

## Testimony

### Hearing of the Science, Technology and Innovation Subcommittee of the Committee on Commerce, Science, and Transportation

#### United States Senate

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#### Introduction

Thank you, Mr. Chairman, Ranking Member Ensign, and Members of the Subcommittee. I am Bryan Hannegan, Vice President of Environment for the Electric Power Research Institute (EPRI), a non-profit, collaborative R&D organization. EPRI has principal locations in Palo Alto, California, Charlotte, North Carolina, and Knoxville, Tennessee. EPRI appreciates the opportunity to provide testimony to the Committee on the topic of carbon sequestration technologies.

Through the development and deployment of advanced coal plants with integrated CO<sub>2</sub> capture and storage (CCS) technologies, coal power can become part of the solution to satisfying both our energy needs and our global climate change concerns. However, a sustained RD&D program at heightened levels of investment and the resolution of legal and regulatory unknowns for long-term geologic CO<sub>2</sub> storage will be required to achieve the promise of advanced coal with CCS technologies. The members of EPRI's *CoalFleet for Tomorrow*<sup>®</sup> program—a research collaborative comprising more than 60 organizations representing U.S. utilities, international power generators, equipment suppliers, government research organizations, coal and oil companies, and a railroad—see crucial roles for both industry and governments worldwide in aggressively pursuing collaborative RD&D over the next 20+ years to create a full portfolio of commercially self-sustaining, competitive advanced coal power generation and CCS technologies.

The key points I will make today include:

- Advanced coal power plant technologies with integrated CO<sub>2</sub> capture and storage (CCS) will be crucial to lowering U.S. electric power sector CO<sub>2</sub> emissions. They will also be crucial to substantially lowering world CO<sub>2</sub> emissions.
- The availability of advanced coal power and integrated CCS and other technologies could dramatically reduce the projected increases in the cost of wholesale electricity under a carbon cap, thereby saving the U.S. economy as much as \$1 trillion by 2050.

- It is important to avoid choosing between coal technology options. We should foster a full portfolio of technology options.
- While there are well proven methods for capturing CO<sub>2</sub> resulting from coal gasification, no integrated gasification combined cycle (IGCC) yet captures CO<sub>2</sub>. IGCC technology is still relatively new and needs more commercial installations. In contrast, pulverized coal (PC) technology is already well proven commercially in the power industry; the need is for demonstration of post combustion capture at a commercial and affordable scale.
- There will inevitably be additional costs associated with CCS. EPRI's latest estimates suggest that the levelized cost of electricity (COE) from new coal plants (IGCC or supercritical PC) designed for capture, compression, transportation and storage of the CO<sub>2</sub> will be 40-80% higher than the COE of a conventional supercritical PC (SCPC) plant..
- EPRI's technical assessment work indicates that the preferred technology and the additional cost of electricity for CCS will depend on the coal type, location and the technology employed. Without CCS, supercritical pulverized coal (SCPC) has an advantage over IGCC. However, the additional CCS cost is generally lower with IGCC than for SCPC.
- Some studies show an advantage for IGCC with CCS with bituminous coal. With lignite coal SCPC with CCS is generally preferred. With sub-bituminous coals, SCPC with CCS and IGCC with CCS appear to show similar costs.
- Our initial work with post-combustion CO<sub>2</sub> capture technologies suggests we can potentially reduce the current estimated 30% energy penalty associated with CCS to about to 15% over the longer-term. Improvements in IGCC plants offer the same potential for reducing cost and energy penalty as well.
- The key to proving CCS capability is the demonstration of CCS at large-scale (on the order of 1 million tons CO<sub>2</sub>/year) for both pre- and post-combustion capture with storage in a variety of geologies. Large combined capture and storage demonstrations should be encouraged in different regions and with different coals and technologies.
- EPRI's *CoalFleet for Tomorrow*® program has identified the RD&D pathways to demonstrate, by 2025, a full portfolio of economically attractive, commercial-scale advanced coal power and integrated CCS technologies suitable for use with the broad range of U.S. coal types. Some technologies will be ready for some fuels sooner, but the economic benefits of competition will not be realized until the full portfolio is developed.

- The identified RD&D is estimated to cost \$8 billion between now and 2017 and \$17 billion cumulatively by 2025, and we need to begin immediately to ensure that these climate change solution technologies will be fully tested at scale by 2025.
- Major non-technical barriers associated with CO<sub>2</sub> storage must be addressed before CCS can become a commercial reality, including resolution of regulatory and long-term liability uncertainties.

## **Background**

Coal currently provides over half of the electricity used in the United States, and most forecasts of future energy use in the United States show that coal will continue to have a dominant share in our electric power generation for the foreseeable future. Coal is a stably priced, affordable, domestic fuel that can be used in an environmentally responsible manner. Through development of advanced pollution control technologies and sensible regulatory programs, emissions of criteria air pollutants from new coal-fired power plants have been reduced by more than 90% over the past three decades. And by displacing otherwise needed imports of natural gas or fuel oil, coal helps address America's energy security and reduces our trade deficit with respect to energy.

By 2030, according to the Energy Information Administration, the consumption of electricity in the United States is expected to increase by approximately 40% over current levels. At the same time, to responsibly address the risks posed by potential climate change, we must substantially reduce the greenhouse gas emissions intensity of our economy in a way which allows for continued economic growth and the benefits that energy provides. This is not a trivial matter – it implies a substantial change in the way we produce and consume electricity. Technologies to reduce CO<sub>2</sub> emissions from coal will necessarily be one part of an economy-wide solution that includes greater end-use efficiency, increasing renewable energy, more efficient use of natural gas, expanded nuclear power, and similar transformations in the transportation, commercial, industrial and residential sectors of our economy. In fact, our work at EPRI on climate policy has consistently shown that non-emitting technologies for electricity generation will likely be less expensive than technologies for limiting emissions of direct fossil fuel end uses in other sectors. Paradoxically, as we seek greater limits on CO<sub>2</sub> across our economy, our work at EPRI suggests we will see greater amounts of electrification – but only if the technologies to do so with near-zero emissions are at hand.

## **The Role of Advanced Coal Generation with CO<sub>2</sub> Capture and Storage in a Carbon-Constrained Future**

EPRI's "Electricity Technology in a Carbon-Constrained Future" study suggests that it is technically feasible to reduce U.S. electric sector CO<sub>2</sub> emissions by 25–30% relative to current emissions by 2030 while meeting the increased demand for electricity. The study showed that the largest single contributor to emissions reduction would come from the integration of CCS technologies with advanced coal-based power plants coming on-line after 2020.

Economic analyses of scenarios to achieve the study's emission reduction goals show that in 2050, a U.S. electricity generation mix based on a full portfolio of technologies, including advanced coal technologies with integrated CCS and advanced light water nuclear reactors, results in wholesale electricity prices at less than half of the wholesale electricity price for a generation mix without advanced coal/CCS and nuclear power. In the case with advanced coal/CCS and nuclear power, the cost to the U.S. economy of a CO<sub>2</sub> emissions reduction policy is \$1 trillion less than in the case without advanced coal/CCS and nuclear power, with a much stronger manufacturing sector. Both of these analyses are documented in the 2007 EPRI Summer Seminar Discussion paper, "The Power to Reduce CO<sub>2</sub> Emissions—the Full Portfolio," available at <http://epri-reports.org/DiscussionPaper2007.pdf>.

### **Accelerating RD&D on Advanced Coal Technologies with CO<sub>2</sub> Capture and Storage—Investment and Time Requirements**

The portfolio aspect of advanced coal with integrated CCS technologies must be emphasized because no single advanced coal technology (or any generating technology) has clear-cut economic advantages across the range of U.S. applications. The best strategy for meeting future electricity needs while addressing climate change concerns and minimizing economic disruption lies in developing a *full portfolio* of technologies from which power producers (and their regulators) can choose the option best suited to local conditions and preferences and provide power at the lowest cost to the customer. Toward this end, four major technology efforts related to CO<sub>2</sub> emissions reduction from coal-based power systems must be undertaken:

1. Increased efficiency and reliability of integrated gasification combined cycle (IGCC) power plants
2. Increased thermodynamic efficiency of pulverized-coal (PC) power plants
3. Improved technologies for capture of CO<sub>2</sub> from coal combustion- and gasification-based power plants
4. Reliable, acceptable technologies for long-term storage of captured CO<sub>2</sub>

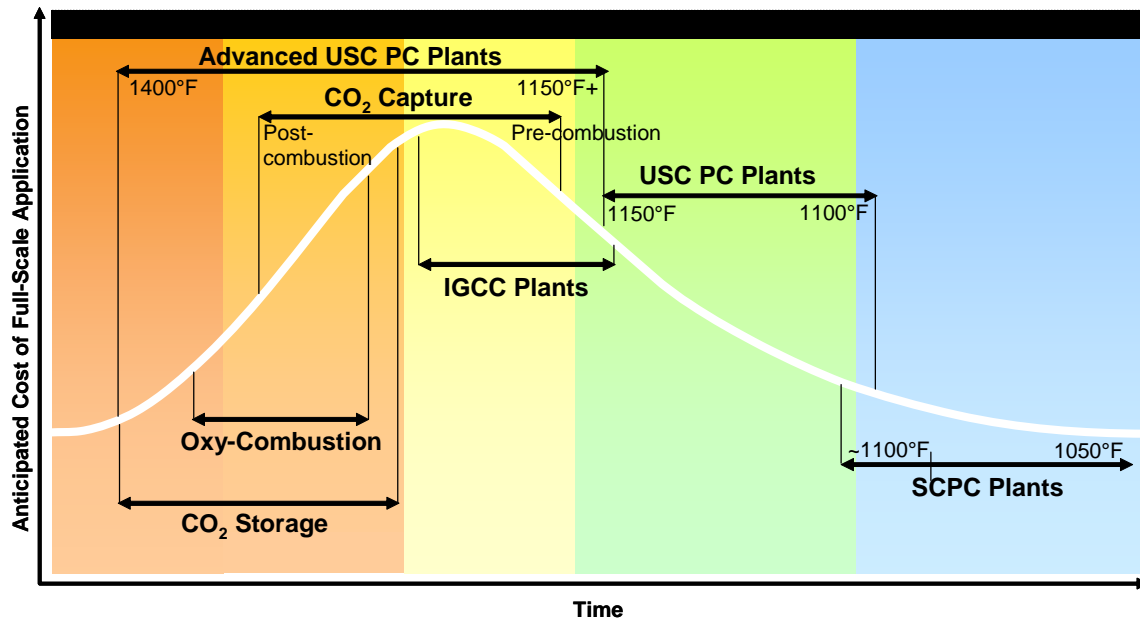
Identification of mechanisms to share RD&D financial and technical risks and to address legal and regulatory uncertainties must take place as well.

In short, a comprehensive recognition of all the factors needed to hasten deployment of competitive, commercial advanced coal and integrated CO<sub>2</sub> capture and storage technologies—and implementation of realistic, pragmatic plans to overcome barriers—is the key to meeting the challenge to supply affordable, environmentally responsible energy in a carbon-constrained world.

A typical path to develop a technology to commercial maturity consists of moving from the conceptual stage to laboratory testing, to small pilot-scale tests, to larger-scale tests, to multiple full-scale demonstrations, and finally to deployment in full-scale commercial operations. For capital-intensive technologies such as advanced coal power systems, each stage can take years or even a decade to complete, and each sequential stage entails

increasing levels of investment. As depicted in Figure 1, several key advanced coal power and CCS technologies are now in (or approaching) an “adolescent” stage of development. This is a time of particular vulnerability in the technology development cycle, as it is common for the expected costs of full-scale application to be higher than earlier estimates when less was known about scale-up and application challenges. Public agency and private funders can become disillusioned with a technology development effort at this point, but as long as fundamental technology performance results continue to meet expectations, and a path to cost reduction is clear, perseverance by project sponsors in maintaining momentum is crucial.

Unexpectedly high costs at the mid-stage of technology development have historically come down following market introduction, experience gained from “learning-by-doing,” realization of economies of scale in design and production as order volumes rise, and removal of contingencies covering uncertainties and first-of-a-kind costs. An International Energy Agency study led by Carnegie Mellon University (CMU) observed this pattern of cost-reduction-over-time for power plant environmental controls, and CMU predicts a similar reduction in the cost of power plant CO<sub>2</sub> capture technologies as the cumulative installed capacity grows.<sup>1</sup> EPRI concurs with their expectations of experience-based cost reductions and believes that RD&D on specifically identified technology refinements can lead to greater cost reductions sooner in the deployment phase.



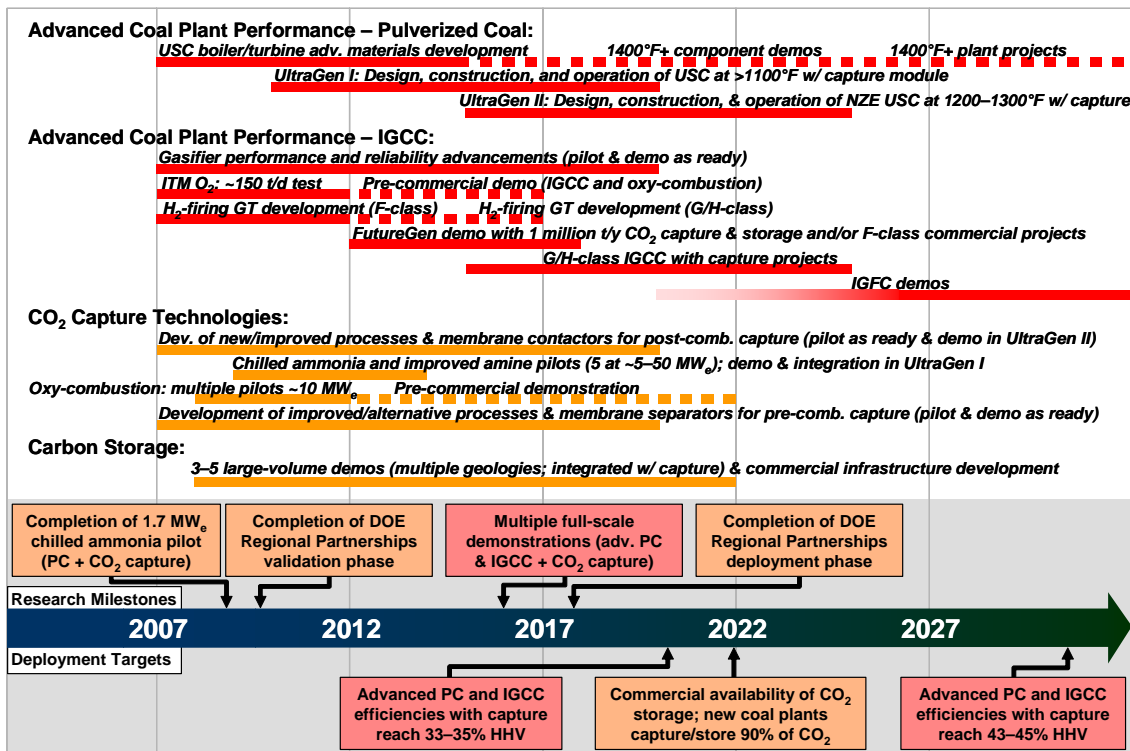
**Figure 1 – Model of the development status of major advanced coal and CO<sub>2</sub> capture and storage technologies (temperatures shown for pulverized coal technologies are turbine inlet steam temperatures)**

Of the coal-based power generating and carbon sequestration technologies shown in Figure 1, only supercritical pulverized coal (SCPC) technology has reached commercial maturity.

<sup>1</sup> IEA Greenhouse Gas R&D Programme (IEA GHG), “Estimating Future Trends in the Cost of CO<sub>2</sub> Capture Technologies,” 2006/5, January 2006.

It is crucial that other technologies in the portfolio—namely ultra-supercritical (USC) PC, integrated gasification combined cycle (IGCC), CO<sub>2</sub> capture (pre-combustion, post-combustion, and oxy-combustion), and CO<sub>2</sub> storage—be given sufficient support to reach the stage of declining constant dollar costs *before* society’s requirements for greenhouse gas reductions compel their application in large numbers.

Figure 2 depicts the major activities in each of the four technology areas that must take place to achieve a robust set of integral advanced coal/CCS solutions. Important, but not shown in the figure, are the interactions between RD&D activities. For example, the ion transport membrane (ITM) oxygen supply technology shown under IGCC can also be applied to oxy-combustion PC units. Further, while the individual goals related to efficiency, CO<sub>2</sub> capture, and CO<sub>2</sub> storage present major challenges, significant challenges also arise from complex interactions that occur when CO<sub>2</sub> capture processes are integrated with gasification- and combustion-based power plant processes.



Source: *The Power to Reduce CO<sub>2</sub> Emissions – the Full Portfolio*, <http://epri-reports.org/DiscussionPaper2007.pdf>

**Figure 2 – Timing of advanced coal power system and CO<sub>2</sub> capture and storage RD&D activities and milestones**

## **Reducing CO<sub>2</sub> Emissions Through Improved Coal Power Plant Efficiency—A Key Companion to CCS that Lowers Cost and Energy Requirements**

Improved thermodynamic efficiency reduces CO<sub>2</sub> emissions by reducing the amount of fuel required to generate a given amount of electricity. A two-percentage point gain in efficiency provides a reduction in fuel consumption of roughly 5% and a similar reduction in flue gas and CO<sub>2</sub> output. Because the size and cost of CO<sub>2</sub> capture equipment is determined by the volume of flue gas to be treated, higher power block efficiency reduces the capital and energy requirements for CCS. Depending on the technology used, improved efficiency can also provide similar reductions in criteria air pollutants, hazardous air pollutants, and water consumption.

A typical baseloaded 500 MW (net) coal plant emits about 3 million metric tons of CO<sub>2</sub> per year. Individual plant emissions vary considerably given differences in plant steam cycle, coal type, capacity factor, and operating regimes. For a given fuel, however, a new supercritical PC unit built today might produce 5–10% less CO<sub>2</sub> per megawatt-hour (MWh) than the existing fleet average for that coal type.

With an aggressive RD&D program on efficiency improvement, new ultra-supercritical (USC PC) plants could reduce CO<sub>2</sub> emissions per MWh by up to 25% relative to the existing fleet average. Significant efficiency gains are also possible for IGCC plants by employing advanced gas turbines and through more energy-efficient oxygen plants and synthesis (fuel) gas cleanup technologies.

EPRI and the Coal Utilization Research Council (CURC), in consultation with DOE, have identified a challenging but achievable set of milestones for improvements in the efficiency, cost, and emissions of PC and coal-based IGCC plants. The EPRI-CURC Roadmap projects an overall improvement in the thermal efficiency of state-of-the-art generating technology from 38–41% in 2010 to 44–49% by 2025 (on a higher heating value [HHV] basis; see Table 1). As Table 1 indicates, power-block efficiency gains (i.e., without capture systems) will be offset by the energy required for CO<sub>2</sub> capture, but as noted, they are important in reducing the overall cost of CCS. Coupled with opportunities for major improvements in the energy efficiency of CO<sub>2</sub> capture processes per se, aggressive pursuit of the EPRI-CURC RD&D program offers the prospect of coal power plants *with* CO<sub>2</sub> capture in 2025 that have net efficiencies meeting or exceeding current-day power plants without CO<sub>2</sub> capture.

It is also important to note that the numeric ranges in Table 1 are not simply a reflection of uncertainty, but rather they underscore an important point about differences among U.S. coals. The natural variations in moisture and ash content and combustion characteristics between coals have a significant impact on attainable efficiency. An advanced coal plant firing Wyoming and Montana's Powder River Basin (PRB) coal, for example, would likely have an HHV efficiency two percentage points lower than the efficiency of a comparable plant firing Appalachian bituminous coals. Equally advanced plants firing lignite would likely have efficiencies two percentage points lower than their counterparts firing PRB.

Any government incentive program with an efficiency-based qualification criterion should recognize these inherent differences in the attainable efficiencies for plants using different ranks of coal.

**Table 1 – Efficiency Milestones in EPRI-CURC Roadmap**

	2010	2015	2020	2025
PC & IGCC Systems ( <i>Without CO<sub>2</sub> Capture</i> )	38–41% HHV	39–43% HHV	42–46% HHV	44–49% HHV
PC & IGCC Systems ( <i>With CO<sub>2</sub> Capture*</i> )	31–32% HHV	31–35% HHV	33–39% HHV	39–46% HHV

*\*Efficiency values reflect impact of 90% CO<sub>2</sub> capture, but not compression or transportation.*

### **New Plant Efficiency Improvements–IGCC**

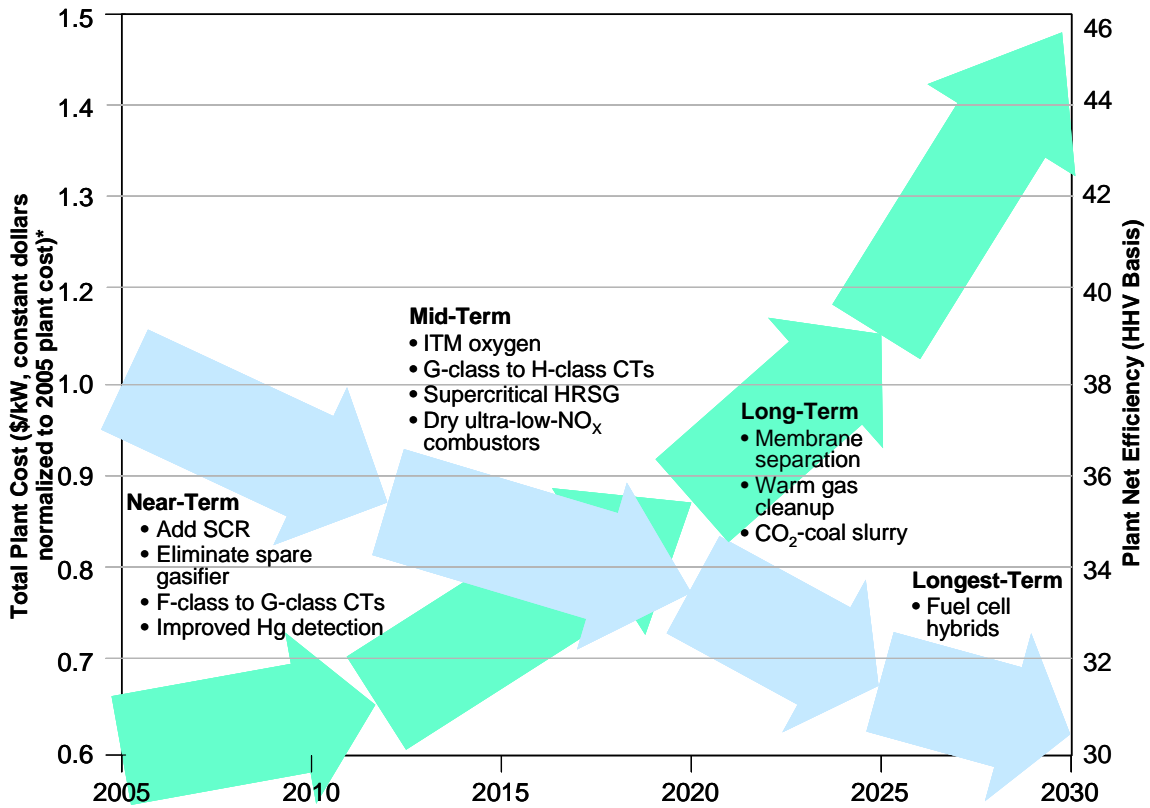
Although IGCC is not yet a mature technology for coal-fired power plants, chemical plants around the world have accumulated a 100-year experience base operating coal-based gasification units and related gas cleanup processes. The most advanced of these units are similar to the front end of a modern IGCC facility. Similarly, several decades of experience firing natural gas and petroleum distillate have established a high level of maturity for the basic combined cycle generating technology. Nonetheless, ongoing RD&D continues to provide significant advances in the base technologies, as well as in the suite of technologies used to integrate them into an IGCC generating facility.

Efficiency gains in currently proposed IGCC plants will come from the use of new “FB-class” gas turbines, which will provide an overall plant efficiency gain of about 0.6 percentage point (relative to IGCC units with FA-class models, such as Tampa Electric’s Polk Power Station). This corresponds to a decrease in the rate of CO<sub>2</sub> emissions per MWh of about 1.5%. Alternatively, this means 1.5% less fuel is required per MWh of output, and thus the required size of pre-combustion water-gas shift and CO<sub>2</sub> separation equipment would be slightly smaller.

Figure 3 depicts the anticipated timeframe for further developments identified by EPRI’s *CoalFleet for Tomorrow*® program that promise a succession of significant improvements in IGCC unit efficiency. Key technology advances under development include:

- larger capacity gasifiers (often via higher operating pressures that boost throughput without a commensurate increase in vessel size)
- integration of new gasifiers with larger, more efficient G- and H-class gas turbines
- use of ion transport membrane or other more energy-efficient technologies in oxygen plants
- warm synthesis gas cleanup and membrane separation processes for CO<sub>2</sub> capture that reduce energy losses in these areas
- recycle of liquefied CO<sub>2</sub> to replace water in gasifier feed slurry (reducing heat loss to water evaporation)
- hybrid combined cycles using fuel cells to achieve generating efficiencies exceeding those of conventional combined cycle technology

Improvements in gasifier reliability and in control systems also contribute to improved annual average efficiency by minimizing the number and duration of startups and shutdowns.



**Figure 3 – RD&D path for capital cost reduction (falling arrows) and efficiency improvement (rising arrows) for IGCC power plants with 90% CO<sub>2</sub> capture**

\* For a slurry-fed gasifier designed for 90% unit availability and 90% pre-combustion CO<sub>2</sub> capture using Pittsburgh #8 bituminous coal; cost normalization using Chemical Engineering Plant Cost Index or equivalent. A similar trend is observed in analyses of dry-fed gasifiers using Power River Basin subbituminous coal, although the absolute values vary somewhat from those shown.

**Counteracting Gas Turbine Output Loss at High Elevations.** IGCC plants designed for application in high-elevation locations must account for the natural reduction in gas turbine power output that occurs where the air is thin. This phenomenon is rooted in the fundamental volumetric flow limitation of a gas turbine, and can reduce power output by up to 15% at an elevation of 5000 feet (relative to a comparable plant at sea level). EPRI is exploring measures to counteract this power loss, including inlet air chilling (a technique used at natural gas power plants to mitigate the power loss that comes from thinning of the air on a hot day) and use of supplemental burners between the gas turbine and steam turbine to boost the plant’s steam turbine section generating capacity.

**Larger, Higher Firing Temperature Gas Turbines.** For plants coming on-line around 2015, the larger size G-class gas turbines, which operate at higher firing temperatures (relative to F-class machines) can improve efficiency by 1 to 2 percentage points while also decreasing capital cost per kW capacity. The H-class gas turbines coming on-line in the same timeframe, which also feature higher firing temperatures as well as steam-based

internal cooling of hot turbine components, will provide a further increase in efficiency and capacity.

**Ion Transport Membrane–Based Oxygen Plants.** Most gasifiers used in IGCC plants require a large quantity of high-pressure, high purity oxygen, which is typically generated on site with an expensive and energy-intensive cryogenic process. The ITM process allows the oxygen in high-temperature air to pass through a membrane while preventing passage of non-oxygen atoms. According to developers, an ITM-based oxygen plant consumes 35–60% less power and costs 35% less than a cryogenic plant. EPRI is performing a due diligence assessment of this technology in advance of potential participation in technology scale-up efforts.

**Supercritical Heat Recovery Steam Generators.** In IGCC plants, hot exhaust gas exiting the gas turbine is ducted into a heat exchanger known as a heat recovery steam generator (HRSG) to transfer energy into water-filled tubes producing steam to drive a steam turbine. This combination of a gas turbine and steam turbine power cycles produces electricity more efficiently than either a gas turbine or steam turbine alone. As with conventional steam power plants, the efficiency of the steam cycle in a combined cycle plant increases when turbine inlet steam temperature and pressure are increased. The higher exhaust temperatures of G- and H-class gas turbines offer the potential for adoption of more-efficient supercritical steam cycles. Materials for use in a supercritical HRSG are generally established, and thus should not pose a barrier to technology implementation once G- and H-class gas turbines become the standard for IGCC designs.

**Synthesis Gas Cleaning at Higher Temperatures.** The acid gas recovery (AGR) processes currently used to remove sulfur compounds from synthesis gas require that the gas and solvent be cooled to about 100°F, thereby causing a loss in efficiency. Further costs and efficiency loss are inherent in the process equipment and auxiliary steam required to recover the sulfur compounds from the solvent and convert them to useable products. Several DOE-sponsored RD&D efforts aim to reduce the energy losses and costs imposed by this recovery process. These technologies (described below) could be ready—with adequate RD&D support—by 2020:

- The Selective Catalytic Oxidation of Hydrogen Sulfide process eliminates the Claus and Tail Gas Treating units, along with the traditional solvent-based AGR contactor, regenerator, and heat exchangers, by directly converting hydrogen sulfide (H<sub>2</sub>S) to elemental sulfur. The process allows for a higher operating temperature of approximately 300°F, which eliminates part of the low-temperature gas cooling train. The anticipated benefit is a net capital cost reduction of about \$60/kW along with an efficiency gain of about 0.8 percentage point.
- The RTI/Eastman High-Temperature Desulfurization System uses a regenerable dry zinc oxide sorbent in a dual loop transport reactor system to convert H<sub>2</sub>S and COS to H<sub>2</sub>O, CO<sub>2</sub>, and SO<sub>2</sub>. Tests at Eastman Chemical Company have shown sulfur species removal rates above 99.9%, with 10 ppm output versus 8000+ ppm input sulfur, using operating temperatures of 800–1000°F. This process is also being tested for its ability to provide a high-pressure CO<sub>2</sub> by-product. The anticipated benefit for IGCC, compared with using a standard oil-industry process for sulfur removal, is a net capital cost reduction of \$60–90 per kW, a thermal efficiency gain of 2–4% for the gasification

process, and a slight reduction in operating cost. Tests are also under way for a multi-contaminant removal processes that can be integrated with the transport desulfurization system at temperatures above 480°F.

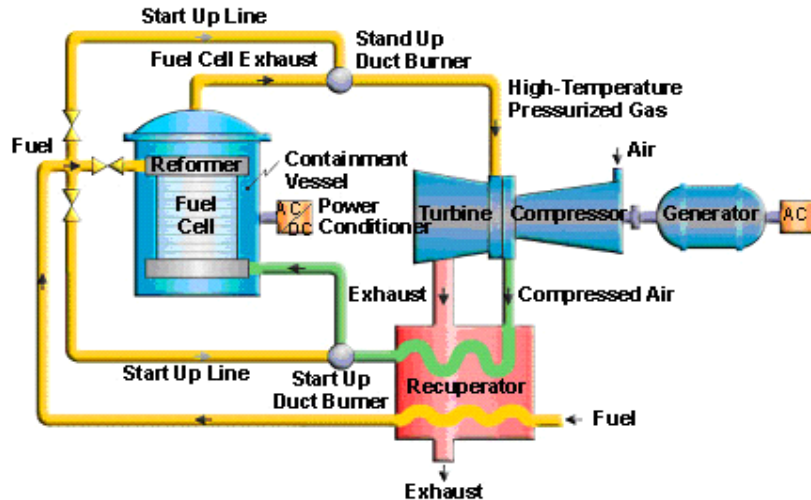
**Liquid CO<sub>2</sub>-Coal Slurrying for Gasification of Low-Rank Coals.** Future IGCC plants with CCS may recycle some of the recovered liquid CO<sub>2</sub> to replace water as the slurrying medium for the coal feed. This is expected to increase gasification efficiency for all coals, but particularly for subbituminous coal and lignite, which have naturally high moisture contents. The liquid CO<sub>2</sub> has a lower heat of vaporization than water and is able to carry more coal per unit mass of fluid. The liquid CO<sub>2</sub>-coal slurry will flash almost immediately upon entering the gasifier, providing good dispersion of the coal particles and potentially yielding the higher performance of a dry-fed gasifier with the simplicity of a slurry-fed system.

Traditionally, slurry-fed gasification technologies have a cost advantage over conventional dry-fed fuel handling systems, but they suffer a large performance penalty when used with coals containing a large fraction of water and ash. EPRI identified CO<sub>2</sub> coal slurrying as an innovative fuel preparation concept 20 years ago, when IGCC technology was in its infancy. At that time, however, the cost of producing liquid CO<sub>2</sub> was too high to justify the improved thermodynamic performance. Requirements for CCS change that, as it will substantially reduce the incremental cost of producing a liquid CO<sub>2</sub> stream.

To date, CO<sub>2</sub>-coal slurrying has only been demonstrated at pilot scale and has yet to be assessed in feeding coal to a gasifier, so the estimated performance benefits remain to be confirmed. It will first be necessary, however, to update previous studies to quantify the potential benefit of liquid CO<sub>2</sub> slurries with IGCC plants designed for CO<sub>2</sub> capture. If the predicted benefit is economically advantageous, a significant amount of scale-up and demonstration work would be required to qualify this technology for commercial use.

**Fuel Cells and IGCC.** No matter how far gasification and turbine technologies advance, IGCC power plant efficiency will never progress beyond the inherent thermodynamic limits of the gas turbine and steam turbine power cycles (along with lower limits imposed by available materials technology). Several IGCC–fuel cell hybrid power plant concepts (IGFC) aim to provide a path to coal-based power generation with net efficiencies that exceed those of conventional combined cycle generation.

Along with its high thermal efficiency, the fuel cell hybrid cycle reduces the energy consumption for CO<sub>2</sub> capture. The anode section of the fuel cell produces a stream that is highly concentrated in CO<sub>2</sub>. After removal of water, this stream can be compressed for sequestration. The concentrated CO<sub>2</sub> stream is produced without having to include a water-gas shift reactor in the process (see Figure 4). This further improves the thermal efficiency and decreases capital cost. IGFC power systems are a long-term solution, however, and are unlikely to see full-scale demonstration until about 2030.



Source: U.S. Department of Energy; <http://www.netl.doe.gov/technologies/coalpower/fuelcells/hybrids.html>

**Figure 4 – Schematic of fuel cell-turbine hybrid**

**Role of FutureGen.** The FutureGen Industrial Alliance and DOE are building a first-of-its-kind, near-zero emissions coal-fed IGCC power plant integrated with CCS. The commencement of full-scale operations is targeted for 2013. The project aims to sequester CO<sub>2</sub> in a representative geologic formation at a rate of at least one million metric tons per year.

The FutureGen design will address scaling and integration issues for coal-based, zero emissions IGCC plants. In its role as a “living laboratory,” FutureGen is designed to validate additional advanced technologies that offer the promise of clean environmental performance at a reduced cost and increased reliability. FutureGen will have the flexibility to conduct full-scale and slipstream tests of such scalable advanced technologies as:

- Membrane processes to replace cryogenic separation for oxygen production
- An advanced transport reactor sidestream with 30% of the capacity of the main gasifier
- Advanced membrane and solvent processes for H<sub>2</sub> and CO<sub>2</sub> separation
- A raw gas shift reactor that reduces the upstream clean-up requirements
- Ultra-low-NO<sub>x</sub> combustors that can be used with high-hydrogen synthesis gas
- A fuel cell hybrid combined cycle pilot
- Challenging first-of-a-kind system integration
- Smart dynamic plant controls including a CO<sub>2</sub> management system

Figure 5 provides a schematic of the “backbone” and “research platform” process trains envisioned for the FutureGen plant.

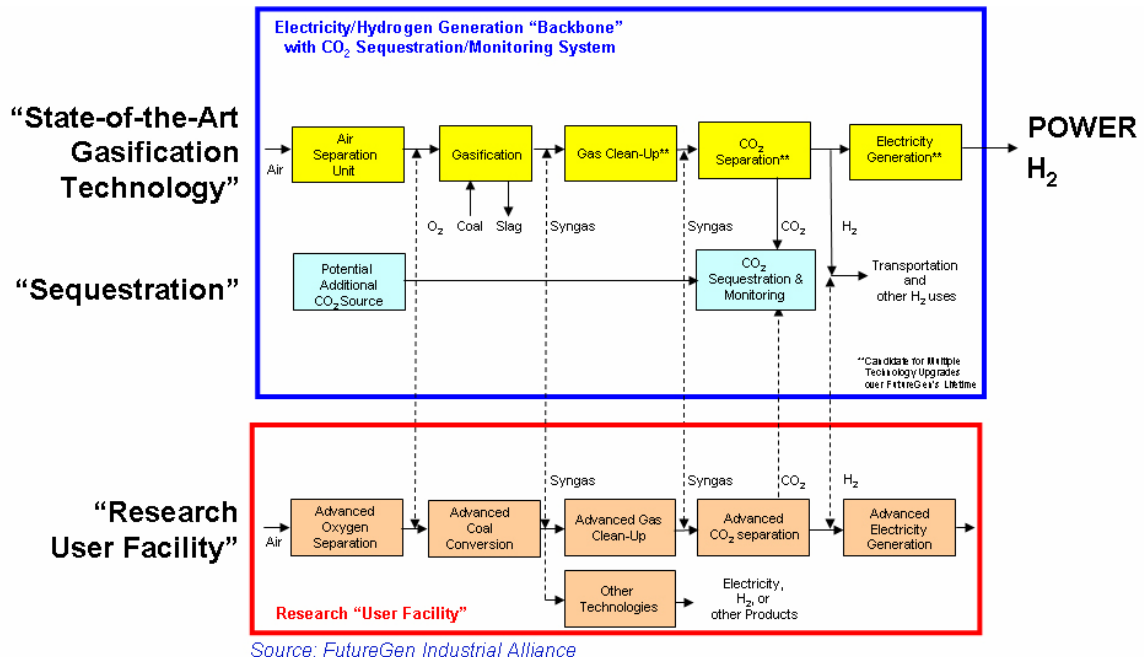


Figure 5 – FutureGen technology platforms

Figure 6 summarizes EPRI’s recommended major RD&D activities for improving the efficiency and cost of IGCC technologies with CO<sub>2</sub> capture.

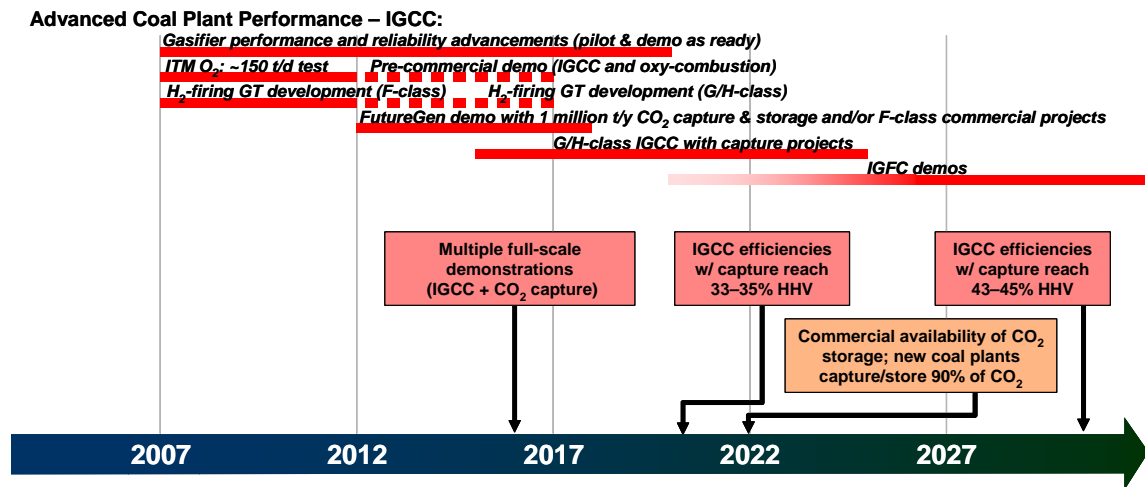


Figure 6 – Timing of advanced IGCC and CO<sub>2</sub> capture integration RD&D activities and milestones

### New Plant Efficiency Improvements – Advanced Pulverized Coal

Pulverized-coal power plants have long been a primary source of reliable and affordable power in the United States and around the world. The advanced level of maturity of the technology, along with basic thermodynamic principles, suggests that significant efficiency gains can most readily be realized by increasing the operating temperatures and pressures of the steam cycle. Such increases, in turn, can be achieved only if there is adequate

development of suitable materials and new boiler and steam turbine designs that allow use of higher steam temperatures and pressures.

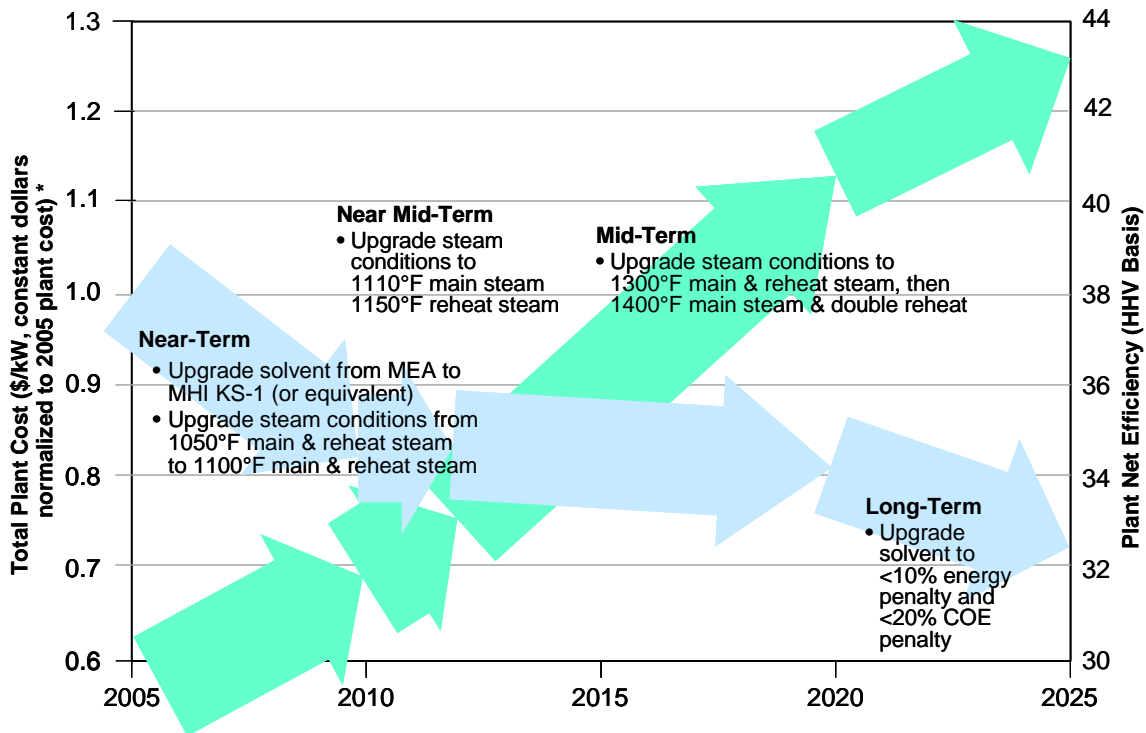
Current state-of-the-art plants use supercritical main steam conditions (i.e., temperature and pressure above the “critical point” where the liquid and vapor phases of water are indistinguishable). SCPC plants typically have main steam conditions up to 1100°F. The term “ultra-supercritical” is used to describe plants with main steam temperatures in excess of 1100°F and potentially as high as 1400°F.

Achieving higher steam temperatures and higher efficiency will require the development of new corrosion-resistant, high-temperature nickel alloys for use in the boiler and steam turbine. In the United States, these challenges are being address by the Ultra-Supercritical Materials Consortium, a DOE R&D program involving Energy Industries of Ohio, EPRI, the Ohio Coal Development Office, and numerous equipment suppliers. EPRI provides technical management for the consortium. Results are applicable to all ranks of coal. As noted, higher power block efficiencies translate to lower costs for post-combustion CO<sub>2</sub> capture equipment.

It is expected that a USC PC plant operating at about 1300°F will be built during the next seven to ten years, following the demonstration and commercial availability of advanced materials from these programs. This plant would achieve an efficiency (before installation of CO<sub>2</sub> capture equipment) of about 45% (HHV) on bituminous coal, compared with 39% for a current state-of-the-art plant, and would reduce CO<sub>2</sub> production per net MWh by about 15%.

Ultimately, nickel-base alloys are expected to enable steam temperatures in the neighborhood of 1400°F and pre-capture generating efficiencies up to 47% HHV with bituminous coal. This approximately 10 percentage point improvement over the efficiency of a new subcritical pulverized-coal plant would equate to a decrease of about 25% in CO<sub>2</sub> and other emissions per MWh. The resulting saving in the cost of subsequently installed CO<sub>2</sub> capture equipment is substantial.

Figure 7 illustrates a timeline developed by EPRI’s *CoalFleet for Tomorrow*® program to establish efficiency improvement and cost reduction goals for USC PC plants with CO<sub>2</sub> capture.



**Figure 7 – RD&D path for capital cost reduction (falling arrows) and efficiency improvement (rising arrows) for PC power plants with 90% CO<sub>2</sub> capture**

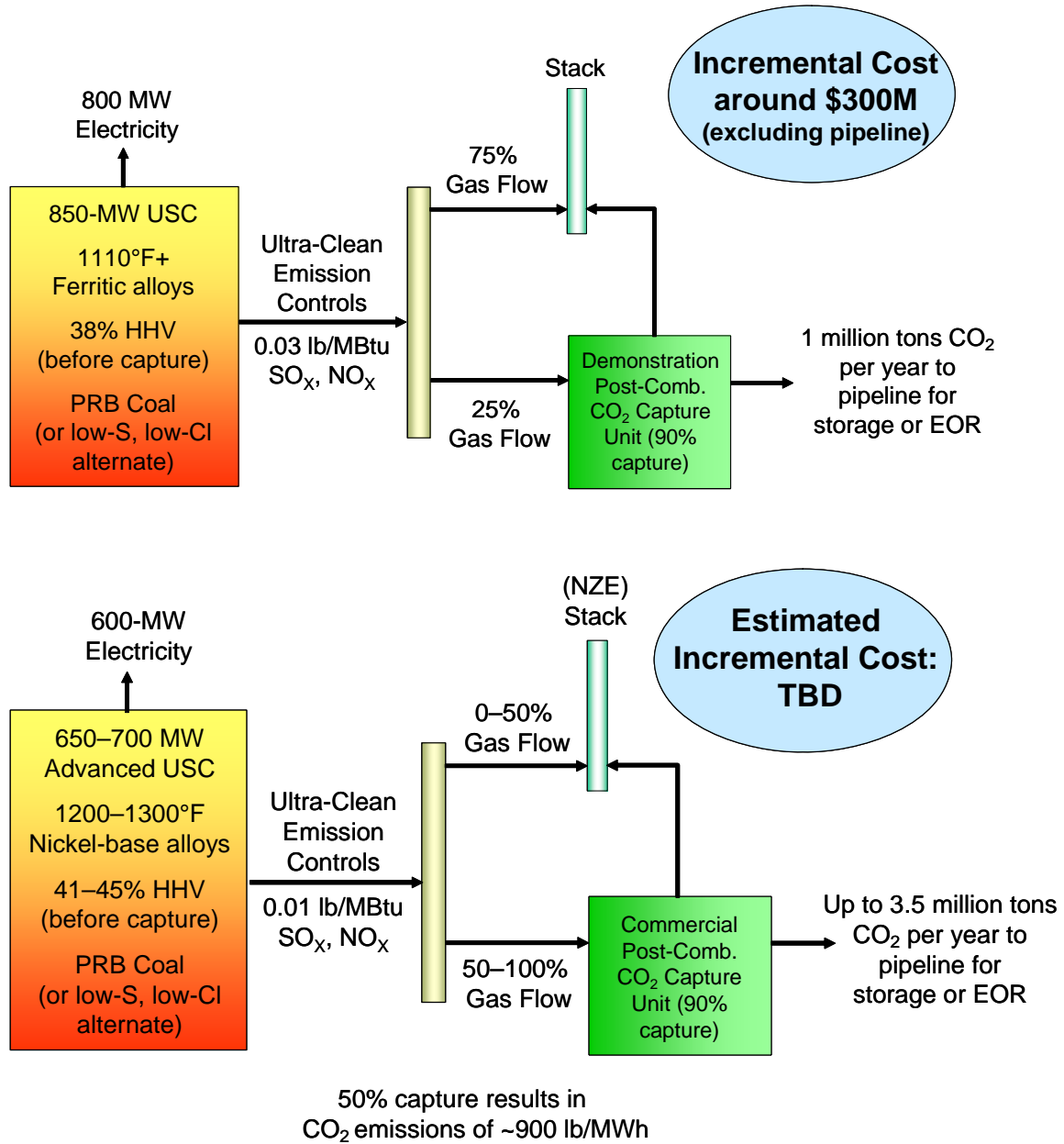
\* For a unit designed for 90% unit availability and 90% post-combustion CO<sub>2</sub> capture firing a Pittsburgh #8 bituminous coal; cost normalization using Chemical Engineering Plant Cost Index or equivalent. A similar trend is observed in analyses of PC units with CCS using other U.S. coals, although the efficiency values are up to two percentage points lower for units firing subbituminous coal such as Powder River Basin and up to four percentage points lower for units firing lignite.

**UltraGen Ultrasupercritical (USC) Pulverized Coal (PC) Commercial Projects.** EPRI and industry representatives have proposed a program to support commercial projects that demonstrate advanced PC and CCS technologies. The vision entails construction of two (or more) commercially operated USC PC power plants that combine state-of-the-art pollution controls, ultra-supercritical steam power cycles, and innovative CO<sub>2</sub> capture technologies.

The UltraGen I plant will use the best of today’s proven ferritic steels in high-temperature boiler and steam turbine components, while UltraGen II will be the first plant in the United States to feature nickel-based alloys that are able to withstand the higher temperatures of advanced ultra-supercritical steam conditions.

UltraGen I will demonstrate CO<sub>2</sub> capture modules that separate about 1 million tons CO<sub>2</sub>/yr using the best established technology. This system will be about 6 times the size of the largest CO<sub>2</sub> capture system operating on a coal-fired boiler today. UltraGen II will double the size of the UltraGen I CO<sub>2</sub> capture system, and may demonstrate a new class of chemical solvent if one of the emerging low-regeneration-energy processes has reached a sufficient stage of development. Both plants will demonstrate ultra-low emissions. Both UltraGen demonstration plants will dry and compress the captured CO<sub>2</sub> for long-term

geologic storage and/or use in enhanced oil or gas recovery operations. Figure 8 depicts the proposed key features of UltraGen I and II.



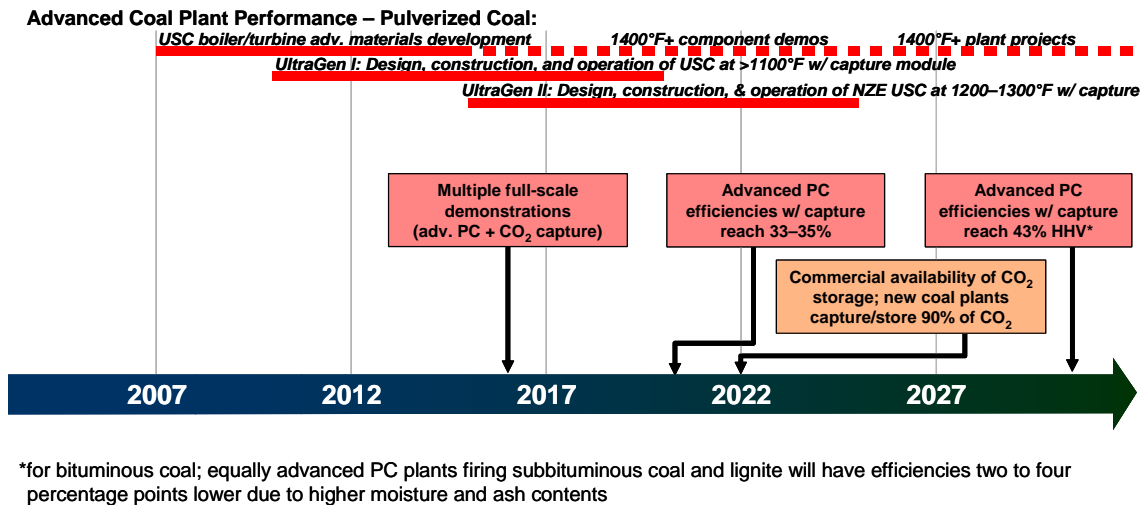
**Figure 8 – Key parameters for UltraGen I (upper schematic) and UltraGen II (lower schematic), assuming a subbituminous feed coal such as Powder River Basin**

To provide a platform for testing and developing emerging PC and CCS technologies, the UltraGen program will allow for technology trials at existing sites as well as at the sites of new projects. Unlike FutureGen, EPRI expects the UltraGen projects will be commercially dispatched by electricity grid operators. The differential cost to the host company for demonstrating these improved features are envisioned to be offset by any available tax credits (or other incentives) and by funds raised through an industry-led consortium formed by EPRI.

The UltraGen projects represent the type of “giant step” collaborative efforts that need to be taken to advance integrated PC/CCS technology to the next phase of evolution and assure competitiveness in a carbon-constrained world. Because of the time and expense for each “design and build” iteration for coal power plants (3 to 5 years not counting the permitting process and ~\$2 billion), there is no room for hesitation in terms of commitment to advanced technology validation and demonstration projects.

The UltraGen projects will resolve technical and economic barriers to the deployment of USC PC and CCS technology by providing a shared-risk vehicle for testing and validating high-temperature materials, components, and designs in plants also providing superior environmental performance.

Figure 9 summarizes EPRI’s recommended major RD&D activities for improving the efficiency and cost of USC PC technologies with CO<sub>2</sub> capture.



**Figure 9 – Timing of advanced PC and CO<sub>2</sub> capture integration RD&D activities and milestones**

**Efficiency Improvement and CCS Retrofits for the Existing PC Fleet.** It would be economically advantageous to operate the many reliable subcritical PC units in the U.S. fleet well into the future. Premature replacement of these units or mandatory retrofit of these units for CO<sub>2</sub> capture en masse would be economically prohibitive. Their flexibility for load following and provision of support services to ensure grid stability makes them highly valuable. With equipment upgrades, many of these units can realize modest efficiency gains, which, when accumulated across the existing generating fleet could make a sizeable reduction in CO<sub>2</sub> emissions. For some existing plants, retrofit of CCS will make sense, but specific plant design features, space limitations, and economic and regulatory considerations must be carefully analyzed to determine whether retrofit-for-capture is feasible.

These upgrades depend on the equipment configuration and operating parameters of a particular plant and may include:

- turbine blading and steam path upgrades
- turbine control valve upgrades for more efficient regulation of steam
- cooling tower and condenser upgrades to reduce circulating water temperature, steam turbine exhaust backpressure, and auxiliary power consumption
- cooling tower heat transfer media upgrades
- condenser optimization to maximize heat transfer and minimize condenser temperature
- condenser air leakage prevention/detection
- variable speed drive technology for pump and fan motors to reduce power consumption
- air heater upgrades to increase heat recovery and reduce leakage
- advanced control systems incorporating neural nets to optimize temperature, pressure, and flow rates of fuel, air, flue gas, steam, and water
- optimization of water blowdown and blowdown energy recovery
- optimization of attemperator design, control, and operating scenarios
- sootblower optimization via “intelligent” sootblower system use
- coal drying (for plants using lignite and subbituminous coals)

**Coal Drying for Increased Generating Efficiency.** Boilers designed for high-moisture lignite have traditionally employed higher feed rates (lb/hr) to account for the large latent heat load to evaporate fuel moisture. An innovative concept developed by Great River Energy (GRE) and Lehigh University uses low-grade heat recovered from within the plant to dry incoming fuel to the boiler, thereby boosting plant efficiency and output. [In contrast, traditional thermal drying processes are complex and require high-grade heat to remove moisture from the coal.] Specifically, the GRE approach uses steam condenser and boiler exhaust heat exchangers to heat air and water fed to a fluidized-bed coal dryer upstream of the plant pulverizers. Based on successful tests with a pilot-scale dryer and more than a year of continuous operation with a prototype dryer at its Coal Creek station, GRE (with U.S. Department of Energy support and EPRI technical consultation) is now building a full suite of dryers for Unit 2 (i.e., a commercial-scale demonstration). In addition to the efficiency and CO<sub>2</sub> emission reduction benefits from reducing the lignite feed moisture content by about 25%, the plant’s air emissions will be reduced as well.<sup>2</sup> Application of this technology is not limited to PC units firing lignite. EPRI believes it may find application in PC units firing subbituminous coal and in IGCC units with dry-fed gasifiers using low-rank coals.

## **Improving CO<sub>2</sub> Capture Technologies**

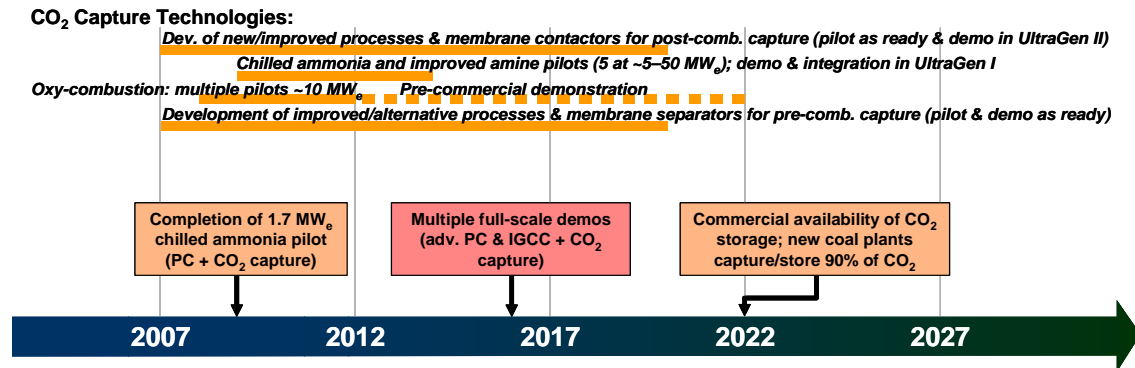
CCS entails pre-combustion or post-combustion CO<sub>2</sub> capture technologies, CO<sub>2</sub> drying and compression (and sometimes further removal of impurities), and the transportation of

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<sup>2</sup> C. Bullinger, M. Ness, and N. Sarunac, “One Year of Operating Experience with Prototype Fluidized Bed Coal Dryer at Coal Creek Generating Station,” 32nd International Technical Conference on Coal Utilization and Fuel Systems, Clearwater FL, June 10–15, 2007.

separated CO<sub>2</sub> to locations where it can be stored away from the atmosphere for centuries or longer.

Albeit at considerable cost, CO<sub>2</sub> capture technologies can be integrated into all coal-based power plant technologies. For both new plants and retrofits, there is a tremendous need (and opportunity) to reduce the energy required to remove CO<sub>2</sub> from fuel gas or flue gas. Figure 10 shows a selection of the key technology developments and test programs needed to achieve commercial CO<sub>2</sub> capture technologies for advanced coal combustion- and gasification-based power plants at a progressively shrinking constant-dollar leveled cost-of-electricity premium. Specifically, the target is a premium of about \$6/MWh in 2025 (relative to plants at that time without capture) compared with an estimated 2010 cost premium of perhaps \$40/MWh (not counting the cost of transportation and storage). Such a goal poses substantial engineering challenges and will require major investments in RD&D to roughly halve the currently large energy requirements (operating costs) associated with CO<sub>2</sub> solvent regeneration. Achieving this goal will allow power producers to meet the public demand for stable electricity prices while reducing CO<sub>2</sub> emissions to address climate change concerns.



**Figure 10 – Timing of CO<sub>2</sub> capture technology development RD&D activities and milestones**

### **Pre-Combustion CO<sub>2</sub> Capture (IGCC)**

IGCC technology allows for CO<sub>2</sub> capture to take place via an added fuel gas processing step at elevated pressure, rather than at the atmospheric pressure of post-combustion flue gas, permitting capital savings through smaller equipment sizes as well as lower operating costs.

Currently available technologies for such pre-combustion CO<sub>2</sub> removal use a chemical and/or physical solvent that selectively absorbs CO<sub>2</sub> and other “acid gases,” such as hydrogen sulfide. Application of this technology requires that the CO in synthesis gas (the principal component) first be “shifted” to CO<sub>2</sub> and hydrogen via a catalytic reaction with water. The CO<sub>2</sub> in the shifted synthesis gas is then removed via contact with the solvent in an absorber column, leaving a hydrogen-rich synthesis gas for combustion in the gas turbine. The CO<sub>2</sub> is released from the solvent in a regeneration process that typically reduces pressure and/or increases temperature.

Chemical plants currently employ such a process commercially using methyl diethanolamine (MDEA) as a chemical solvent or the Selexol and Rectisol processes,

which rely on physical solvents. Physical solvents are generally preferred when extremely high (>99.8%) sulfur species removal is required. Although the required scale-up for IGCC power plant applications is less than that needed for scale-up of post-combustion CO<sub>2</sub> capture processes for PC plants, considerable engineering challenges remain and work on optimal integration with IGCC cycle processes has just begun.

The impact of current pre-combustion CO<sub>2</sub> removal processes on IGCC plant thermal efficiency and capital cost is significant. In particular, the water-gas shift reaction reduces the heating value of synthesis gas fed to the gas turbine. Because the gasifier outlet ratios of CO to methane to H<sub>2</sub> are different for each gasifier technology, the relative impact of the water-gas shift reactor process also varies. In general, however, it can be on the order of a 10% fuel energy reduction. Heat regeneration of solvents further reduces the steam available for power generation. Other solvents, which are depressurized to release captured CO<sub>2</sub>, must be re-pressurized for reuse. Cooling water consumption is increased for solvents needing cooling after regeneration and for pre-cooling and interstage cooling during compression of separated CO<sub>2</sub> to a supercritical state for transportation and storage. Heat integration with other IGCC cycle processes to minimize these energy impacts is complex and is currently the subject of considerable RD&D by EPRI and others.

**Membrane CO<sub>2</sub> Separation.** Technology for separating CO<sub>2</sub> from shifted synthesis gas (or flue gas from PC plants) offers the promise of lower auxiliary power consumption but is currently only at the laboratory stage of development. Several organizations are pursuing different approaches to membrane-based applications. In general, however, CO<sub>2</sub> recovery on the low-pressure side of a selective membrane can take place at a higher pressure than is now possible with solvent processes, reducing the subsequent power demand for compressing CO<sub>2</sub> to a supercritical state. Membrane-based processes can also eliminate steam and power consumption for regenerating and pumping solvent, respectively, but they require power to create the pressure difference between the source gas and CO<sub>2</sub>-rich sides. If membrane technology can be developed at scale to meet performance goals, it could enable up to a 50% reduction in capital cost and auxiliary power requirements relative to current CO<sub>2</sub> capture and compression technology.

### **Post-Combustion CO<sub>2</sub> Capture (PC and CFB Plants)**

The post-combustion CO<sub>2</sub> capture processes being discussed for power plant boilers in the near-term draw upon commercial experience with amine solvent separation at much smaller scale in the food, beverage and chemical industries, including three U.S. applications of CO<sub>2</sub> capture from coal-fired boilers.

These processes contact flue gas with an amine solvent in an absorber column (much like a wet SO<sub>2</sub> scrubber) where the CO<sub>2</sub> chemically reacts with the solvent. The CO<sub>2</sub>-rich liquid mixture then passes to a stripper column where it is heated to change the chemical equilibrium point, releasing the CO<sub>2</sub>. The “regenerated” solvent is then recirculated back to the absorber column, while the released CO<sub>2</sub> may be further processed before compression to a supercritical state for efficient transportation to a storage location.

After drying, the CO<sub>2</sub> released from the regenerator is relatively pure. However, successful CO<sub>2</sub> removal requires very low levels of SO<sub>2</sub> and NO<sub>2</sub> entering the CO<sub>2</sub> absorber, as these

species also react with the solvent, requiring removal of the degraded solvent and replacement with fresh feed. Thus, high-efficiency SO<sub>2</sub> and NO<sub>x</sub> control systems are essential to minimizing solvent consumption costs for post-combustion CO<sub>2</sub> capture; currently the approach to achieving such ultra-low SO<sub>2</sub> concentrations is to add a polishing scrubber, a costly venture. Extensive RD&D is in progress to improve the solvent and system designs for power boiler applications and to develop better solvents with greater absorption capacity, less energy demand for regeneration, and greater ability to accommodate flue gas contaminants.

At present, monoethanolamine (MEA) is the “default” solvent for post-combustion CO<sub>2</sub> capture studies and small-scale field applications. Processes based on improved amines, such as Fluor’s Econamine FG Plus and Mitsubishi Heavy Industries’ KS-1, await demonstration at power boiler scale and on coal-derived flue gas. The potential for improving amine-based processes appears significant. For example, a recent study based on KS-1 suggests that its impact on net power output for a supercritical PC unit would be 19% and its impact on the levelized cost-of-electricity would be 44%, whereas earlier studies based on suboptimal MEA applications yielded output penalties approaching 30% and cost-of-electricity penalties of up to 65%.

Accordingly, amine-based engineered solvents are the subject of numerous ongoing efforts to improve performance in power boiler post-combustion capture applications. Along with modifications to the chemical properties of the sorbents, these efforts are addressing the physical structure of the absorber and regenerator equipment, examining membrane contactors and other modifications to improve gas-liquid contact and/or heat transfer, and optimizing thermal integration with steam turbine and balance-of-plant systems. Although the challenge is daunting, the payoff is potentially massive, as these solutions may be applicable not only to new plants, but to retrofits where sufficient plot space is available at the back end of the plant.

Finally, as discussed earlier, deploying USC PC technology to increase efficiency and lower uncontrolled CO<sub>2</sub> per MWh can further reduce the cost impact of post-combustion CO<sub>2</sub> capture.

**Ammonia-Based Processes.** Post-combustion CO<sub>2</sub> capture using ammonia-based solvents offers the promise of significantly lower solvent regeneration requirements relative to MEA. In the “chilled ammonia” process currently under development and testing by ALSTOM and EPRI, respectively, CO<sub>2</sub> is absorbed in a solution of ammonium carbonate, at low temperature and atmospheric pressure.

Compared with amines, ammonium carbonate has over twice the CO<sub>2</sub> absorption capacity and requires less than half the heat to regenerate. Further, regeneration can be performed under higher pressure than amines, so the released CO<sub>2</sub> is already partially pressurized. Therefore, less energy is subsequently required for compression to a supercritical state for transportation to an injection location. Developers have estimated that the parasitic power loss from a full-scale supercritical PC plant using chilled ammonia CO<sub>2</sub> capture could be as low as 15%, with an associated cost-of-electricity penalty of just 25%. Part of the reduction in power loss comes from the use of low quality heat to regenerate ammonia and reduce the quantity of steam required for regeneration. Following successful experiments at 0.25 MW<sub>e</sub>,

scale, ALSTOM and a consortium of EPRI members are constructing a 1.7 MWe pilot unit to test the chilled ammonia process on a flue gas slipstream at We Energies' Pleasant Prairie Power Plant. The American Electric Power Co. (AEP) has announced plans to test a scaled-up (20 MWe) design, incorporating the lessons learned on the 1.7 MWe unit, at its Mountaineer station in West Virginia in the 2009 time frame

Other "multi-pollutant" control system developers are also exploring ammonia-based processes for CO<sub>2</sub> removal. For example, Powerspan and NRG Energy, Inc. just last week announced plans to demonstrate a 125 MWe design of Powerspan's ECO<sub>2</sub> system at the Parish station in Texas starting up in 2012.

**Other Processes.** EPRI has identified over 40 potential CO<sub>2</sub> separation processes that are being developed by various firms or institutes. They include absorption systems (typically solvent-based similar to the amine and ammonia processes discussed above), adsorbed (attachment of the CO<sub>2</sub> to a solid that is then regenerated and re-used), membranes, and biological systems. Funding comes from a variety of sources, primarily DOE or internal funds, but the funding is neither sufficient or well-enough coordinated to advance the most promising technologies at the speed needed to achieve the goals of high CO<sub>2</sub> capture at societally-acceptable cost and energy drain.

### **Oxy-Fuel Combustion Boilers**

Fuel combustion in a blend of oxygen and recycled flue gas rather than in air (known as oxy-fuel combustion, oxy-coal combustion, or oxy-combustion) is gaining interest as a viable CO<sub>2</sub> capture alternative for PC and CFB plants. The process is applicable to virtually all fossil-fueled boiler types and is a candidate for retrofits as well as new power plants.

Firing coal with high-purity oxygen alone would result in too high of a flame temperature, which would increase slagging, fouling, and corrosion problems, so the oxygen is diluted by mixing it with a slipstream of recycled flue gas. As a result, the flue gas downstream of the recycle slipstream take-off consists primarily of CO<sub>2</sub> and water vapor (although it also contains small amounts of nitrogen, oxygen, and criteria pollutants). After the water is condensed, the CO<sub>2</sub>-rich gas is compressed and purified to remove contaminants and prepare the CO<sub>2</sub> for transportation and storage.

Oxy-combustion boilers have been studied in laboratory-scale and small pilot units of up to 3 MW<sub>t</sub>. Two larger pilot units, at ~10 MWe, are now under construction by Babcock & Wilcox (B&W) and Vattenfall. An Australian-Japanese project team is pursuing a 30 MWe repowering project in Australia. These larger tests will allow verification of mathematical models and provide engineering data useful for designing pre-commercial systems.

### **CO<sub>2</sub> Transport and Geologic Storage**

Application of CO<sub>2</sub> capture technologies implies that there will be secure and economical forms of long-term storage that can assure CO<sub>2</sub> will be kept out of the atmosphere. Natural underground CO<sub>2</sub> reservoirs in Colorado, Utah, and other western states testify to the effectiveness of long-term geologic CO<sub>2</sub> storage. CO<sub>2</sub> is also found in natural gas

reservoirs, where it has resided for millions of years. Thus, evidence suggests that similarly sealed geologic formations will be ideal for storing CO<sub>2</sub> for millennia or longer.

The most developed approach for large-scale CO<sub>2</sub> storage is injection into depleted or partially depleted oil and gas reservoirs and similar geologically sealed “saline formations” (porous rocks filled with brine that is impractical for desalination). Partially depleted oil reservoirs provide the potential added benefit of enhanced oil recovery (EOR). [EOR is used in mature fields to recover additional oil after standard extraction methods have been used. When CO<sub>2</sub> is injected for EOR, it causes residual oil to swell and become less viscous, allowing some to flow to production wells, thus extending the field’s productive life.] By providing a commercial market for CO<sub>2</sub> captured from industrial sources, EOR may help the economics of CCS projects where it is applicable, and in some cases might reduce regulatory and liability uncertainties. Although less developed than EOR, researchers are exploring the effectiveness of CO<sub>2</sub> injection for enhancing production from depleted natural gas fields (particularly in compartmentalized formations where pressure has dropped) and from deep methane-bearing coal seams. DOE and the International Energy Agency are among the sponsors of such efforts. However, at the scale that CCS needs to be deployed to help achieve atmospheric CO<sub>2</sub> stabilization at an acceptable level, EPRI believes that the primary economic driver for CCS will be the value of carbon that results from a future climate policy.

Geologic sequestration as a CCS strategy is currently being demonstrated in several RD&D projects around the world. The three largest projects (which are non-power)—Statoil’s Sleipner Saline Aquifer CO<sub>2</sub> Storage project in the North Sea off of Norway; the Weyburn Project in Saskatchewan, Canada; and the In Salah Project in Algeria—each sequester about 1 million metric tons of CO<sub>2</sub> per year, which matches the output of one baseloaded 150–200 MW coal-fired power plant. With 17 collective operating years of experience, these projects have thus far demonstrated that CO<sub>2</sub> storage in deep geologic formations can be carried out safely and reliably. Statoil estimates that Norwegian greenhouse gas emissions would have risen incrementally by 3% if the CO<sub>2</sub> from the Sleipner project had been vented rather than sequestered.<sup>3</sup>

Table 2 lists a selection of current and planned CO<sub>2</sub> storage projects as of early 2007. In October 2007, the DOE awarded the first three large scale carbon sequestration projects in the United States. The Plains Carbon Dioxide Reduction Partnership, Southeast Regional Carbon Sequestration Partnership, and Southwest Regional Partnership for Carbon Sequestration, will conduct large volume tests for the storage of one million or more tons of CO<sub>2</sub> in deep saline reservoirs in the U.S.

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<sup>3</sup> [http://www.co2captureandstorage.info/project\\_specific.php?project\\_id=26](http://www.co2captureandstorage.info/project_specific.php?project_id=26)

**Table 2 – Select Existing and Planned CO<sub>2</sub> Storage Projects as of Early 2007**

PROJECT	CO <sub>2</sub> SOURCE	COUNTRY	START	Anticipated amount injected by:		
				2006	2010	2015
Sleipner	Gas. Proc.	Norway	1996	9 MT	13 MT	18 MT
Weyburn	Coal	Canada	2000	5 MT	12 MT	17 MT
In Salah	Gas. Proc.	Algeria	2004	2 MT	7 MT	12 MT
Snohvit	Gas. Proc.	Norway	2007	0	2 MT	5 MT
Gorgon	Gas. Proc.	Australia	2010	0	0	12 MT
DF-1 Miller	Gas	U.K.	2009	0	1 MT	8 MT
DF-2 Carson	Pet Coke	U.S.	2011	0	0	16 MT
Draugen	Gas	Norway	2012	0	0	7 MT
FutureGen	Coal	U.S.	2012	0	0	2 MT
Monash	Coal	Australia	NA	0	0	NA
SaskPower	Coal	Canada	NA	0	0	NA
Ketzin/CO <sub>2</sub> STORE	NA	Germany	2007	0	50 KT	50 KT
Otway	Natural	Australia	2007	0	100 KT	100 KT
<b>TOTALS</b>				<b>16 MT</b>	<b>35 MT</b>	<b>99 MT</b>

Source: Sally M. Benson (Stanford University GCEP), “Can CO<sub>2</sub> Capture and Storage in Deep Geological Formations Make Coal-Fired Electricity Generation Climate Friendly?” Presentation at Emerging Energy Technologies Summit, UC Santa Barbara, California, February 9, 2007. [Note: Statoil has subsequently suspended plans for the Draugen project and announced a study of CO<sub>2</sub> capture at a gas-fired power plant at Tjeldbergodden. BP and Rio Tinto have announced the coal-based “DF-3” project in Australia.]

**Enhanced Oil Recovery.** Experience relevant to CCS comes from the oil industry, where CO<sub>2</sub> injection technology and modeling of its subsurface behavior have a proven record of accomplishment. EOR has been conducted successfully for 35 years in the Permian Basin fields of west Texas and Oklahoma. Regulatory oversight and community acceptance of injection operations for EOR seem well established.

Although the purpose of EOR heretofore has not been to sequester CO<sub>2</sub>, the practice can be adapted to include large-volume residual CO<sub>2</sub> storage. This approach is being demonstrated in the Weyburn-Midale CO<sub>2</sub> monitoring projects in Saskatchewan, Canada. The Weyburn project uses captured and dried CO<sub>2</sub> from the Dakota Gasification Company’s Great Plains synfuels plant near Beulah, North Dakota. The CO<sub>2</sub> is transported via a 200-mile pipeline constructed of standard carbon steel. Over the life of the project, the net CO<sub>2</sub> storage is

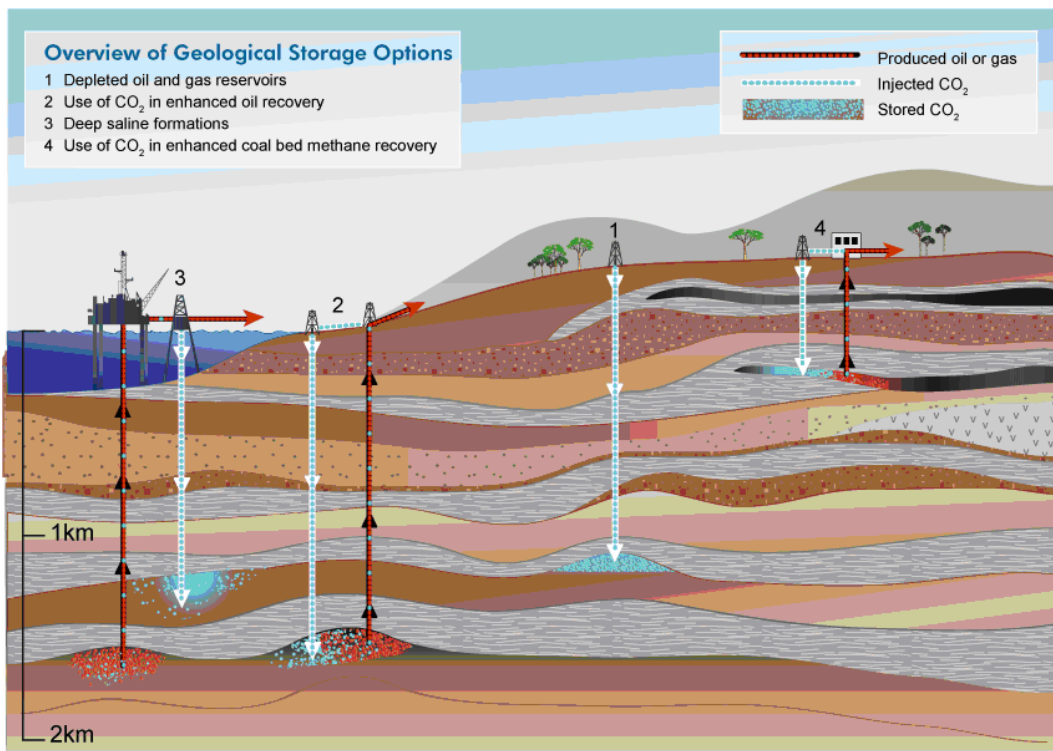
estimated at 20 million metric tons, while an additional 130 million barrels of oil will be produced.

Although EOR might help the economics of early CCS projects in oil-patch areas, EOR sites are ultimately too few and too geographically isolated to accommodate much of the CO<sub>2</sub> from widespread industrial CO<sub>2</sub> capture operations. In contrast, saline formations are available in many—but not all—U.S. locations.

### CCS in the United States

A DOE-sponsored R&D program, the “Regional Carbon Sequestration Partnerships,” is engaged in mapping U.S. geologic formations suitable for CO<sub>2</sub> storage. Evaluations by these Regional Partnerships and others suggest that enough geologic storage capacity exists in the U.S. to hold many centuries’ production of CO<sub>2</sub> from coal-based power plants and other large point sources.

The Regional Partnerships are also conducting pilot-scale CO<sub>2</sub> injection validation tests across the country in differing geologic formations, including saline formations, deep unmineable coal seams, and older oil and gas reservoirs. Figure 11 illustrates some of these options. These tests, as well as most commercial applications for long-term storage, will use CO<sub>2</sub> compressed for volumetric efficiency to a liquid-like “supercritical” state; thus, virtually all CO<sub>2</sub> storage will take place in formations at least a half-mile deep, where the risk of leakage to shallower groundwater aquifers or to the surface is usually very low.



Source: Peter Cook, CO<sub>2</sub>CRC, in Intergovernmental Panel on Climate Change, Special Report “Carbon Dioxide Capture and Storage,” <http://www.ipcc.ch/pub/reports.htm>

**Figure 11 – Illustration of potential geological CO<sub>2</sub> storage site types**

After successful completion of pilot-scale CO<sub>2</sub> storage validation tests, the Partnerships will undertake large-volume storage tests, injecting quantities of ~1 million metric tons of CO<sub>2</sub> or more over a several year period, along with post-injection monitoring to track the absorption of the CO<sub>2</sub> in the target formation(s) and to check for potential leakage.

The EPRI-CURC Roadmap identifies the need for several large-scale integrated demonstrations of CO<sub>2</sub> capture and storage. This assessment was echoed by MIT in its recent *Future of Coal* report, which calls for three to five U.S. demonstrations of about 1 million metric tons of CO<sub>2</sub> per year and about 10 worldwide.<sup>4</sup> These demonstrations could be the critical path item in commercialization of CCS technology. In addition, EPRI has identified 10 key topics<sup>5</sup> where further technical and/or policy development is needed before CCS can become fully commercial:

- Caprock integrity
- Injectivity and storage capacity
- CO<sub>2</sub> trapping mechanisms
- CO<sub>2</sub> leakage and permanence
- CO<sub>2</sub> and mineral interactions
- Reliable, low-cost monitoring systems
- Quick response and mitigation and remediation procedures
- Protection of potable water
- Mineral rights
- Long-term liability

Figure 12 shows that EPRI’s recommended large-scale integrated CO<sub>2</sub> capture and storage demonstrations is temporally consistent with the Regional Partnerships’ “Phase III” large-volume CO<sub>2</sub> storage test program. EPRI believes that many of the storage demonstrations should use CO<sub>2</sub> that comes from coal-fired boilers to address any uncertainties that may exist about the impact of coal-derived CO<sub>2</sub> on its behavior in underground formations.

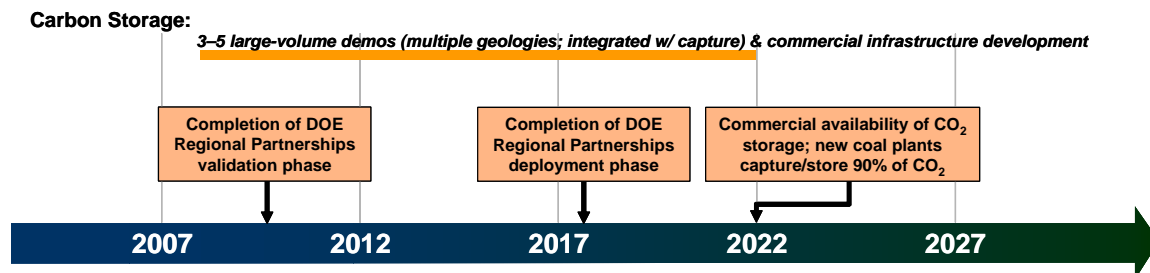


Figure 12 – Timing of CO<sub>2</sub> storage technology RD&D activities and milestones

<sup>4</sup> [http://web.mit.edu/coal/The\\_Future\\_of\\_Coal.pdf](http://web.mit.edu/coal/The_Future_of_Coal.pdf)

<sup>5</sup> EPRI, Overview of Geological Storage of CO<sub>2</sub>, Report ID 1012798

## **CO<sub>2</sub> Transportation**

Mapping of the distribution of potentially suitable CO<sub>2</sub> storage formations across the country, as part of the research by the Regional Partnerships, shows that some areas have ample storage capacity while others appear to have little or none. Thus, implementing CO<sub>2</sub> capture at some power plants may require pipeline transportation for several hundred miles to suitable injection locations, possibly in other states. Although this adds cost, it should not represent a technical hurdle because long-distance, interstate CO<sub>2</sub> pipelines have been used commercially in oilfield EOR applications. Economic considerations dictate that the purity requirements of coal-derived CO<sub>2</sub> be established so that the least-cost pipeline and compressor materials can be used at each application. From an infrastructure perspective, EPRI expects that early commercial CCS projects will take place at coal-based power plants near sequestration sites or an existing CO<sub>2</sub> pipeline. As the number of projects increases, regional CO<sub>2</sub> pipeline networks connecting multiple industrial sources and storage sites will be needed.

## **Policy-Related Long-Term CO<sub>2</sub> Storage Issues**

Beyond developing the technological aspects of CCS, public policy needs to address issues such as CO<sub>2</sub> storage site permitting, long-term monitoring requirements, and post-closure liability. CCS represents an emerging industry, and the jurisdictional roles among federal and state agencies for regulations and their relationship to private carbon credit markets operating under federal oversight has yet to be determined.

Currently, efforts are under way in some states to establish regulatory frameworks for long-term geologic CO<sub>2</sub> storage. Additionally, stakeholder organizations such as the Interstate Oil and Gas Compact Commission (IOGCC) are developing their own suggested regulatory recommendations for states drafting legislation and regulatory procedures for CO<sub>2</sub> injection and storage operations.<sup>5</sup> Other stakeholders, such as environmental groups, are also offering policy recommendations. EPRI expects this field to become very active soon.

A state-by-state approach to sequestration may not be adequate because some geologic formations, which are ideal for storing CO<sub>2</sub>, underlie multiple states. At the federal level, the U.S. EPA published a first-of-its-kind guidance (UICPG # 83) on March 1, 2007, for permitting underground injection of CO<sub>2</sub>.<sup>6</sup> This guidance offers flexibility for pilot projects evaluating the practice of CCS, while leaving unresolved the requirements that could apply to future large-scale CCS projects.

## **Long-Term CO<sub>2</sub> Storage Liability Issues**

Long-term liability for injected CO<sub>2</sub> will need to be assigned before CCS can become fully commercial. Because CCS activities will be undertaken to serve the public good, as determined by government policy, and will be implemented in response to anticipated or actual government-imposed limits on CO<sub>2</sub> emissions, a number of policy analysts have suggested that the entities performing these activities should be granted a measure of long-

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<sup>5</sup> <http://www.iogcc.state.ok.us/PDFS/CarbonCaptureandStorageReportandSummary.pdf>

<sup>6</sup> [http://www.epa.gov/safewater/uic/pdfs/guide\\_uic\\_carbonsequestration\\_final-03-07.pdf](http://www.epa.gov/safewater/uic/pdfs/guide_uic_carbonsequestration_final-03-07.pdf)

term risk reduction assuming adherence to proper procedures during the storage site injection operations and closure phases.

### **RD&D Investment for Advanced Coal and CCS Technologies**

Developing the suite of technologies needed to achieve competitive advanced coal and CCS technologies will require a sustained major investment in RD&D. As shown in Table 3, EPRI estimates that an expenditure of approximately \$8 billion will be required in the 10-year period from 2008–17. The MIT *Future of Coal* report estimates the funding need at up to \$800–850 million per year, which approaches the EPRI value. Further, EPRI expects that an RD&D investment of roughly \$17 billion will be required over the next 25 years.

Investment in earlier years may be weighted toward IGCC, as this technology is less developed and will require more RD&D investment to reach the desired level of commercial viability. As interim progress and future needs cannot be adequately forecast at this time, the years after 2023 do not distinguish between IGCC and PC.

**Table 3 – RD&D Funding Needs for Advanced Coal Power Generation Technologies with CO<sub>2</sub> Capture**

	<b>2008–12</b>	<b>2013–17</b>	<b>2018–22</b>	<b>2023–27</b>	<b>2028–32</b>
Total Estimated RD&D Funding Needs (Public + Private Sectors)	\$830M/yr	\$800M/yr	\$800M/yr	\$620M/yr	\$400M/yr
<i>Advanced Combustion, CO<sub>2</sub> Capture</i>	25%	25%	40%	80%	80%
<i>Integrated Gasification Combined Cycle (IGCC), CO<sub>2</sub> Capture</i>	50%	50%	40%		
<i>CO<sub>2</sub> Storage</i>	25%	25%	20%	20%	20%

By any measure, these estimated RD&D investments are substantial. EPRI and the members of the *CoalFleet for Tomorrow*® program, by promoting collaborative ventures among industry stakeholders and governments, believe that the costs of developing critical-path technologies for advanced coal and CCS can be shouldered by multiple participants. EPRI believes that government policy and incentives will also play a key role in fostering CCS technologies through early RD&D stages to achieve widespread, economically feasible deployment capable of achieving major reductions in U.S. CO<sub>2</sub> emissions.