Looking at the Future of CCUS and Clean Coal Technologies

Angelos Kokkinos
Associate Deputy Assistant Secretary
Office of Clean Coal and Carbon Management
Mission:

Discover and develop advanced coal technologies that ensure America’s access to resilient, affordable, reliable, and near-zero emitting coal energy resources.

R&D Priorities:

1. Advancing small-scale modular coal plants of the future, which are highly efficient and flexible, with near-zero emissions
2. Improving the performance, reliability, and efficiency of the existing coal-fired fleet
3. Reducing the cost of carbon capture
4. Creating new market opportunities for coal

HOLISTIC APPROACH TO ENERGY GENERATION FROM FOSSIL FUELS
COAL R&D OVERVIEW

**Advanced Energy Systems**

- Efficiency improvements for new and existing units
  - Advanced energy materials
  - Advanced gasification
  - Solid oxide fuel cells
  - Advanced coal processing
  - Advanced turbines
  - Advanced combustion
  - Sensors and controls

**Crosscutting Research**

- Crosscutting technology development program
  - Power generation efficiency
  - Supercritical transformational electric power
  - Critical minerals
  - Coal utilization science
  - Transformational coal pilots
  - University research
  - SBIR/STTR*
  - Technology Commercialization Fund (TCF)*

**CO₂ Capture and Utilization**

- Reducing the cost of CO₂ capture for new and existing units
  - Post-combustion capture
  - Pre-combustion capture
  - New pathways to utilize captured CO₂

**CO₂ Storage**

- Safely and permanently storing CO₂
  - Safe use and permanent storage of CO₂ from power generation and industry
  - Minimizing subsurface risks (coordinated with other subsurface offices, e.g., Office of Oil and Natural Gas)
  - CO₂ infrastructure analysis

---

*SBIR/STTR and TCF are managed under the Crosscutting Program but funded by all R&D programs*
CLEAN COAL AND CARBON MANAGEMENT BUDGET OVERVIEW
(SUBJECT TO APPROPRIATION)

Coal R&D Budget Priorities

- **Implementing** the **Coal FIRST** (Flexible, Integrated, Resilient, Small, Transformative) initiative: R&D on first-of-a-kind small-scale modular coal plants of the future, which are highly efficient and flexible, with near-zero emissions
- **Improving** the performance, reliability, and efficiency of the existing coal-fired fleet
- **Reducing** the cost and risk of carbon capture for commercial deployment
- **Creating** new market opportunities for coal

### Coal R&D Budget Priorities ($ in thousands)

<table>
<thead>
<tr>
<th>CCS and Power Systems</th>
<th>FY 2019 Enacted</th>
<th>FY 2020 House</th>
<th>FY 2020 Senate</th>
<th>Future Plants</th>
<th>Existing Plants</th>
<th>Cost of Capture</th>
<th>New Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Capture</td>
<td>100,671</td>
<td>125,000</td>
<td>113,000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Carbon Storage</td>
<td>98,096</td>
<td>102,000</td>
<td>103,000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Advanced Energy Systems</td>
<td>129,683</td>
<td>107,000</td>
<td>139,000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Crosscutting Research*</td>
<td>56,350</td>
<td>65,255</td>
<td>64,300</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Rare Earth Elements*</td>
<td>18,000</td>
<td>23,000</td>
<td>25,000</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>STEP (Supercritical CO2)</td>
<td>22,430</td>
<td>24,000</td>
<td>14,000</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Transformational Coal Pilots</td>
<td>25,000</td>
<td>20,000</td>
<td>17,000</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>NETL Coal R&amp;D*</td>
<td>36,000</td>
<td>38,000</td>
<td>42,000</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>TOTAL CCS &amp; Power Systems</strong></td>
<td><strong>486,230</strong></td>
<td><strong>504,255</strong></td>
<td><strong>517,300</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Coal FIRST: THE FUTURE OF POWER GENERATION
(Flexible, Innovative, Resilient, Small, Transformative)

- **Secure, Stable, Reliable Power**
- **Near-Zero Emissions**

- **Flexible** coal plant operations to meet the needs of the grid
- **Innovative** and cutting-edge components; improved efficiency and near-zero emissions
- **Resilient** power generation
- **Transformative** how coal technologies are designed and manufactured
- **Smaller** than conventional utility-scale coal plants
COAL FIRST – A FLAGSHIP INITIATIVE

➢ Provides a **zero or near zero CO₂ emissions**

➢ Provides **low cost power generation**; economically competitive

➢ Uses advanced materials and processes; **maximizes efficiency**

➢ **Global solution for CO₂ emissions** -- carbon capture

➢ **Only** zero or near zero CO₂ emissions power plant **R&D effort in the world**

➢ Potential to **revive the US coal industry**; provide a source of **high value exports**

➢ Provides stability and reliability to the grid of the future, and offers both **“firm and flexible” operations**

Per International Energy Agency (IEA), coal will be the largest source of electricity production in the world by 2040, and likely beyond
TRAITS OF THE COAL FIRST TECHNOLOGIES

- High overall plant efficiency (40%+ HHV or higher at full load)
- Small (unit sizes of approximately 50 to 350 MW)
- Near-zero emissions
- Capable of high ramp rates and minimum loads
- Integration with thermal or other energy storage (e.g., chemical production)
- Minimized water consumption
- Reduced design, construction, and commissioning schedules from conventional norms (e.g., advanced process engineering and parametric design methods for modular design)
- Enhanced maintenance features to reduce maintenance and minimize forced outages
- Integration with coal upgrading, or other plant value streams (e.g., co-production)

CO₂ Capture Integral to the Design
As of October 2019

**FOA – Accelerated FEED Studies**
Up to 2 FEED studies in 3 Areas of Interest (AOI)

AOI 1: Flexible Ultra Supercritical (USC) Coal-Fired Power Plant
AOI 2: Pressurized Fluidized Bed Combustor with Supercritical Steam Cycle Power Plant
AOI 3: Hybrid Natural Gas Turbine / USC Coal Boiler Power Plant

**FOA – R&D of Critical Components**
Up to 20 awards in 8 Areas of Interest (AOI)

AOI 1: Pressurized Fluidized Bed Combustion with USC power Cycle
AOI 2: Indirect Supercritical Carbon Dioxide Power Cycle
AOI 3: Direct-fired Supercritical Carbon Dioxide Power Cycle
AOI 4: Gasification Based Poly-generation
AOI 5: Coal-Fired Direct Injection Combustion Engine & Gas Turbine Compound Reheat Combined Cycle
AOI 6: Modular Staged Pressurized Oxy-combustion
AOI 7: Flameless Pressurized Oxy-combustion
AOI 8: Modular Gasification Syngas Combined Heat and Power Engine

**FOA – Pilot Plant FEED Study & NEPA**
Up to 2

Sept ’25 Complete

**Pilot Plant**
Detailed Design, Construction, & Operation
Up to 1 project

**Coal FIRST Pilot Plant Operation**

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028
## Coal FIRST: THE FUTURE OF POWER GENERATION

<table>
<thead>
<tr>
<th>Selectee</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barr Engineering Co.</td>
<td>USC Coal Boiler with Gas Turbine</td>
</tr>
<tr>
<td>Electric Power Research Institute</td>
<td>Small-Scale Flexible AUSC Power Plant</td>
</tr>
<tr>
<td>Nexant Inc.</td>
<td>DICE w/Gas Turbine and Steam Bottoming Cycle</td>
</tr>
<tr>
<td>Barr Engineering Co.</td>
<td>Gasification w/Syngas Chemical Looping and H2 Storage</td>
</tr>
<tr>
<td>Allegheny Science &amp; Technology</td>
<td>Gasification/Polygeneration w/Bottoming Cycle</td>
</tr>
<tr>
<td>HECA</td>
<td>IGCC w/Chemical Plant, H₂ Fuel Cells, and Battery Storage</td>
</tr>
<tr>
<td>WES Inc.</td>
<td>All Steam IGCC w/Polygeneration</td>
</tr>
</tbody>
</table>

### Selectee (cont.)

<table>
<thead>
<tr>
<th>Selectee</th>
<th>Project Description (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSOL Pennsylvania Coal Company</td>
<td>PFBC w/SC Steam and Benfield Process</td>
</tr>
<tr>
<td>Constantem Technologies</td>
<td>Pressurized Oxy CFB</td>
</tr>
<tr>
<td>Washington University</td>
<td>Stage Pressurized Oxy-Combustion USC or SC steam</td>
</tr>
<tr>
<td>Echogen Power Systems</td>
<td>Indirect SO₂ and Electrothermal Energy Storage</td>
</tr>
<tr>
<td>WES Inc.</td>
<td>Direct Fired SO₂ All Steam Gasification w/Allam Cycle</td>
</tr>
<tr>
<td>8 Rivers Capital LLC</td>
<td>Direct Fired SO₂ - Coal-fired w/Allam Cycle</td>
</tr>
</tbody>
</table>
GLOBAL LEADERSHIP

U.S. Leading on CCUS Research, Development, and Deployment

- The strongest country in developing the human capital and enablers for CCUS deployment (scientists, engineers, trades)
  - Broad R&D program engaging Private Industry, Universities, National Laboratories, small business, and the financial community.
- More major CCUS demonstrations than any other country
- Through the DOE/FE, leading one of the most globally recognized and successful RD&D programs on CCUS.... And leveraging this technology, science, and knowledge with other agencies for sound policy development

Key international partnerships

40+ year history of CO₂ utilization for EOR

Over 600 million tons of associated storage with EOR

Over 4,000 miles of CO₂ pipelines in the United States

40+ year history of CO₂ utilization for EOR
EXCITING TIME FOR CCUS

Carbon capture, utilization, and storage (CCUS) is increasingly becoming widely accepted as a viable option for fossil-based energy to lower their carbon dioxide (CO₂) emissions.

Here’s what we can do moving forward...

- Capture FEED Studies
- CarbonSAFE Initiative
- Regional Initiative to Accelerate CCUS
- 45Q Tax credit
- CCUS Demonstration Projects
“Technology push” through R&D is matched with “market pull” through financial incentives

❖ Tax benefits in “45Q” for qualified CCUS projects have been available since 2008
❖ The February 2018 “Bipartisan Budget Act of 2018” extended and significantly expanded the tax benefits:

- **Increased the credit amount:** $20/ton $50/ton for geologic storage, $10/ton $35/ton for EOR (by 2026)
- **Qualified facilities** must begin construction by January 1, 2024, include carbon capture in original design, and capture 25,000/500,000 tons of CO$_2$
- **Expanded the qualified carbon oxides** to include carbon monoxide (CO) and CO$_2$ captured from an industrial source or the ambient air
- **Expanded qualified uses** to include CO$_2$ utilization (beyond EOR)
- **Lowered the qualifying threshold** for the amount of CO$_2$ captured
- **Increased the flexibility for assignment of credits**
- **Removed the program cap**

Treasury working to finalize guidance for project developers
HIGH-LEVEL R&D PROGRAM GOALS AND CHALLENGES

Reduce the cost of capture by 50%
- Capital cost
- Energy penalty
- Integration or process intensification

Develop viable carbon utilization alternatives ($1T opportunity)
- Reduce Capital cost
- Reduce energy requirements
- Lifecycle assessment better than existing products

Reduce the risk of geologic storage – improve monitoring and simulation
- Higher resolution and quantification (e.g., accurate characterization of faults and fractures)
- Geomechanics (pressure and state of stress)
- Costs/uncertainty/enabling real-time decision making


2012: $80/tonne
2016: $60
2020: $40
2030: $30

$ Millions

FY 2015 ENACTED
$207.0

FY 2016 ENACTED
$196.3

FY 2017 ENACTED
$198.7

FY 2018 ENACTED
$198.7

FY 2019 ENACTED
$198.7


2012: $80/tonne
2016: $60
2020: $40
2030: $30
## CCUS FEED STUDIES SELECTIONS

**Front-End Engineering Design (FEED) Studies for Carbon Capture Systems on Coal and Natural Gas Power Plants (DE-FOA-0002058, 000001)**

Projects will support FEED studies for commercial-scale carbon capture systems

- $55.4 million in Federal funding awarded
- Nine projects selected

<table>
<thead>
<tr>
<th>Awardee</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bechtel National</td>
<td>FEED Study for Retrofitting a 2x2x1 Natural Gas-Fired Gas Turbine Combined Cycle Power Plant for Carbon Capture Storage/Utilization – MEA Solvent</td>
</tr>
<tr>
<td>The Board of Trustees of the University of Illinois</td>
<td>Full-Scale FEED Study for Retrofitting the Prairie State Generating Station with an 816 MWe Capture Plant Using Mitsubishi Heavy Industries of America Post-Combustion CO2 Capture Technology – MHI Solvent</td>
</tr>
<tr>
<td>Electric Power Research Institute</td>
<td>Front End Engineering Design Study for Retrofit Post-Combustion Carbon Capture on a Natural Gas Combined Cycle Power Plant – Fluor’s amine-based Econamine FG Plus</td>
</tr>
<tr>
<td>Enchant Energy</td>
<td>Large-Scale Commercial Carbon Capture Retrofit of the San Juan Generating Station – Commercial Solvent</td>
</tr>
<tr>
<td>Membrane Technology and Research Inc.</td>
<td>Commercial-Scale Front-End Engineering Study for MTR’s Membrane CO2 Capture Process – MTR, Inc Polymeric Membrane</td>
</tr>
<tr>
<td>Minnkota Power Cooperative Inc.</td>
<td>Front-End Engineering &amp; Design: Project Tundra Carbon Capture System – Fluor’s amine-based Econamine FG Plus</td>
</tr>
<tr>
<td>Southern Company Services</td>
<td>Front End Engineering Design of Linde-BASF Advanced Post-Combustion CO2 Capture Technology at a Southern Company Natural Gas-Fired Power Plant – Linde BASF amine Solvent</td>
</tr>
<tr>
<td>The University of Texas at Austin</td>
<td>Piperazine Solvent/Advanced Stripper Front-End Engineering Design (PZAS FEED)</td>
</tr>
</tbody>
</table>
CARBON CAPTURE FRONT-END ENGINEERING DESIGN (FEED) STUDIES

Applicant Locations and Host Sites
FUTURE CARBON CAPTURE ACTIVITIES

- $30/tonne - Transformational Carbon Capture Technologies for both pre and post combustion capture

- Expanding beyond coal: natural gas, industrial, direct air capture (leverage historical investments)

- Process development and design – R&D and Carbon Capture Simulation Initiative for Industry

- Technology Validation – National Carbon Capture Center and other test centers
FUTURE CARBON STORAGE ACTIVITIES

CarbonSAFE Phase III – directed by Congress in FY2019 Appropriations

Machine learning applications

Transformational sensor development
- Improved accuracy, reliability and performance
- Characterize faults and fractures

Modeling and simulation tools
**CARBON UTILIZATION**
OFFSET CO₂ CAPTURE COSTS + FIX CO₂ IN STABLE PRODUCTS

### Biological Capture & Conversion

- **Catalysis and Biological Pathways - Fuels and Chemicals**
  - Projects creating CO or direct to fuels using low-carbon energy and/or hydrogen

- **Concrete: Solidia Technologies - Utilizes CO₂ to make cement and concrete**
  - Reduce carbon footprint up to 70%
  - $1.9M DOE investment leveraged by industry
  - Oil and Gas Climate Initiative’s Climate Investment Funded and other parties

---

**24 Active Projects – Recently selected 11 lab and 4 field-scale projects**
COAL & BYPRODUCTS END USE APPLICATIONS

Iron and Steelmaking
- Metallurgical Coke
- Slag Foaming Agent
- Charge Carbon
- DRI Reductant

Non-Ferrous Metallurgy
- Ferroalloys
- Silicon Metal
- Aluminum
- Titanium
- Germanium

Environmental Applications
- Municipal Water/Wastewater Filtration Media
- Activated Carbons

Construction Products
- Cement Additives (Pozzalons)
- Lightweight Aggregates

Chemicals
- Wood Preservatives
- Fertilizer
- Aromatics

Consumer Products
- Medicines
- Shampoo

Carbon Products
- Graphite
- Fibers
- Rubber Fillers
- Electrodes

Source: National Archives
FOSSIL ENERGY IS CRITICAL IN ALL SECTORS
CCUS IS A PLATFORM TECHNOLOGY FOR MANY INDUSTRIAL SECTORS

SKYONIC “SKYMINE” PROJECT, SAN ANTONIO, TX

75,000 tons/y CO$_2$ captured - >200,000 tons avoided
Carbon Storage Infrastructure/Field Tests
Addressing Large-Scale Challenges

Regional Carbon Sequestration Partnerships (RCSPs)

CarbonSAFE

Offshore Storage

Unconventional EOR

Brine Extraction Storage Tests (BEST)
The intent of CarbonSAFE is to address the R&D knowledge gaps and technologies needed for a 50+ million metric tons CO$_2$ storage:

**Phase I: Integrated CCS Pre-Feasibility (18 months)**
- Formation of a CCS team, Development of a feasibility plan and High-level technical evaluation of the sub-basin and potential CO$_2$ sources

**Phase II: Storage Complex Feasibility (2 years)**
- Data collection, Geologic analysis, Identification of contractual and regulatory requirements and plans to satisfy them, Subsurface modelling to support geologic characterization, risk assessment, and monitoring, and Public outreach

**Subject to Funding Phase III: Site Characterization (2-3 years)**
- Tentative - Address pore/surface rights, Rights of way, Permitting processes and requirements, Liability relief and Finance agreements

**Subject to Funding Phase IV: Permitting and Construction of storage complex**
- Tentative - Submission of Class VI permits, Drill and Complete injection and monitoring wells, Acquisition of baseline monitoring data and Risk management and mitigation plan

**Funding Opportunity DE-FOA-0001999**
- Now Open
Injecting more than 10 million metric tons of CO$_2$ was a great achievement. But there is much more...

The RCSP Initiative has:

- Established the first U.S. carbon storage national network
- Provided the foundation for validating CCUS commercial deployment and monitoring
- Demonstrated the effectiveness of multiple secure storage technologies and use of storage resources
- Participated in the development of technologies regulatory and legal frameworks
- Documented 15 years of experience in a series of topical Best Practice Manuals (BPMs)
EXAMPLES OF MAJOR LEARNINGS

- Geochemical risks are small and manageable
  - Caprocks tend to get better over time
  - Wellbore geochemistry risks smaller than first thought

- Far-field hydrology risks are small
  - E.g., brine volume displacement

- Many effective options for characterization and monitoring
  - Seeking lower cost/higher certainty options
  - Sorting types and terrains
The 45Q tax credit provides an additional positive economic incentive for potential CCUS projects.

Regardless of modeling platform, analysts are finding that 45Q enables deployment of CCS in the power and industrial sectors.
Carbon Capture: Post-Combustion, Pre-Combustion, and Direct Air Capture
Focus on Cost Reduction, Energy Penalty, and Integration

Requires improvements in multiple areas

Summary of Carbon Capture R&D Program Advancement of 2nd Generation Technologies

<table>
<thead>
<tr>
<th>Cost Reduction</th>
<th>Energy Penalty Reduction</th>
<th>Program Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100+/tonne</td>
<td>30+ %</td>
<td>180+ Projects</td>
</tr>
<tr>
<td>$41/tonne</td>
<td>14-15%</td>
<td>15 Technologies Tested at Pilot Scale</td>
</tr>
</tbody>
</table>

Pilot-scale Testing

<table>
<thead>
<tr>
<th>TECHNOLOGY HIGHLIGHTS</th>
<th>PRINCIPAL DEVELOPER</th>
</tr>
</thead>
<tbody>
<tr>
<td>POST-COMBUSTION</td>
<td></td>
</tr>
<tr>
<td>Imbedded Amine Sorbent</td>
<td>AOA-CS</td>
</tr>
<tr>
<td>Low-water Amine Solvent</td>
<td>Fluor/MI-1</td>
</tr>
<tr>
<td>Hybrid Solvent/Membrane</td>
<td>Gas Technology Institute</td>
</tr>
<tr>
<td>Amino-silicone Solvent*</td>
<td>General Electric Company</td>
</tr>
<tr>
<td>Amines/imidazoles Solvent Mixture*</td>
<td>Ionic Engineering</td>
</tr>
<tr>
<td>Advanced Amine Solvent Process*</td>
<td>Linds/EASF</td>
</tr>
<tr>
<td>Advanced Membrane Process*</td>
<td>MTR</td>
</tr>
<tr>
<td>Nozzle-based Solvent Reactor*</td>
<td>Neumann Systems Group</td>
</tr>
<tr>
<td>Mixed Salt Solvent Process*</td>
<td>SRI International</td>
</tr>
<tr>
<td>Carbon-based Sorbent*</td>
<td>SRI International</td>
</tr>
<tr>
<td>Alkalized Alumina Sorbent*</td>
<td>TDA Research</td>
</tr>
<tr>
<td>Optimized Amine Solvent Process</td>
<td>University of Kentucky</td>
</tr>
<tr>
<td>Piperazine Solvent/Flash Stripper</td>
<td>UNL/University of Texas</td>
</tr>
<tr>
<td>PRE-COMBUSTION</td>
<td></td>
</tr>
<tr>
<td>Ammonium Carbonate/Bicarbonate Solvent*</td>
<td>SRI International</td>
</tr>
<tr>
<td>Integrated Sorbent Process</td>
<td>TDA Research</td>
</tr>
</tbody>
</table>

Case Study of Technology Development Progression Through the Carbon Capture R&D Program – Membrane Technology Research, Inc.
Development of an economically competitive and sustainable domestic supply of rare earth elements (REEs) and critical materials (CMs) to assist in maintaining our Nation’s economic growth and National Security.

Eliminate materials criticality as an impediment to the commercialization of clean energy technologies for today and tomorrow.
KNOWLEDGE SHARING PRODUCTS

- Annual Carbon Storage Meeting
- RCSP Working Groups
- Domestic Collaborations
- International Collaborations
- Technical Workshops

Worldwide CCS Project Database
MAJOR CCUS DEMONSTRATION PROJECTS

Air Products Facility (Port Arthur, TX) – operations began in 2013

- Built and operated by Air Products and Chemicals Inc. at Valero Oil Refinery
- State-of-the-art system to capture CO₂ from two large steam methane reformers
- **5.0 million metric tons of CO₂** captured and transported via pipeline to oil fields in eastern Texas for enhanced oil recovery (EOR) since March 2013

Petra Nova CCS (Thompsons, TX) – operations began in 2017

- Joint venture by NRG Energy, Inc. (USA) and JX Nippon Oil and Gas Exploration (Japan)
- Demonstrating Mitsubishi Heavy Industries’ solvent technology to **capture 90% of CO₂ from 240-MW flue gas stream** (designed to capture/store 1.4 million metric tons of CO₂ per year)
- **Nearly 2.5 million metric tons of CO₂** used for EOR in West Ranch Oil Field in Jackson County, Texas since January 2017

ADM Ethanol Facility (Decatur, IL) – operations began in 2017

- Built and operated by Archer Daniels Midland (ADM) at its existing biofuel plant
- CO₂ from ethanol biofuels production captured and stored in deep saline reservoir
- **First-ever CCS project** to use new U.S. Environmental Protection Agency (EPA) Underground Injection Class VI well permit, specifically for CO₂ storage
- **1.0 million metric tons of CO₂** captured, **0.8 million metric tons** of which stored, since April 2017