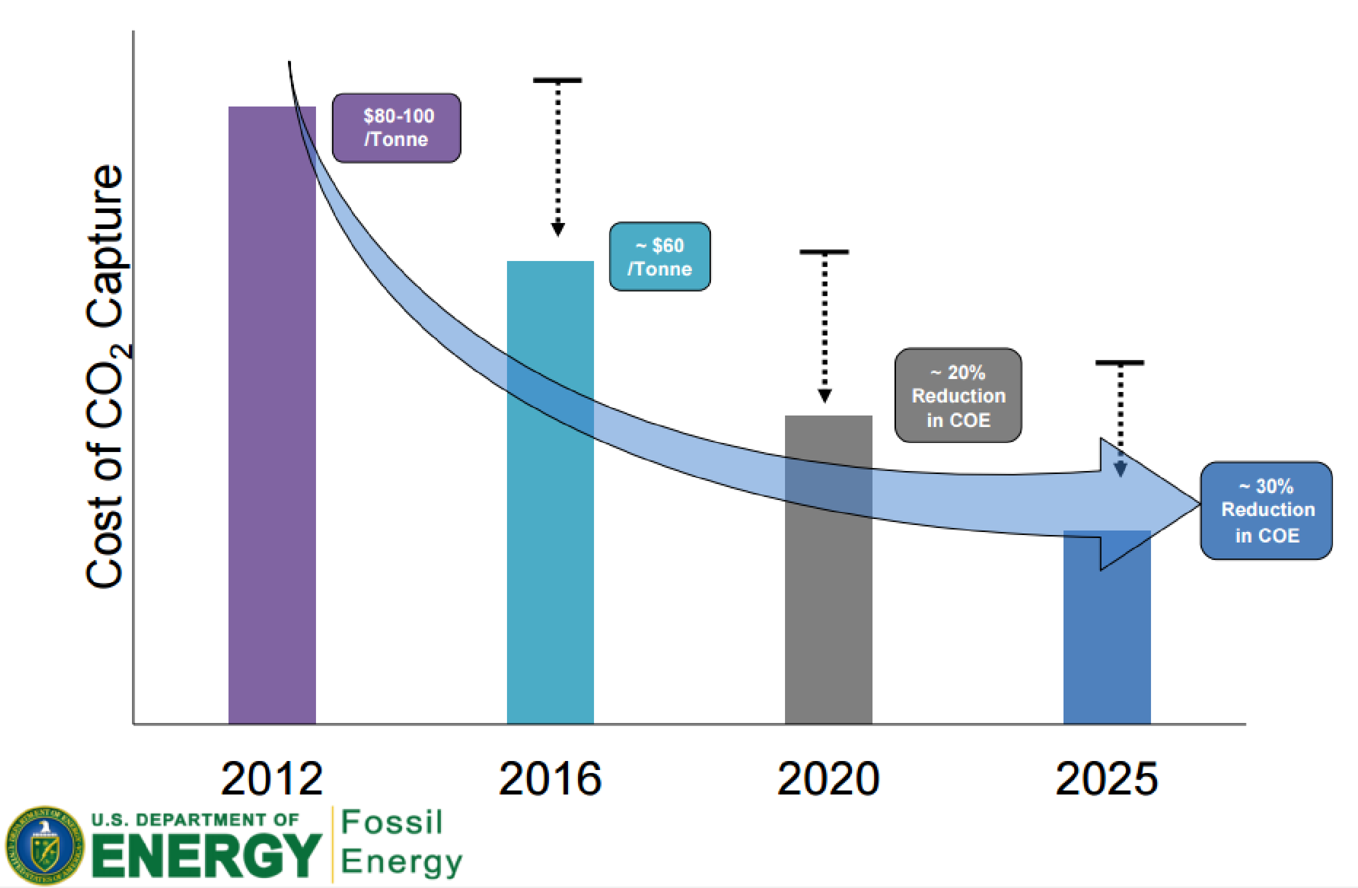
Coal Remains Significant for Future World Electricity Generation



Source: EIA, International Energy Outlook 2016

CO_2 Capture Remains a Need for Long-term Utilization of Coal

- Long-term global concerns are still expected to drive ultimate reduction of carbon emissions from use of coal.
- To ensure coal remains competitive, current carbon capture costs must be reduced.



U.S. DOE Goals for Cost of CO_2 Capture

Source: US DOE-NETL

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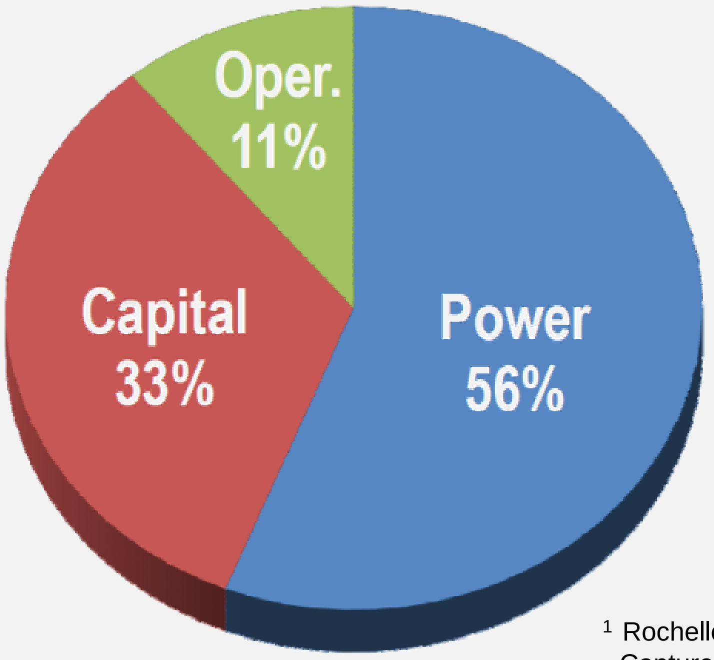
Pathway to Reducing the Cost of CO_2 Capture

CO_2 Capture Cost Elements for Current Solvent Systems



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

Pathway to Reducing LCOE and Cost of CO_2 Capture

- Primary focus on reducing energy consumption – regeneration energy / reboiler duty
- Reduce capture process capital expenditure
  - Simplify process arrangement
  - Lower cost materials of construction
- Limit operating cost increases for carbon capture

Examples of Current Large-Scale Carbon Capture and Storage Projects

Source: SaskPower

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


Source: NRG Energy

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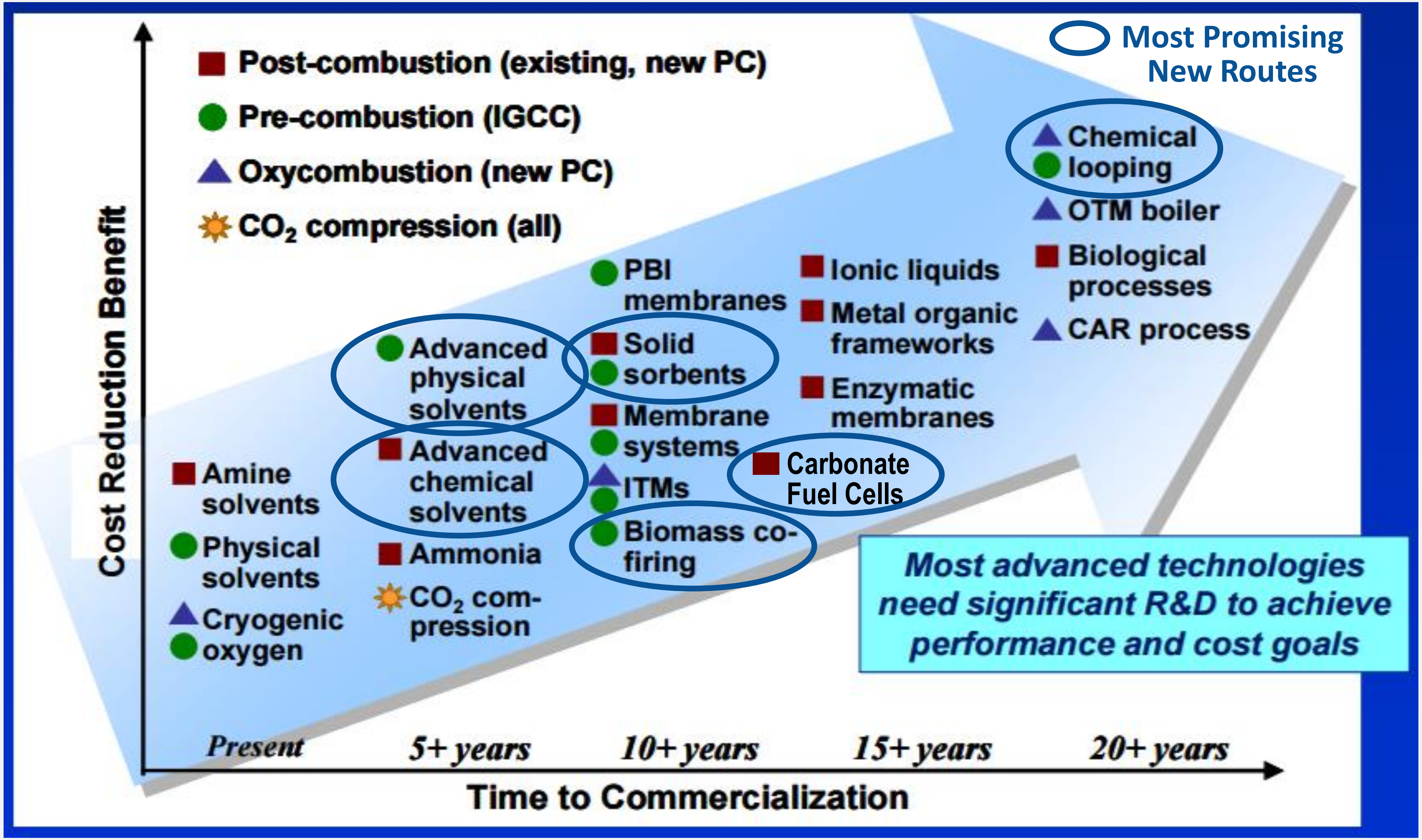
Examples of Current Large-Scale Carbon Capture Projects

Source: Mississippi Power

Kemper County IGCC Project – Kemper County, MS

- **Company/Alliance:** Mississippi Power / Southern Company
- **Location:** Kemper County, about 20 miles north of Meridian, MS
- **Source:** 582-MW lignite-fueled IGCC power plant
- **Start Date:** Anticipated in 2017
- **Capture:** 3.0 Mt of CO_2/yr (65% capture) for EOR
- **Capture Technology**: Pre-combustion: Selexol™ physical solvent-based absorption process developed by UOP

Numerous Advanced CO_2 Capture Technologies under Development

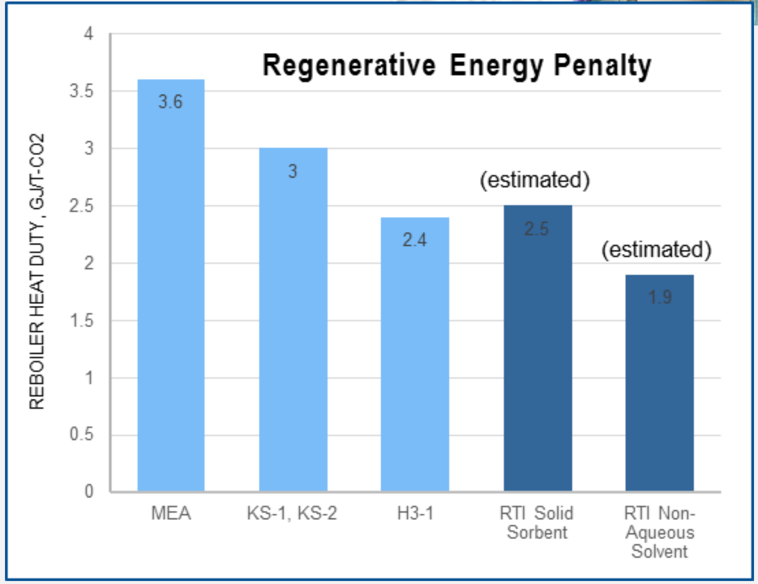


Source: US DOE-NETL

Innovative CO_2 Capture Technology 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



RTI's Partnerships in CO_2 Capture & Utilization

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arpa-e

Solid Sorbent-Based

- Masdar Institute
- amec foster wheeler
- PENNSTATE 1855
- CLARIANT

Novel NAS Solvents

- THE LINDE GROUP
- BASF The Chemical Company
- SINTEF

CO_2 Utilization

- EMISSIONS REDUCTION ALBERTA

CO_2 Capture from Cement Plants

- NORCEM HEIDELBERGCEMENTGroup
- GASSNOVA

Warm Syngas Cleanup

- TECO TAMPA ELECTRIC
- CLARIANT
- EASTMAN
- amec foster wheeler
- BASF The Chemical Company
- ch2m

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Advanced Solid Sorbent CO_2 Capture Process

RTI has developed a solid sorbent-based CO_2 capture process that uses a supported, polymeric sorbent and a fluid-bed process arrangement for post-combustion applications.

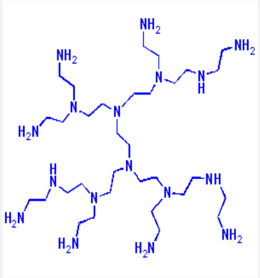
CO_2 Sorbents

Masdar (A MUBADALA COMPANY), amec foster wheeler, PENNSTATE

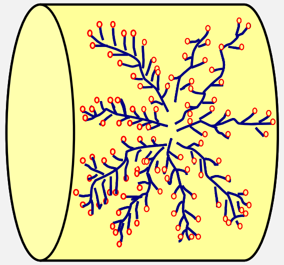
CO_2 Capture from Cement Plants

NORCEM (HEIDELBERGCEMENT Group), GASSNOVA

- Technology benefits:
  - >25% reduction in cost of CO_2 capture, potential for up to 40% cost reduction
  - ~ 40% energy reduction
  - Reduction in CAPEX
  - High CO_2 loading capacity
  - Relatively low heat of absorption; no heat of vaporization penalty
  - No evaporative emissions
- 4-yr cooperative effort between RTI, Masdar, and DOE has developed the technology to pilot scale
- Additional tests in U.S. and on-site in Norway are ongoing through 2017



CO_2-philic polymer (e.g., polyethylenimine)



Immobilize polymer into nano-porous material

Promising sorbent chemistry

RTI bench-scale unit

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Technology Roadmap – RTI Solid CO_2 Sorbents

Bridge to Pilot Testing

Knowledge Gained:

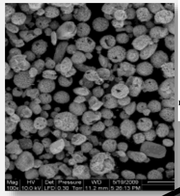
- Lessons learned from bench-scale testing
- Optimal process design and operating conditions
- Sorbent scale-up and optimization

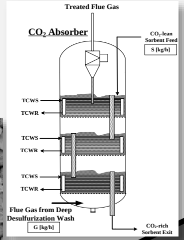
Additional Work:

- More extensive performance testing
- Testing in flue gas
- Application to multiple CO_2 sources
- Sorbent cost reduction

Commercial / Demo

Concept





Scale

2008 2011 2013 2015 2018 2025

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RTI-Norcem – Cement Plant Application Pilot Testing for RTI Solid Sorbent

Objective

Demonstrate the technical and economic feasibility of RTI's advanced, solid sorbent CO_2 capture process in an operating cement plant

Period of Performance:

- 5/1/2013 to present

GASSNOVA

NORCEM
HEIDELBERGCEMENTGroup

Two Phases

Phase I – Feasibility Review – *Complete*
- Sorbent exposure to actual cement plant flue gas
- Economic evaluation
- Commercial design for cement application

Phase II – Demonstration – *In Progress*
- Design, build, and test a prototype of RTI's solid sorbent CO_2 capture technology
- Evaluate CO_2 capture performance
- Update economics with pilot test data

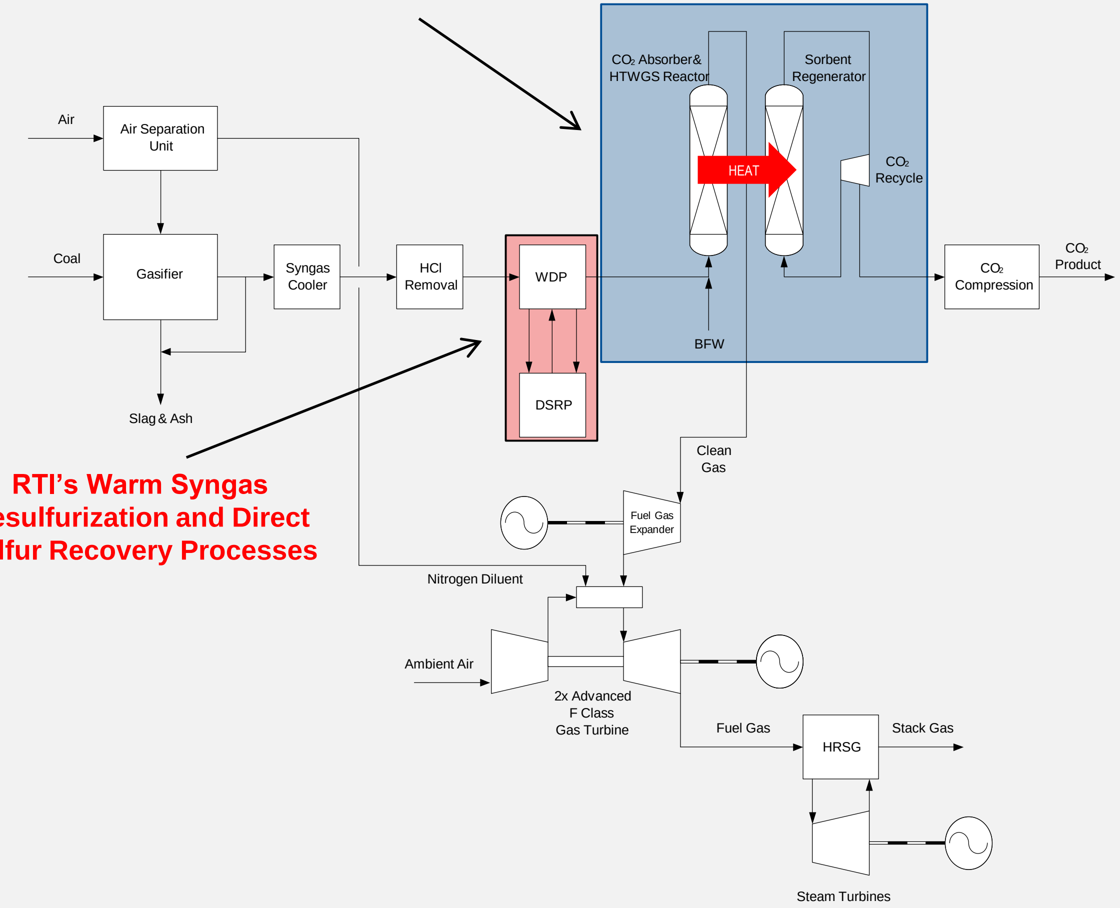

RTI's Lab Scale


RTI's Prototype Scale


Norcem's Brevik Cement Plant
(Source: Norcem)

Pre-combustion Sorbent-based Process for CO_2 Removal from Warm Syngas

Solid Sorbent-based Warm CO_2 Capture Process

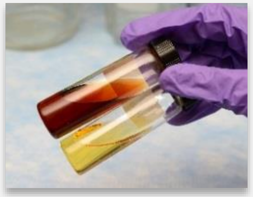


RTI's Warm Syngas Desulfurization and Direct Sulfur Recovery Processes

RTI Process Development

- Developing a solid sorbent-based CO_2 removal process that integrates directly with RTI's overall warm syngas clean-up technology package
- Sorbent removes CO_2 from syngas at ~400°C
- Formulation and stability optimized
- Transitioning to a fluidizable particle form
- Developed a novel process arrangement that:
  - Maximizes sorbent utilization and capture/release rate
  - Integrates heat between absorber and regenerator
  - Combines water-gas-shift and CO_2 absorption
- Experimental work shows concept is feasible
- Preliminary techno-economic assessment completed

RTI Non-aqueous Solvent (NAS) Based CO_2 Capture


RTI High-Bay Test System

CO_2 Solvents

THE LINDE GROUP Linde GASSNOVA SINTEF

- Novel non-aqueous solvents have been developed and tested by RTI.
- Projected technology benefits of NAS systems:
  - Don't absorb water like conventional amine systems
  - Reduce regeneration energy penalty ~40-50% lower than MEA solvents (and better than state-of-the-art systems)
  - Reduce the increase in cost of electricity associated with CO_2 capture
  - Substantially reduce capital costs for carbon capture
- Scale-up testing underway at SINTEF pilot facility:
  - Successful cooperation between RTI, Linde, and SINTEF (Scandinavia's leading research organization)
  - Cooperation between the U.S. and Norway governments enables a lower cost, lower risk, but accelerated pathway for CO_2 capture technology development.

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NAS Pilot Testing Underway in SINTEF Tiller Pilot Plant (Norway)

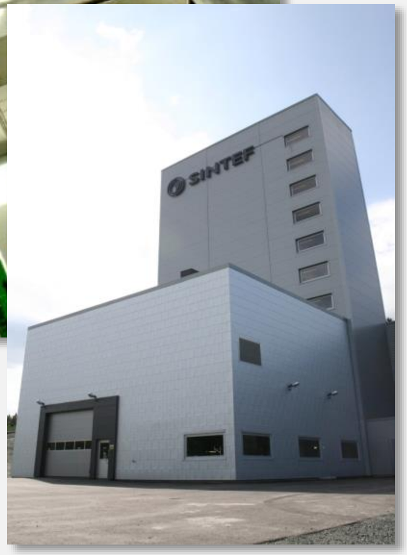
Objective:

- Design/build unique process modifications for the existing Tiller unit
- Demonstrate the process on coal-derived flue gas
- Compare and benchmark performance versus conventional amine solvents
- Techno-economic and EHS evaluations

Progress:

- MEA baseline testing completed
- Confirmed reported reboiler heat duty of 3.5-3.6 GJ/T-CO_2 for amine (MEA)
- NAS pilot testing now underway with coal-based flue gas
- Initial results are validating projected regeneration energy reductions
- All testing expected to be completed this year

Source: SINTEF



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.)

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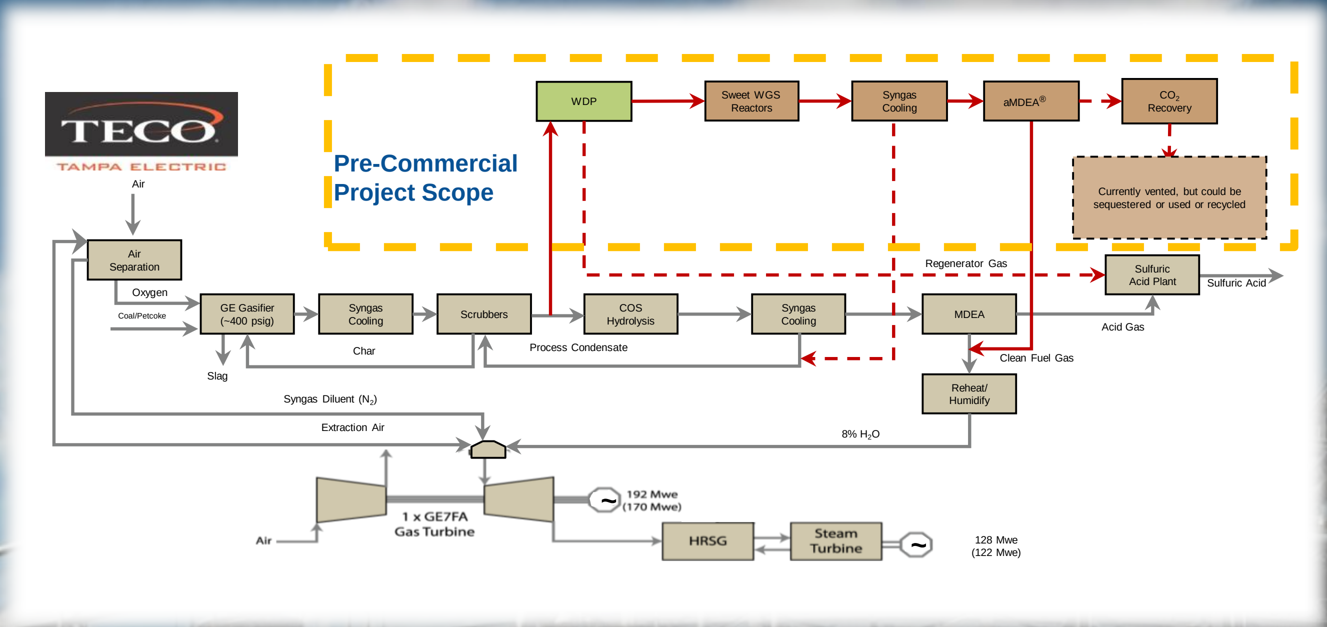
Applicability of RTI NAS for Gasification Syngas Carbon Capture

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.

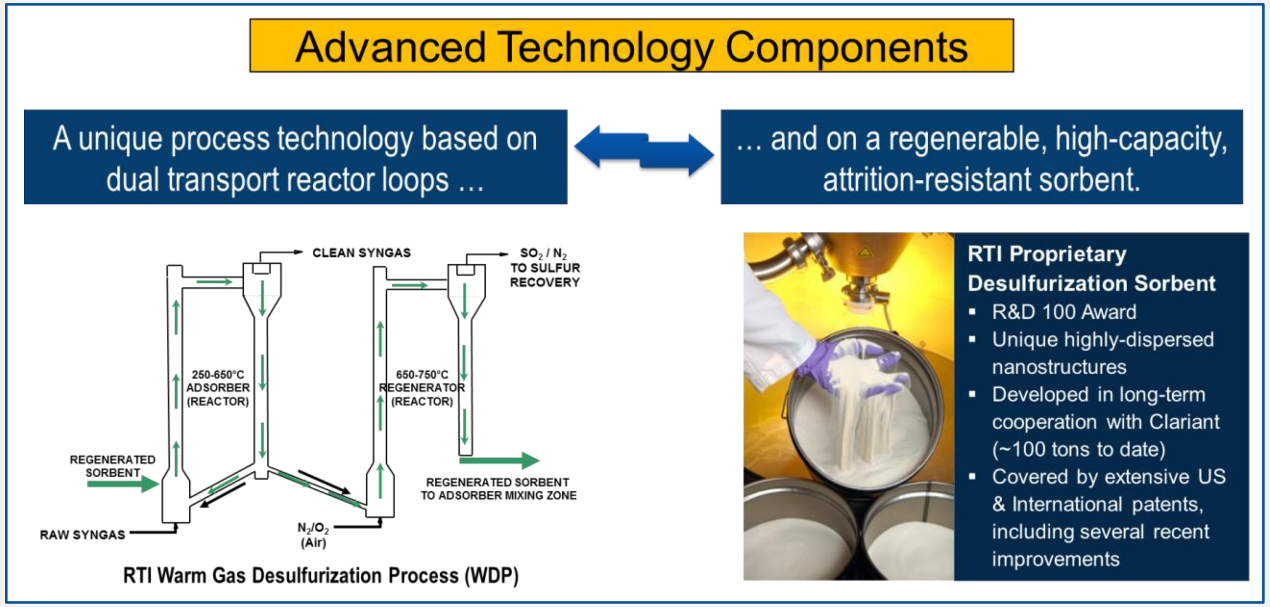
RTI CO_2 Removal at Demonstration Scale at Tampa Electric Polk 1 IGCC Site

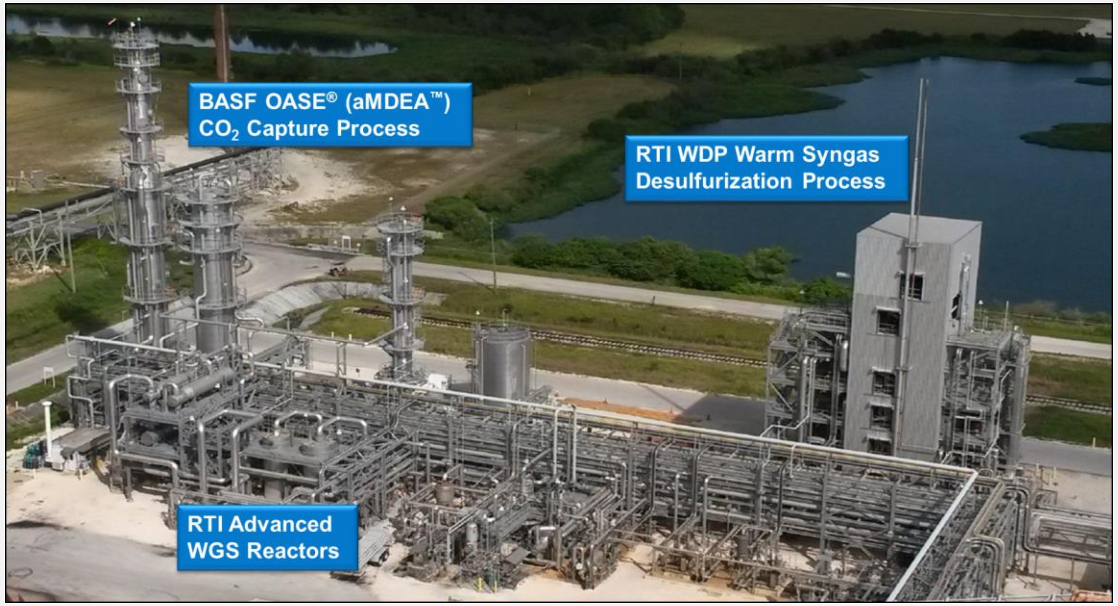


- **Designed, built, and operated an aMDEA™ based CO_2 capture system as part of a demonstration of RTI's novel warm syngas desulfurization technology.**
- **Processed over 2MMscfh (~50,000 Nm^3/hr) of syngas and captured up to 1,000+ ton/day of CO_2, which was subsequently released.**
- **Original plans were to sequester CO_2 in a saline aquifer on-site, but permit issues (e.g., monitoring requirements for extended years beyond the project timeline and funding) led the site to decide against actual sequestration.**

RTI Technology for Coal to Ultra Clean Power, Chemicals, and Fuels

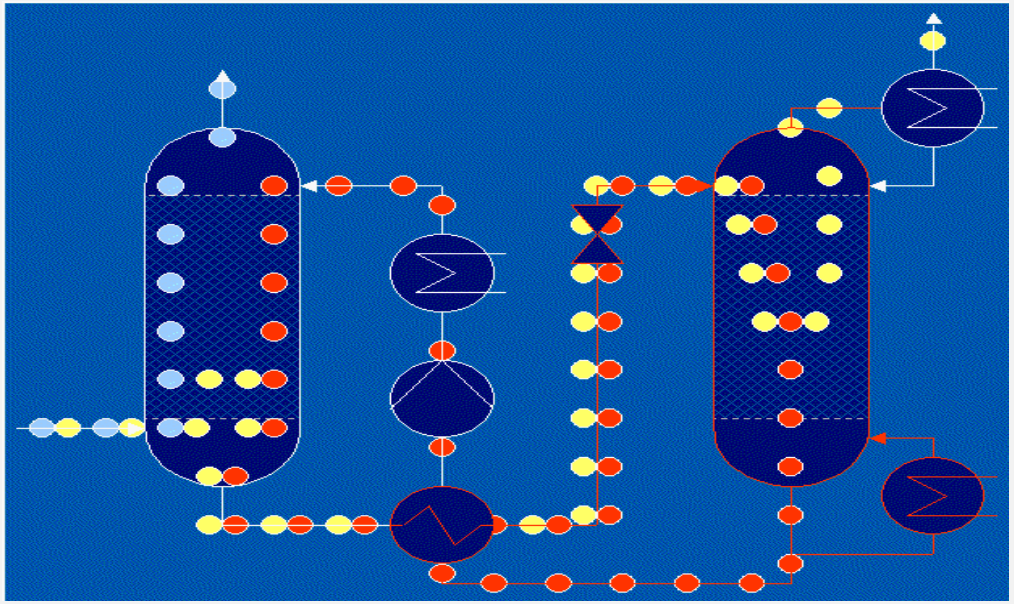
- RTI completed large-scale (50-MW_e) pre-commercial testing of its warm gas desulfurization process (WDP) technology at Tampa Electric Company's Polk 1 IGCC Power Station in April 2016, and the technology is now ready for commercial licensing via Casale S.A.





- Benefits:
  - RTI WDP removes ~99.9% of sulfur contaminants from syngas at warm process temperatures (250-600°C) with up to 50% lower capital and operating costs and up to 10% higher efficiency (pressure independent process).
  - RTI advanced water-gas-shift (WGS) process can enrich H_2 content requiring ~50% less steam and 30% lower capital cost.
  - Coupled with carbon capture, WDP can produce ultra-clean syngas (up to 99.999% total S removal, down to sub-ppmv) suitable for ultra-clean power generation or rigorous coal-to-chemicals/fuels applications.
  - WDP is proven with ~7,000 hours of testing at pilot scale (Eastman Chemical) and demonstration scale (Tampa).

CO_2 Capture: BASF OASE® (aMDEA™) Activated Amine Process



Feed Syngas

CO_2, H_2S

aMDEA™

Source: BASF

OASE® has the lowest specific energy consumption of any standard amines for acid gas removal.

OASE® 's higher absorption kinetics and capacity reduce equipment size resulting in lower capex and opex.

OASE® is chemically and thermally stable, non-corrosive, non-toxic, and readily biodegradable.

But, exploiting OASE® for CCS in IGCC requires upstream selective sulfur removal technology for syngas.

Design rate ~1200 tpd of carbon dioxide captured by RTI demonstration plant

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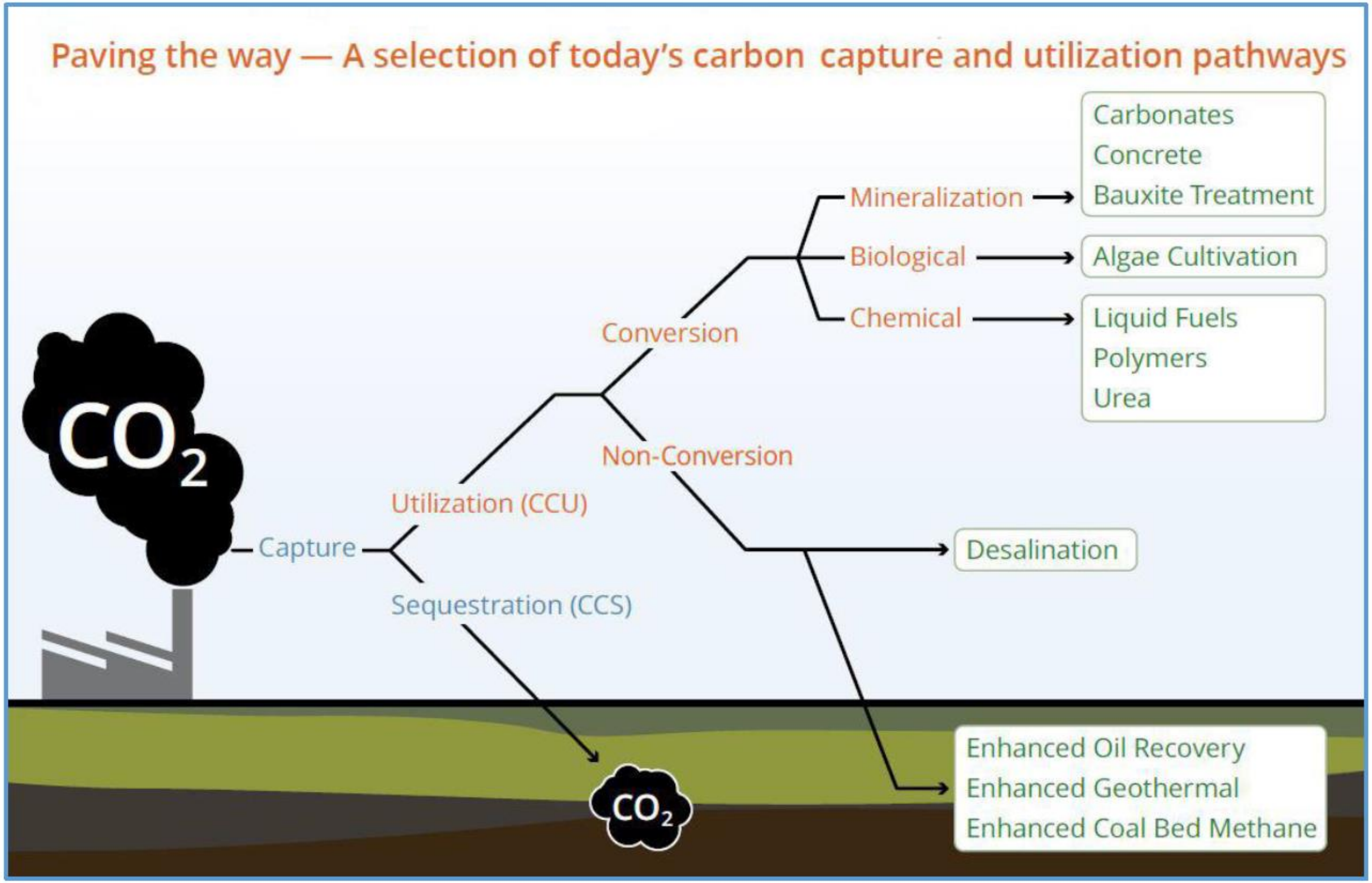
RTI Warm Gas Cleanup (WDP) Demo Testing Carbon Capture Performance

- Carbon capture process performed as expected.
- Carbon dioxide capture efficiency was >99%.
- RTI achieved >90% overall carbon capture goal.
- Primary impurities in the captured and released carbon dioxide were H_2 (about 1 mol%), CO (anticipated <1,000 ppmv or 0.1 mol%), and H_2S and COS (<100 ppmv).
- The combination of RTI's WDP and activated amine CO_2 capture (90% capture) results in:
  - A reduction in levelized cost of electricity (LCOE),
  - A reduction in overall IGCC capex/kW,
  - A reduction in overall IGCC opex/MWh, and
  - A significant (~75%) reduction in overall sulfur emissions

  compared with a base case IGCC using dual-stage Selexol™.
- The WDP + activated amine process is now commercially available from Casale S.A.

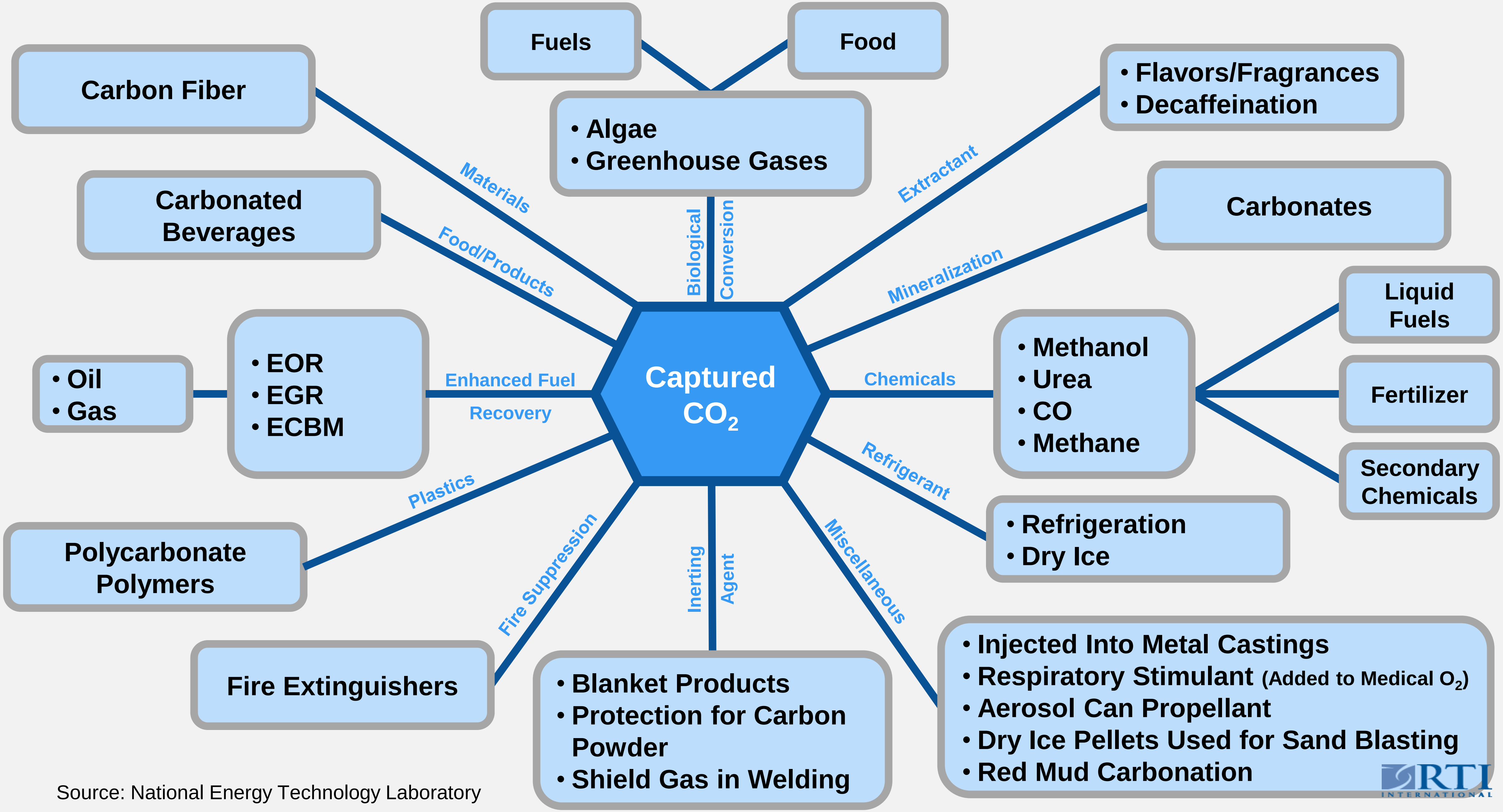
Carbon Capture Utilization and Storage Pathways



- Safe storage of CO_2 is being proven but still faces legal and regulatory risks that need to be addressed through policy measures.
- Innovations in CO_2 utilization offer interesting technology and business options beyond CO_2 storage.

Source: Global CCS Institute

CO_2 Utilization – Broad Market Potential but Must be Economically Competitive

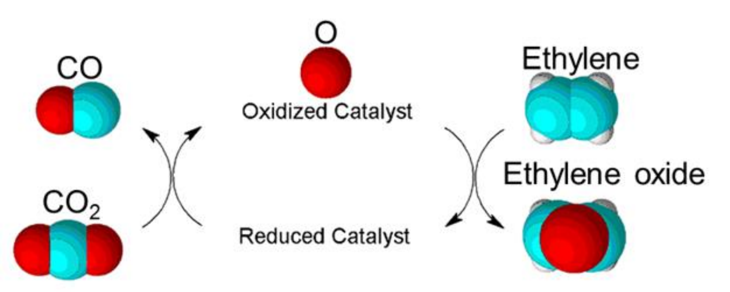


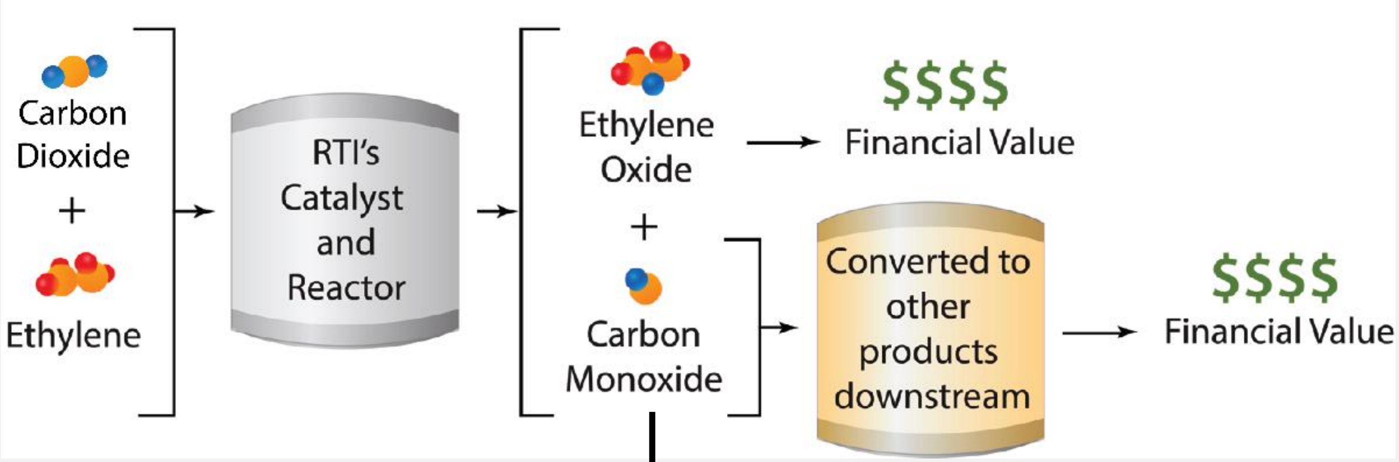
Source: National Energy Technology Laboratory

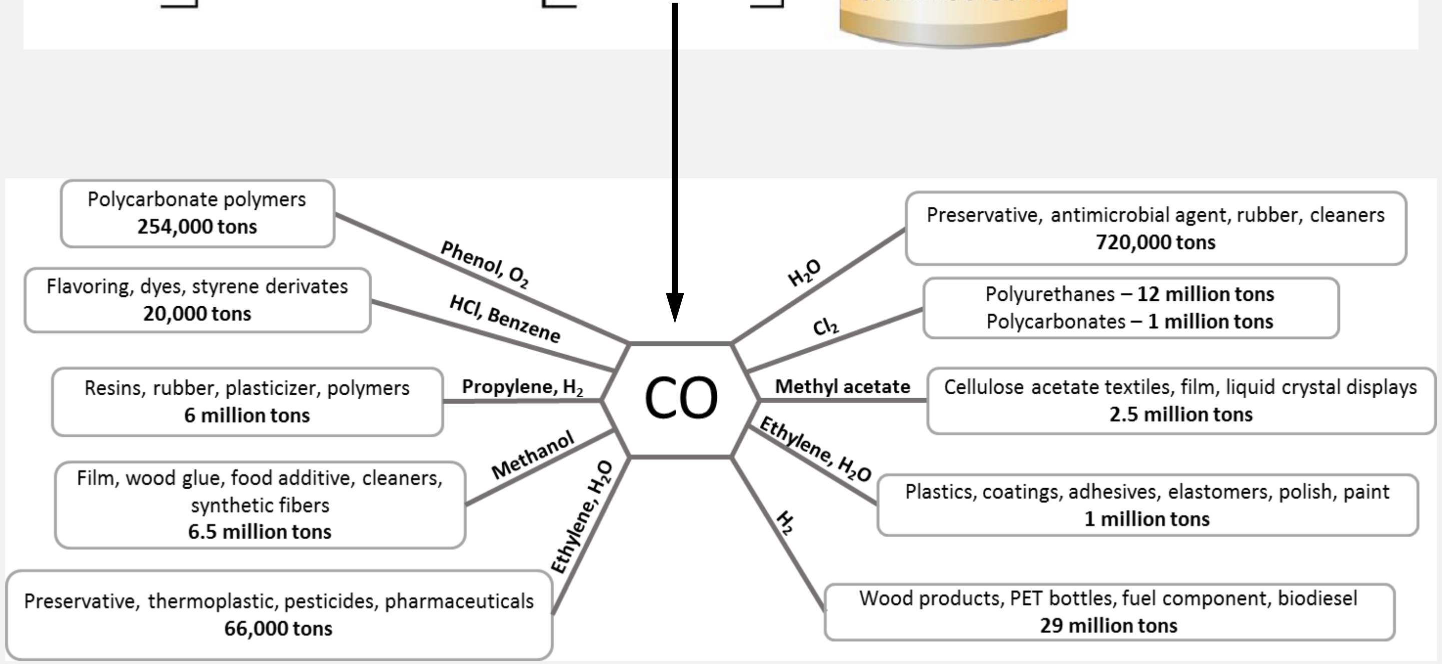
RTI Novel CO_2 Utilization Approach

CONCEPT

Novel catalyst platform for CO_2 utilization for oxidation reactions







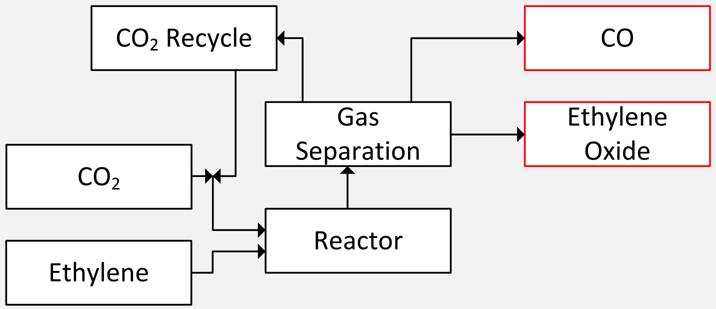
INNOVATION

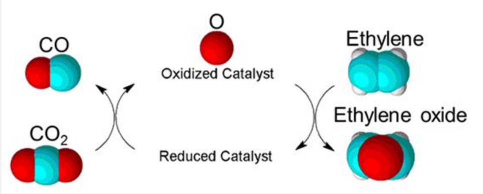
- Utilizing CO_2 as a feedstock for large volume chemicals with broad industrial interest.
- Based on novel catalysts that can extract an oxygen (O) atom from CO_2, co-producing carbon monoxide (CO), while driving reactions such as dry methane reforming or oxidations such as ethylene to ethylene oxide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

Example: Utilization of CO_2 for Ethylene Oxide (EtO) Production

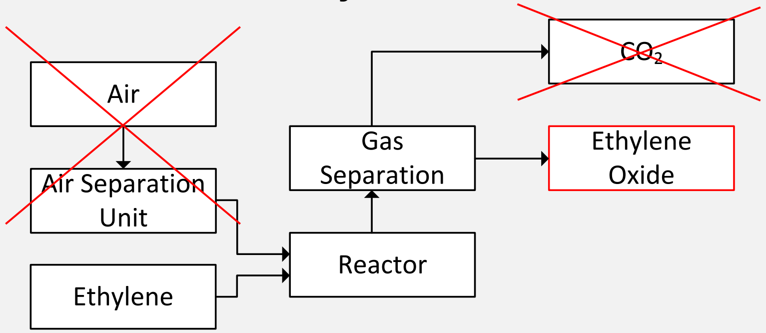
- **RTI's technology is based on a novel catalyst**
  - Extraction of an O atom from CO_2 and transfer to ethylene, at lower energy threshold
  - Consumes CO_2 and ethylene, producing EtO and CO
- **Enables EtO + CO process simplification**
  - Removes need for energy intensive air separation unit
  - Eliminates CO_2 emissions from EtO process
  - Eliminates conventional CO production by steam methane reforming plus its CO_2 emissions
- **Enables safer operation**
  - Removes explosion potential of conventional ethylene oxide production
  - Changes highly exothermic process to moderately endothermic process
- **Acceptable economics** (at current EtO prices)
  - Penalty for CO_2 use offset by process simplification
  - Byproduct CO is also a valuable chemical intermediate
- **Reduces CO_2 emissions**
  - >2.8 net tons of CO_2 reduction per ton of EtO product
  - 350 Kta EtO plant could reduce CO_2 emissions 1 Mta

RTI's Ethylene Oxide Production

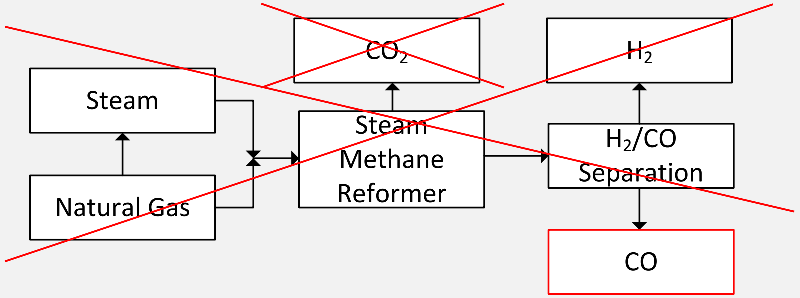




Conventional Ethylene Oxide Production



Conventional CO Production



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.

Source: Robert Nickelsberg/Getty Images

Acknowledgement:
RTI's Energy Technology Team + U.S. DOE and Other Public/Private Partners

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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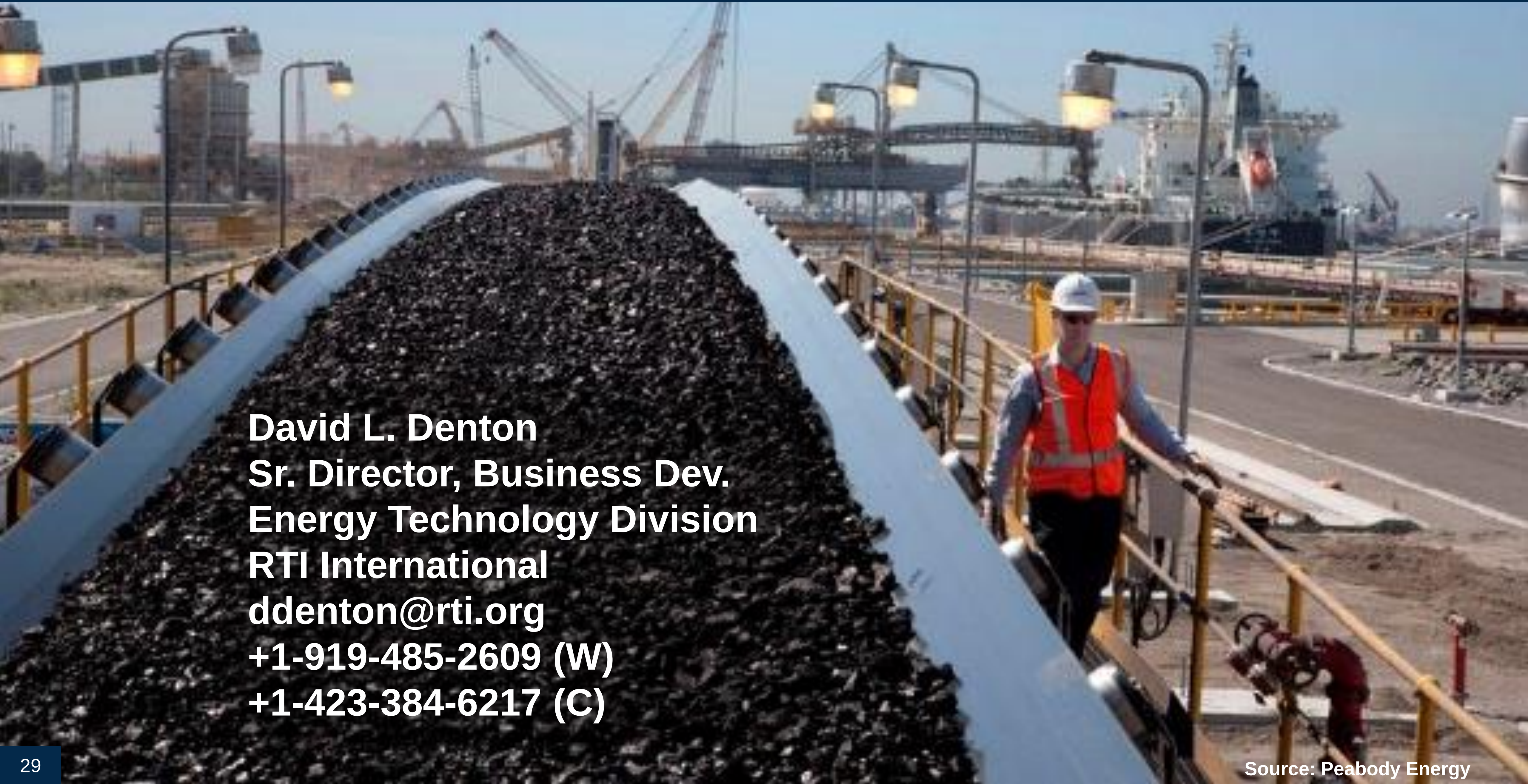
QUESTIONS?



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Source: Peabody Energy