Testimony
Advancing Coal Research and Development for a Secure Energy Future: Insights from EPRI

U.S. House of Representatives
Committee on Science, Space and Technology
Subcommittee on Energy and the Environment

Stuart Dalton
Senior Government Representative, Generation
Electric Power Research Institute
October 13, 2011

My name is Stuart M. Dalton. I am the Senior Government Representative, Generation, for the Electric Power Research Institute (EPRI, www.epri.com). EPRI conducts research and development relating to the generation, delivery, and use of electricity for the benefit of the public.

As an independent, nonprofit corporation, EPRI brings together its scientists and engineers, as well as experts from industry, academia, and government, to help address challenges in electricity, including reliability, efficiency, health, safety, and the environment. EPRI also provides technology, policy, and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, California; Charlotte, North Carolina; Knoxville, Tennessee; and Lenox, Massachusetts. EPRI appreciates the opportunity to provide this testimony today.

Introduction and summary

EPRI analysis including our Prism/MERGE reports shows multiple future scenarios in which coal will be an important fuel in the US generation mix. In the wake of recently proposed environmental rules and other regulations, U.S. power producers have estimated that tens of thousands of megawatts of coal-fired power generation capacity could be retired prematurely. At the same time, studies by EPRI, the International Energy Agency and others demonstrate that in order to *reliably* and *affordably* meet the nation's energy needs and environmental goals all types of power plants—from renewables to advanced coal and natural gas to nuclear— are needed to provide a secure energy future.

For coal-based generation to fulfill its potential to contribute to the nation's clean energy supply, new technologies and practices must be developed and demonstrated to address concerns over air, water, and thermal emissions, as well as secure solids disposal and CO_2 storage.

The U.S. Department of Energy (DOE) has excellent research, development, and demonstration (RD&D) programs in place on CO_2 capture and storage and conducts significant work on advanced coal generation technology; these were preceded by a long history of successful RD&D on criteria pollutant, particulate, and hazardous pollutant controls for coal power plants.

RD&D on stronger and more durable high-temperature materials as well as improved integration and process configurations for increased plant efficiency have paralleled environmental control technology development. EPRI has worked independently, as well as cooperatively, with DOE and other government agencies to help attain many of these research objectives.

The needs of the electric power industry are evolving rapidly because of changing emission regulations and power grid system requirements. The continued alignment of RD&D efforts to reflect these latest priorities is necessary to help ensure that the nation's coal-based power plants can continue to supply affordable electricity.

Based on EPRI's analysis, three major areas not sufficiently covered by current DOE coal RD&D need additional support and these areas currently compromise the power industry's ability to meet both global competitive challenges in advanced coal power technology and domestic regulatory compliance schedules. A fourth area is relatively well addressed, but would benefit from additional RD&D on basic gasification and power block technology improvements. These areas are listed below and discussed individually in further detail:

1. Ultra-high-efficiency steam power cycles based on American advanced alloy steels: we need to accelerate the pace from successful component fabrication and testing to in-service boiler and steam turbine testing and a complete integrated demonstration plant

2. Improved water management to reduce consumption, accommodate lower-quality/degraded water supplies, and address more complex wastewater treatment and solid by-product management challenges

3. Workable solutions to proposed hazardous air pollutants (HAPs) emission standards accounting for real-world operational issues, flue gas constituent interactions and cross-media impacts, and measurement capabilities

4. Efficiency and cost improvements for gasification power plants independent of CO_2 capture processes: we need to accelerate scale-up, testing, integration engineering, and demonstration of fundamental improvements in synthesis gas cleanup at higher temperatures, higher gas turbine firing temperatures and larger turbines (and associated blade temperature control), lower-energy oxygen supply technologies, and better plant controls

EPRI would like to stress that these areas are identified as necessary to augment, not supplant, DOE's current RD&D programs focusing heavily on CO_2 capture, utilization, and storage (CCS). Continued and sustained support for CCS development and *integrated* demonstration is essential to success in this most overarching of issues facing coal power plants.

Advanced ultra-supercritical steam cycle development using nickel-based alloys: In-service test facility and fully integrated demonstration

Higher plant efficiency reduces the amount of fuel consumed and associated emissions and water consumption per megawatt hour of electricity generated. Notably, CO_2 reduction is significant, up to 20-25% per megawatt hour and the avoided cost per ton of CO_2 is estimated both by DOE and EPRI as being one of the lowest avoided costs compared to any technology for CO_2 capture and storage. This is a win-win approach for utility customers and the environment. Thermodynamics dictates that increasing the efficiency of a steam cycle requires hotter and higher pressure steam conditions known as ultra-supercritical (USC) at the turbine inlet. Maintaining boiler, piping, and turbine safety and longevity at steam temperatures of up to 1400°F (760°C) requires a new class of high-nickel-content steel alloys and, in some cases, coatings, several of which have been pioneered in the United States under a research program sponsored by DOE and the Ohio Coal Development Office (OCDO).

Despite this successful record of fabrication and testing of key boiler and steam turbine components by American manufacturers, the program faces federal funding uncertainties at a time when European competitors have advanced to an in-service boiler test loop and Asian firms are looking to move to higher temperature and pressure cycles. To reach DOE and industry goals for improving coal plant efficiency, EPRI recommends a "managed risk" series of demonstration elements embedded in commercial power projects, concluding with a fully integrated plant (dubbed UltraGen) featuring nickel-alloy high-temperature components, superior environmental controls, and CO_2 capture and compression.

The foundation has been laid with earlier DOE/OCDO materials work managed by Energy Industries of Ohio and EPRI (one team focused on boilers, one on steam turbines), with a joint vision for future scale-up and demonstration established by DOE, EPRI, and the Coal Utilization Research Council. The most developed alloys are Inconel 740, a product of Special Metals Corporation in West Virginia, and Haynes 282 alloy by Haynes International, headquartered in Indiana.

Large-diameter pipe extrusions have been made by Wyman-Gordon in Texas, and Haynes alloy 282 castings have been made by MetalTek in Wisconsin and Flowserve in Ohio. The project also conducted powder metallurgy work at Carpenter Technology Corporation in Pennsylvania. Some of these firms are already receiving inquiries for use of these materials overseas. To reap the benefits of this technology research domestically, we need to adequately fund the next stages of development, namely in-service test and demonstration to allow for commercial deployment.

At a cost of ~$50M over three years, an in-service component test facility at an existing plant would lay the groundwork for the design and installation of a demonstration unit, possibly in later phases of DOE's Clean Coal Power Initiative or via other risk-sharing mechanisms for first applications in the United States. Under this scenario, advanced USC plants would become commercially available after 2020, following successful operation of a demonstration plant. This recommended path to commercialization and prior work on advanced materials development are described in EPRI brochure 1022770, *U.S. Department of Energy and Ohio Coal Development Office Advanced Ultra-Supercritical Materials Project for Boilers and Steam Turbines* (March 2011).

Such a commitment would return the United States to the forefront in thermodynamic efficiency, building upon the legacy of the world's first plants with USC steam conditions – AEP's Philo Unit 6 in 1957 and Exelon's Eddystone Unit 1, in service from 1960 until its retirement this year. Finally, given the prospect of future CO_2 regulations (and efforts by power producers to demonstrate voluntary CO_2 reductions), the impetus for higher efficiency in future coal-based generation units has gained traction worldwide. Many new coal plant projects announced over the last two years will employ supercritical steam cycles, and several will use high-efficiency "moderate USC" steam conditions, building a logical progression toward advanced USC plants with the help of financiers, state regulators, and other key stakeholders.

Improved water management to reduce water consumption, accommodate degraded water supplies, and address wastewater treatment and solid by-product disposal challenges

Water withdrawals and discharges by the power industry are falling under new regulatory requirements, and are posing new engineering challenges, as the sources and composition of water available to power plants are changing, along with restrictions on its discharge.

Water is the lifeblood of a power plant, serving both as the working fluid that converts combustion heat to turbine shaft power and as the cooling medium that allows high-purity steam cycle water to circulate continuously from boiler to turbine and back. Accordingly, water quality and cost are major factors in plant economics.

Cooling water is a power plant's largest use. There are proven low-water-use cooling options—developed in the arid western states and other locations where power plants have faced water limitations for decades—providing a technical foundation for new innovations. However, these alternative cooling options normally require more space than traditional "once through" river, lake, or ocean water cooling, which can create significant challenges when existing plants are compelled to retrofit recirculating cooling systems in response to Clean Water Act Section 316 rules on intake structures and thermal discharges. Thus, there is an RD&D need for retrofit cooling options, as well as designs for new plants.

Even in areas of the United States with historically adequate water supplies, reducing water use is a growing issue for the power industry, so the need is now national rather than regional. Compounding the challenge is the prospect of future regulations limiting CO_2 emissions. Virtually every type of CO_2 capture technology requires steam use for the process and additional cooling. CO_2 compression for sale or geologic storage also requires additional cooling. DOE research in this area will be especially important if CO_2 capture, utilization, and storage become widespread because power plant cooling demand will increase substantially.

In many cases, power plants are finding the only (or most economic) new source of water is from lower-quality and/or degraded supplies, such as municipal wastewater treatment plant discharge. These less-pure waters require different treatment methods and more blowdown (a slipstream sent to the plant's wastewater treatment equipment) than conventional water supplies.

Wastewater treatment also faces new engineering challenges due to tighter air pollution requirements, which result in greater amounts of trace species such as mercury, arsenic, selenium, and acid gases being removed from flue gases and transferred to wastewater streams. These may need to be treated differently before discharge than under prior practices. The particular wastewater treatment needs and available technology options depend on the coal and boiler type and the type and configuration of air pollution equipment used (e.g., wet vs. dry scrubbing for SO_2, different types of particulate and NO_X controls, and different sorbents or additives for mercury control). EPRI in conjunction with industry is developing an initiative to address plant water management and welcomes further collaboration with DOE.

Additional information is being developed in a draft roadmap by EPRI and the Coal Utilization Research Council. Some of the R&D goals being addressed are:

- Demonstrate reduced water consumption technologies
- Improve wet, hybrid, and dry cooling testing in conjunction with water balance modeling
- Moisture/water recovery
    - Test membrane, liquid desiccants, cyclic reheat and/or other new approaches, as well as low-temperature heat recovery plus water capture on coal gasification/combustion
    - Demonstrate integrated treatment, quality management, and moisture recovery
- Create an industry water research center to demonstrate methods for reduced water consumption and improved water management

Researching solutions to hazardous air pollutants issues in a real-world deployment setting: flue gas constituent interactions, cross-media impacts, and measurement capabilities

In the same manner that tailpipe emissions from new cars are a minuscule fraction of the emissions from cars of the 1960s, new coal-fired power plants are vastly cleaner than plants from a generation ago. In addition, many existing plants have been retrofit with technologies to capture SO_2, NO_X, mercury, and SO_3 and fine particulates.

New regulations have been proposed for hazardous air pollutants and the power industry is currently looking at process and operational alternatives for the coal fired stations as well as weighing options to retire plants where compliance with this plus other pending requirements for criteria emissions, water limitations , and solids management is not practical. In the timeframe required it will also be difficult to plan, permit, fabricate, install and place in service the equipment necessary to meet the U.S. Environmental Protection Agency's Maximum Achievable Control Technology (MACT) rule proposed in 2011, and the Cross-State Air Pollution Rule (CSAPR) rule finalized in July 6, 2011.

As the government, industry, and EPRI have tested the various types of plants and process configurations and their emissions, real-world issues and unintended consequences of HAPs reduction methods have been identified. The issues vary, and the solutions have required additional R&D to resolve concerns about water and solid by-product changes that would make current management practices unsuitable. Conditions can vary widely because coals can contain virtually any of the constituents of the earth's crust. Because coal and ash compositions vary, plants must have different plant configurations, firing equipment, and processes existing on the units to operate properly. Testing, modeling, and limited experience has identified a wide variety of issues. Some of these issues are cross-media (i.e., between air, aqueous, solid release streams) and can cause currently useful materials such as fly ash or gypsum used in aggregate, concrete, or wallboard to be questioned or to make them unusable. Research is needed in this area to verify and resolve potential impacts to enable reliable, operable units that consistently meet regulations for criteria air emissions, HAPs, as well as water and solids limits, and allows beneficial use of coal combustion by-products whenever possible.

Current emissions controls reduce criteria pollutant emissions to very low levels, and often capture a significant fraction of mercury in the process. Nonetheless, new regulations call for further reductions in NO_X, SO_2, SO_3, fine particulates, and mercury emissions, with an added focus on other HAPs, including selenium. Chief among these regulatory drivers are the utility HAPs MACT and CSAPR rules. EPRI has commented on the HAPs MACT in a submission dated August 4, 2011, and identified some of the challenges in measurement and compliance that make power company compliance difficult within the proposed timeframe and implies urgent R&D is needed. Some of the summary comments related to the need for additional R&D are quoted below, followed by a comment regarding R&D needs. The entire EPRI submission is available to the public at the following site:
http://mydocs.epri.com/docs/CorporateDocuments/SectorPages/Environment/hapsicr/EPRI_HAPs_Comments_08-04-11.pdf

EPRI comments on the difficulty of meeting proposed limits and the issues with data collection

- "No coal-fired EGU (new and existing coal- and oil-fired electric utility steam generating units) tested in the ICR (EPA's Information Collection Request)would likely meet the new unit MACT limits for all three regulated HAPs—total particulate matter, mercury, and hydrogen chloride (or the alternative acid gas surrogate, sulfur dioxide). The new unit limits are very challenging to achieve as few EGUs have multiple ICR measurements that are consistently below the proposed new unit limits. The use of the lowest test series average introduces biases, and EPA should use the average of all ICR data for setting the HAPs standards for both new and existing EGUs."

The proposed regulations for new and existing coal- and oil-fired electric utility steam generating units (EGUs) have very low limits which have been set based on, in many cases, erroneous data and a limited number of data points. Despite the values that are eventually established, additional R&D will be needed to ensure that the new limits can be met on an ongoing basis and for the variety of coals and plant designs in operation.

EPRI comments on dry sorbent injection and the ability to use the technology without power plant impacts in other areas

- "Additional data are required to evaluate the use of dry sorbent injection as a control for removing hydrochloric acid (HCl) and hydrofluoric acid (HF). Based on the limited available data, there are concerns about whether EGUs firing medium- to high-chloride coals can achieve the HCl standard using dry sorbent injection, and whether there would be impacts to balance-of-plant operations."

A number of firms are considering dry sorbent injection to manage hydrochloric acid (HCl) and hydrofluoric acid (HF). Because data are limited it is unclear the range of coals and conditions which may be able to use this control technique and the type of sorbent that will be effective and able to avoid cross media issues after use (not making an air issue into a solid waste or water issue). R&D is needed to test alternate sorbents and their fitness for the purpose of acid gas control and the cost effectiveness of their use.

EPRI comments on the data not representing the range of operating conditions and the ability to comply under all normal and transient conditions.

- "The ICR did not require EGUs to test over the full range of operating conditions, and therefore the ICR data do not represent the entire range of emissions variability from power plants. Additional measurements are needed to adequately characterize the variability of HAPs and surrogate emissions during normal plant operations. Sources of emissions variability include fuels burned, startup and shutdown conditions, partial load operation, and other reasonably foreseeable changes to operating conditions. Limited measurements at one facility indicated that trace metal variability was comparable to the variability of filterable PM measurements. "

The EPA's Information Collection Request (ICR) collected data for a number of static conditions but data is not available to assure power plants can comply with a range of operating conditions typical of coal plant operation. In order to retain reliable grid operation and maintain the obligation to serve customers with economic, secure power, it is normally necessary to vary load from different types of generation sources. Now that more "non-dispatchable" power such as wind is generated in certain areas of the country such as the upper Midwest and Texas, power companies are seeing added requirements to turn down or reduce coal generation periodically and bring it back if those non-dispatchable sources cannot generate. This variation in demand will mean chemical and physical processes may be called on to operate out of their most efficient or effective ranges and it may be difficult to meet the emission standards during transients or at partial loads. R&D is needed to evaluate and test, understand, model and provide guidelines for design and operation in these instances.

As regulations become more sweeping, with less flexibility in terms of time averaging and emissions banking and trading, fuel-specific nuances become magnified in their impact on compliance assurance, as do the relative effects of emissions from transients (startups, shutdowns, and load changes), seasonal variations, effects of one emission control device (or new additive) on another device, and measurement reliability. Compliance timetables are short and coal plant "back ends" are packed with emissions control devices so many strategies for capturing trace toxics involve modifications to existing systems or operations. A major industry concern is unintended consequences that could risk noncompliance or lead to premature corrosion or other failure of emissions control equipment.

In the near term, EPRI notes particular technology development and demonstration needs as follows:

- Controls consistent with 90%-plus mercury reduction for all applications and fuels
- Managing acid gas removal including HCl and SO_2 as surrogates for acid gases
- Model, test, and develop operation and maintenance practices for wet and dry scrubbers which are also used to remove HAPs, and how to best manage cross-media impacts and implications for operations, such as corrosion due to high levels of chlorides or halogens in plant process water
- Selective catalytic reduction (SCR) NO_X control catalyst regeneration strategies, as well as SCR catalyst management systems consistent with year-round system operation at >90% NO_X removal, minimum SO_3 generation, and maximum oxidation of elemental Hg in the flue gas

- Robust, reliable FGD systems for all coals
- More wear-tolerant, low-pressure-drop, ultra-high-efficiency baghouses for control of particulates from a wide range of fuels; improved performance of electrostatic precipitators (ESPs) for applications not suited to baghouses or amenable to upgrading in existing power plants; and demonstrated wet ESPs for acid mist and fine trace metal particulate capture
- Resolution of balance-of-plant issues and long-term operability issues for recently installed environmental controls.

Recent Testimony by J. Edward Cichanowicz an independent consultant based in Saratoga, California before this subcommittee October 4, 2011 is available on line at the following url (http://science.house.gov/sites/republicans.science.house.gov/files/documents/hearings/100411_Cichanowicz.pdf) his testimony identifies issues with the short time for compliance being proposed under MACT and CSAPR. We agree with the concerns addressed by Mr. Cichanowicz and suggest that this creates an urgent need to get DOE support for understanding the HAPs issues and solutions. We need to understand unintended consequences, the ability to comply under all conditions, and the ability of the planned equipment to address varying coals and water compositions. Given the tight schedule the power industry faces for compliance, DOE could best support industry RD&D efforts by building upon previous work for mercury controls, including management of HAPs control processes to minimize water and/or solids contamination. In other words, power plant operators need help identifying and testing approaches to managing HAPs issues holistically for the variety of plant types and conditions. To summarize, specific areas the industry needs support in are:

1. Understanding HAPs control (mercury, HCl, trace metals) balance of plant issues such as corrosion, increased PM emissions, solid by-product disposal/use, leaching, and wastewater treatment
2. Development of lower cost HAPs control options to maintain the viability of coal-fired power plants
3. Understanding the variability of long term HAPs control effectiveness (startup, shutdown, cycling)
4. Understanding the underlying mechanisms for HAPs formation and control, as well as independent assessments of emerging emission controls

Efficiency and cost improvements for gasification power plants: synthesis gas cleanup at higher temperatures, higher gas turbine firing temperatures and larger turbines, lower-energy oxygen supply technologies, and better plant controls

Gasification technology uses heat and pressure to partially oxidize a carbonaceous fuel to create a combustible “synthesis gas,” which can be fired in a highly efficient combined cycle (gas turbine and steam turbine) power block. In the power industry, gasification plants are used with inexpensive solid fuels, such as coal or petroleum coke, or sustainable fuels such as biomass, and in some cases, the plants sell steam or hydrogen as well as electricity. Gasification technology is also offers a relatively lower incremental cost for incorporation of CO_2 capture and compression, relative to other fossil power technologies. However, a “base” gasification combined cycle power plant (i.e., one without CO_2 capture and compression) usually costs more than other types of fossil power plants. Hence there is an RD&D focus on improving gasifier, power block, and auxiliaries performance and cost by equipment improvements and improved integration. DOE has long and active history in coal gasification RD&D, providing a knowledge and experience base to manage an accelerated program of competitiveness-driven gasification combined cycle technology development and demonstration, which would parallel ongoing efforts on integrating CO_2 capture and compression.

The synthesis gas, or syngas, produced in a gasifier consists chiefly of CO, with varying degrees of methane and heavier hydrocarbons, hydrogen, water vapor, CO_2, nitrogen, and H_2S, COS, and other sulfur compounds. To prevent erosion and corrosion in the gas turbine and associated heat exchangers and ducting, and to limit stack emission of sulfur species, the "raw" syngas is cleaned of particulate matter and sulfur compounds. Traditionally, this is accomplished by cooling the syngas with a water quench and/or a series of heat exchangers, and treating it with sulfur removal processes commonly used in the petrochemical industry. Because cooling reduces the thermodynamic properties of syngas, plant designers would prefer a reliable and effective "warm gas" cleanup process (which is actually quite hot). This has been the subject of numerous DOE RD&D efforts, and new technical options are ready for pilot- and demonstration-scale testing so this needs to be emphasized in the DOE portfolio.

To capture CO_2 from a gasification combined cycle power plant, an additional step (known as water-gas shift) is added to the syngas cleanup train, in which water vapor and syngas react in the presence of a catalyst to form hydrogen and CO_2. Established chemical industry processes can remove the CO_2, leaving a high-hydrogen content that can be combusted in the gas turbine with little CO_2 formation. Emerging technologies, such as membranes, may be able to separate the hydrogen from CO_2 with less energy and in more compact vessels. One promising approach couples the membrane with the water-gas shift reaction, saving additional equipment, space, and cost and could benefit from additional support.

Gas turbines designed specifically to combust high-hydrogen-content syngas are being built, tested, and commercially introduced. These will be essential to reliable and efficient gasification power systems with CO_2 capture and compression. DOE development and demonstration funding has contributed to success in this area. Equally important in EPRI's view is RD&D to move gas turbine technology to higher firing temperatures to improve efficiency and output—for both conventional and high-hydrogen syngas. EPRI economic analyses show larger and more efficient gas turbines to be perhaps the single most important step to improving integrated gasification combined cycle power plant economics. Although the commitment of gas turbine manufacturers is essential to ultimate success in realizing new commercial offerings, advances in the underpinning materials, design concepts and integration engineering can advance with DOE and industry cooperative efforts.

Many gasifier designs use a nearly pure oxygen input to the gasification reaction. That oxygen has traditionally been produced by cryogenic air separation units, which tend to be large, expensive, and large energy consumers. DOE has been funding lower-energy alternative oxygen production technologies, and EPRI has assembled an industry team to participate in one such effort, the scale-up and testing of Air Products' ion transport membrane (ITM) technology. EPRI is assisting in assuring that the product design and test program meet power company "real world" operation and maintenance criteria and also in gasification plant integration engineering.

EPRI believes that this model of cooperative DOE, industry team, and technology developer RD&D speeds the path to successful deployment and attainment of electricity cost reductions for the American economy. EPRI is also investigating whether a variation in the process can be used for supplying oxygen to future oxygen-fired systems (an early example of an oxygen-fired system is the FutureGen 2.0 project). Additional development and demonstrations in this area can support cost, efficiency and energy security from a variety of coal utilization processes.

Gasification power plants will also benefit substantially from improvements in process measurement and control. For example, durable fast sensors that provide real-time readings of temperatures and gas composition within the gasifier would provide operators with more accurate and timely measurement of syngas heating value, which in turn could be fed forward to power block controls. For the last several years, an EPRI program has been investigating the use of laser-based sensors for this purpose, and scale-up and demonstration funding is still needed.

For additional information on gasification power plant RD&D opportunities, refer to EPRI publication 1023468, *Advanced Coal Power Systems with CO_2 Capture: EPRI's CoalFleet for Tomorrow Vision® – 2011 Update*.

Sustaining vital DOE RD&D on CO_2 capture, utilization, and storage

EPRI's analysis of options needed for the future validates DOE's high prioritization of RD&D to establish effective, economical, and publicly acceptable technologies to reduce atmospheric greenhouse gas buildup. This supports DOE's work on coal-based technology including CO_2 capture at power plants, cost-effective cleanup and compression for on-site geologic injection or transportation off-site, CO_2 utilization where economical, and secure long-term storage away from the atmosphere. In particular, EPRI identifies the following current work as warranting continued RD&D to achieve the cost and efficiency improvements necessary to allow viable commercial deployment:

1. R&D, scale-up, and integrated operation of coal power systems based on gasification and oxy-combustion technologies (presently through Clean Coal Power Initiative and American Reinvestment and Recovery Act funding, loan guarantees, and other mechanisms plus base program DOE funding)
2. CO_2 capture, compression, and storage RD&D to seek breakthrough innovations for low-cost capture, lower-energy compression, and for larger scale integrated projects, to understand operational flexibility, cost reduction options, and techniques to verify long-term storage
3. CO_2 utilization: because CO_2 used for enhanced oil recovery (or other means of generating revenue) will be essential to jump-starting CCS deployment, and may also help in reducing dependence on foreign oil, additional geologic characterization of areas near concentrations of power plants may be a logical follow-on under the DOE regional carbon sequestration partnerships programs