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The Potential Growing Role of Post-Combustion CO_2 Capture Retrofits in Early Commercial Applications of CCS to Coal-Fired Power Plants

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Steven Specker
Jeffrey Phillips
Desmond Dillon

Electric Power Research Institute

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute

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This is an EPRI technical document. It is intended as an informal report of continuing research and studies. It is not a final EPRI technical report.

NOTE

For more information, contact EPRI Project Manager Des Dillon at 650.855.2036 or e-mail ddillon@epri.com.

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Changing Circumstances Place New Emphasis on CCS Retrofits

In 2007, EPRI published the PRISM analysis, which defined the technical pathways to achieving large-scale CO_2 emissions reductions while meeting future U.S. electricity demand.[1,2] As shown in Figure 1, the largest potential contribution to CO_2 emissions reductions (relative to an Energy Information Administration baseline case) would be achieved by applying carbon capture and storage (CCS) technologies to advanced coal-based power plants that come on-line after 2020.

The logic behind this projection of CCS potential rests chiefly on two assumptions: that commercial CCS technology will be widely available by 2020, and that the economics of CCS application will be considerably more favorable on a new plant (in terms of \$ per ton-CO_2 avoided) and that enough new plants will be built to assure sufficient CCS market penetration. The former assumption, although not assured, remains on track presuming that heightened investments by the public and private sectors are maintained. The latter assumption—that enough new coal plants will be built to accommodate the needed market penetration—has been recently called into question (at least in the United States) for a variety of reasons. This has focused attention on the prospect of CCS retrofits as an important element in an overall electric-sector greenhouse gas emissions reduction strategy.

Among the factors leading the Energy Information Administration and other forecasters to reduce the projected number and capacity of new U.S. coal-based units expected to be built by 2030 are:

- Reduced electricity demand growth forecasts in the wake of the global recession and accelerated investments in energy efficiency measures
- High and/or uncertain capital costs
- Less available financing (uncertainty in capital markets may make it more difficult to raise the sum necessary for an entire new coal-fired unit with CCS)
- Permitting challenges
- Requirements to expand the fraction of generation from renewable energy sources

Meanwhile, the outlook for retrofitting post-combustion CO_2 capture systems to existing coal-fired plants in the United States has been improved by the following developments:

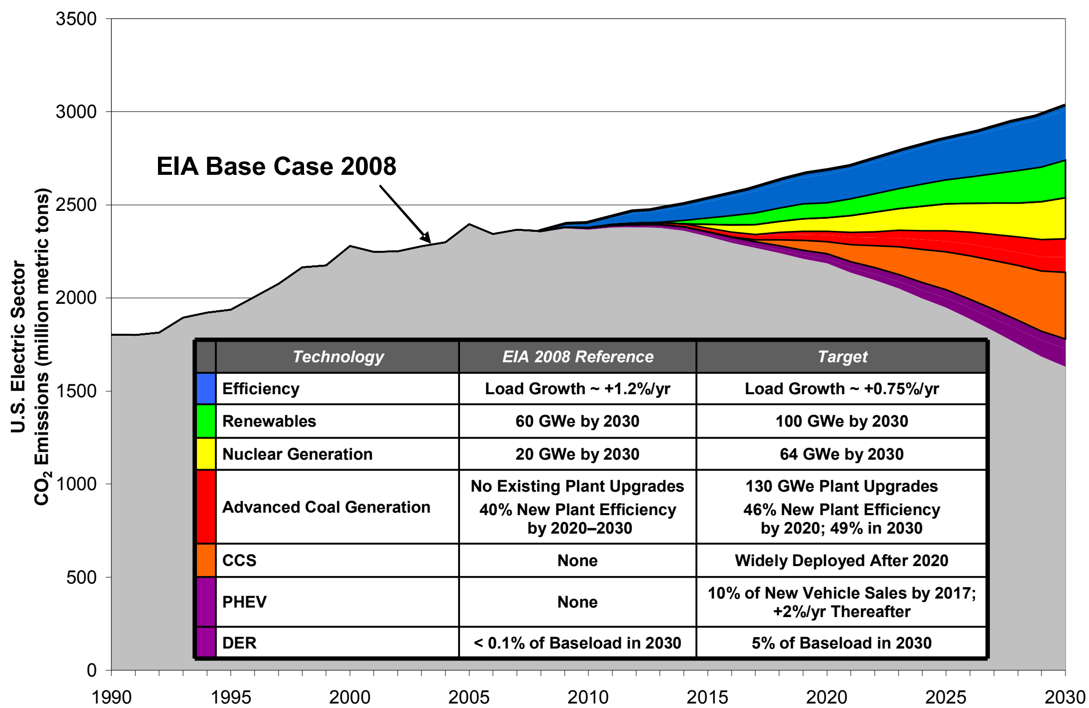
- Incentives for early CCS projects (proposed “bonus allowance” premiums, tax credits, government co-funding opportunities, etc.) that tend to favor retrofit of CCS because it can generally be implemented faster than building a new unit with CCS.
- Fundamental advances in CO_2 capture technologies that reduce overall energy and space requirements and an improved understanding of economical heat integration opportunities. Although such advances apply to all CCS applications—new-build and retrofit—a reduction

1 The Power to Reduce CO_2 Emissions: the Full Portfolio, Discussion Paper by EPRI Energy Technology Assessment Center. EPRI, Palo Alto, CA: August 2007.

2 “Pathways to the Full Portfolio,” EPRI Journal, EPRI, Palo Alto, CA: Fall 2007

in overall cost and energy requirements reduces the magnitude of the incremental cost and energy premium for CCS retrofits relative to new builds with CCS.

- Hybrid concepts such as the addition of solar thermal systems to existing coal plants, which offset the energy demand for CO_2 capture solvent regeneration and also allow power companies to expand their renewables portfolio.



	Technology	EIA 2008 Reference	Target
	Efficiency	Load Growth ~ +1.2%/yr	Load Growth ~ +0.75%/yr
	Renewables	60 GWe by 2030	100 GWe by 2030
	Nuclear Generation	20 GWe by 2030	64 GWe by 2030
	Advanced Coal Generation	No Existing Plant Upgrades 40% New Plant Efficiency by 2020–2030	130 GWe Plant Upgrades 46% New Plant Efficiency by 2020; 49% in 2030
	CCS	None	Widely Deployed After 2020
	PHEV	None	10% of New Vehicle Sales by 2017; +2%/yr Thereafter
	DER	< 0.1% of Baseload in 2030	5% of Baseload in 2030

Figure 1
EPRI's PRISM Analysis Illustrates a Path to Lowering U.S. Electricity-Related CO_2 Emissions by 30% by 2030

Internationally, there is keen interest in post-combustion CO_2 capture retrofits as well. European countries with mature economies share many of the same drivers as the United States—new coal plant cost and permitting challenges, public desire for more renewables, and forthcoming climate policy changes that will reduce allowable emissions. Also important in continental Europe are "climate friendly" coal power options that can limit reliance on imported natural gas. In Asia, particularly China, massive investments have taken place over the last decade in new coal-fired capacity, rivaling the total installed capacity of North America or Europe. Indeed, China is now the world's largest coal consumer and the largest CO_2 emitter. When the U.K. government restricted its CCS demonstration competition to only post-combustion capture options in 2007, it explicitly cited applicability to China and India as a basis for its decision.

Although new coal plant construction will undoubtedly help meet future electricity demand in the United States and elsewhere, present circumstances suggest a greater continued reliance on existing plants than was previously anticipated. Under this scenario, there is a compelling need to assess CCS retrofit options to fully evaluate the potential to reduce CO_2 emissions from the world's current coal-fired generating fleet.

In this regard, work by EPRI and others is already contributing to a better understanding of the plant characteristics that make a unit more or less amendable to CCS retrofit. Further, EPRI is now commencing site-specific engineering design and cost studies for CCS retrofits at five representative plants across North America. Additional work may examine other plants as well. Recognized as essential information for both power generators with existing assets and for policymakers, these real-world studies will provide added insight into generalized cost and performance impact assessments for a variety of existing plant configurations and fuels.

Although the task of retrofitting CCS equipment is more complex than the retrofit of flue gas desulfurization (FGD) systems, the challenges and prospects for CCS retrofits are somewhat analogous to industry experience with SO_2 controls over the last few decades: Collaborative R&D and sharing of lessons learned from early projects helped spur improvements in design and in O&M practices and reliability. In parallel, RD&D by EPRI and the industry identified and fostered multiple advances in FGD processes that significantly reduced the costs of SO_2 capture. Commercial maturity enabled suppliers to take advantage of economies of scale (e.g., single absorber towers are now standard) and to eliminate redundancy. Although CO_2 capture represents a bigger challenge than SO_2 control in terms of energy requirements and impacts on other parts of the power plant, EPRI and others expect that post-combustion CO_2 capture processes and equipment will evolve with experience over time in a manner similar to process for SO_2 capture. Indeed, research by the International Energy Agency predicts a path for "learning by doing" cost reductions for CO_2 capture technologies that mirrors that for FGD technology. With active RD&D programs and open information on O&M experience and costs, multiple innovations for CO_2 capture systems will be indentified and implemented.

U.S. Coal-Fired Power Plant Retrofit Market Potential

The United States has more than 300 GW_e of installed capacity in pulverized-coal (PC) plants, but it is unlikely that CCS retrofits will prove cost-effective for older, smaller units (<300 MW size, 1950–60s vintage) that may also lack FGD or selective catalytic reduction (SCR) NO_X controls. Narrowing the candidate field to boilers that are 300 MW or larger and less than about 35 years old renders a total capacity of 184 GW. If 90% CO_2 capture were to be applied to these units, a 50% reduction in total U.S. coal power sector CO_2 emissions would be achieved.[3]

In addition to unit age and size, other major considerations that can be used to screen PC plants for CCS retrofit suitability include:

- Sufficient space for new CO_2 capture system and compression equipment (typically about 6 acres for a 500 MW unit)
- Adequate cooling water supply (to accommodate increased water demand)
- High-performance NO_X and SO_X controls to reduce concentrations in the flue gas entering the CO_2 absorber to about 10 ppm or less
- Access to a geologic storage or opportunity to sell or otherwise dispose of captured CO_2

3 Source: J. Figueroa, DOE NETL presentation to APPA, June 28, 2006.

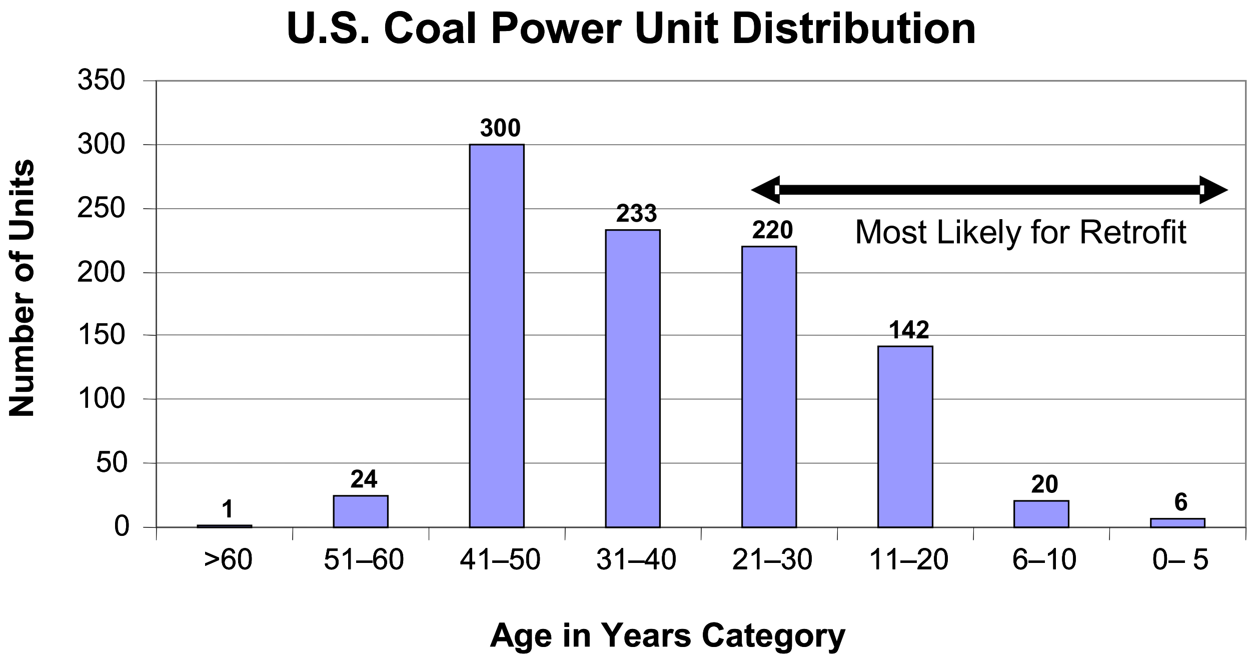


Figure 2
U.S. Coal Power Plant Age Distribution (Reference Year = 2006)

For plants meeting the above criteria, CO_2 capture costs will vary considerably due to a number of factors, including the volume of flue gas to be treated, which will determine capital costs for new capture equipment and operating costs. Due to economies of scale, larger units will tend to have lower costs on a $/ton-$CO_2$ removed basis (for situations where other site-specific retrofit factors are equal).

In terms of examining a specific plant regarding its suitability for post-combustion CO_2 capture retrofit, "second level" screening criteria could include the following:

- Capability to extract significant quantities of low-pressure steam for solvent regeneration (CO_2 liberation), and if the only possible extraction point is the intermediate pressure turbine to low-pressure turbine "crossover," the possibility of including let-down turbines to minimize energy losses
- Capability to extract intermediate-pressure steam intermittently for solvent reclaiming (amine systems)
- Capability to receive significantly increased quantities of hot condensate return
- Capability to significantly increase cooling system duty to meet loads from the CO_2 capture and compression systems
- Capability to increase internal electrical distribution capacity to meet the large power demands of CO_2 compressors and capture system pumps
- Capability to reroute back-end ducting to transfer flue gas to/from the CO_2 absorption and stripper columns

EPRI CO_2 Capture Retrofit Studies

With a focus specifically on CCS retrofit issues, EPRI is now commencing work with five electric utilities in the United States and Canada to quantify the costs and operational impacts of adding advanced amine post-combustion CO_2 capture systems to existing coal-fired plants. As of early 2009, 20 other organizations had joined the project, including eight from Canada and one from Australia.

The five host power companies and their study sites are:

- Edison Mission Group's 1536 MW Powerton Station, operated by Midwest Generation, in Pekin, Illinois
- Great River Energy's 1100 MW Coal Creek Station in Underwood North Dakota
- Nova Scotia Power's two 160 MW units at the Lingan Generating Station in Lingan, Nova Scotia
- Intermountain Power Agency's 950 MW Intermountain Generation Station in Delta, Utah
- FirstEnergy's 176 MW circulating fluidized-bed Unit 1 Bay Shore Plant in Oregon, Ohio

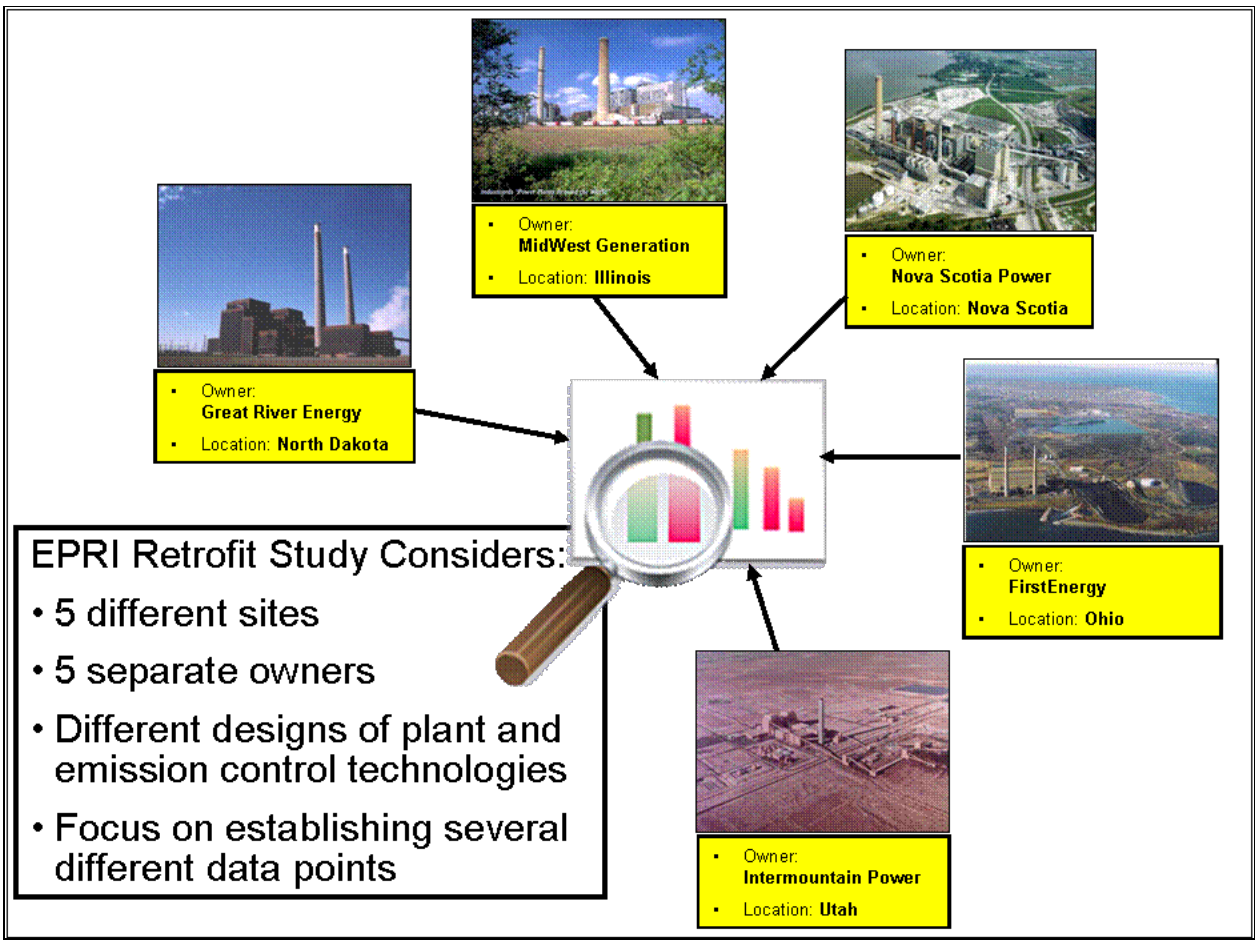


Figure 3
Host Sites for EPRI Retrofit Study

Each site offers a unique combination of unit sizes and ages, existing and planned emissions controls, fuel types, steam conditions, boilers, turbines, cooling systems, and options for CO_2 storage. The data from these real-world studies will provide insight into generalized cost and performance impact estimates for a variety of plant configurations. Specifically, the five studies will:

- Assess the most practical CO_2 capture efficiency configuration based on site constraints
- Determine the space required for the CO_2 capture technology and the interfaces with existing systems
- Estimate performance and costs for the post-combustion CO_2 capture and compression plants
- Assess the features of each plant that materially affect the cost and feasibility of the retrofit

CCS Retrofit Economics: An Illustrative Example

Prior to having any detailed cost information from the five-plant retrofit study, EPRI estimated CO_2 capture retrofit costs for a hypothetical 600 MW PC plant, including compression, transportation, sequestration, and monitoring, for 3.32 million metric tons per year of CO_2:

- Capital cost for adding CO_2 capture and compression equipment = $540 million (in third-quarter 2007 dollars), or $66 million per year if financed
- CO_2 transportation, measurement, and monitoring for 20 years at $10/metric ton (levelized value) = $33 million per year
- If the plant's capital cost has been recovered (i.e., there is no capital carrying charge for the power plant itself), a representative levelized cost-of-electricity value is $20/MWh. [Thus, "breakeven" annual revenue (levelized basis) for operation at an 80% capacity factor is $84 million.]
- As noted above, the levelized annual incremental cost for CCS (including capture plant capital recovery) = $99 million per year
- The new "with CCS" breakeven revenue requirement = $183 million
- Assuming the CCS retrofit reduces net plant output to 425 MW, the breakeven levelized cost-of-electricity value = $61/MWh [This is on par with the levelized cost-of-electricity for new PC plants without CCS in the high capital cost era of 2007–08.]
- If the plant were obligated to purchase replacement power for the 175 MW of lost output, assuming the purchase was from a new PC plant with CCS at a levelized cost of $110/MWh, the breakeven requirement for 600 MW of output with CCS rises to $75/MWh

Without a significant reduction in the forecast total capital requirements for new coal power plants (combustion- or gasification-based), CCS retrofits are likely to be competitive in situations where policies assure their dispatch in baseload mode. Such policies will be crucial in "transitional markets" because the dispatch cost basis ($/MWh) for plants with CCS will rise significantly, and if competing openly in regional transmission organizations with units without CCS (before CO_2 emission allowance markets have matured or carbon tax levels have reached their necessary longer-term value), plants retrofit with CCS may not be dispatched enough to recover incremental CCS costs efficiently.

Of course, EPRI, the power industry, and DOE are also actively working to reduce the capital and levelized costs of new advanced coal power systems with CCS, but in the interim, it appears likely that CCS retrofits will play an important role in early commercial CCS applications.

Reducing the Cost and Energy Penalties for CO_2 Capture and Compression

EPRI sees a tremendous opportunity to improve the economics of post-combustion CO_2 capture systems, both for new plants and retrofits, through RD&D-supported technical advances in the following areas:

- Improved solvent systems—modifications to the chemical properties of the sorbents, as well as the physical structure of the absorber and regenerator equipment to improve gas-liquid contact and/or heat transfer. [Note: EPRI also monitors and evaluates developmental progress for a wide variety of novel CO_2 capture technologies, including alternative solvents, membranes and catalysts, biological processes, and others. Such systems may ultimately make important contributions in reducing the energy penalties for CO_2 capture and possibly even in altering the form of the CO_2 product stream to simplify long-term storage, but these are generally expected to not reach commercial maturity within the "early commercial CCS application" timeframe that is currently the focus of many CCS retrofit studies and policy discussions.]
- Heat integration—optimizing thermal integration both within the CO_2 capture plant and between the CO_2 capture equipment and the power plant steam turbine and balance-of-plant systems
- CO_2 compression—with current technology, applied in a non-integrated manner, compression of the CO_2 imposes a major parasitic load on a PC plant and the compression equipment itself can be very expensive

CO_2 Capture and Compression Heat Integration and Optimization Studies

To help quantify the capital and O&M costs and benefits of proposed process optimizations for amine-based post-combustion capture processes, EPRI established a "reference" post-combustion CO_2 capture plant. The plant consists of an absorption-regeneration process unit using a monoethanol amine (MEA) solvent along with two-stage CO_2 compression. The reference CO_2 capture plant incorporates modest design improvements identified by EPRI since the initial engineering-economic studies conducted with the U.S. Department of Energy (DOE) in the 2000 timeframe, however is not a "highly optimized" design because its primary purpose is to serve as an economic base-case for evaluation of proposed design modifications.

EPRI examined eight proposed modifications to a standard flow sheet that had been suggested as heat and mass optimization opportunities. Of the eight proposed, four proved to be potentially cost-effective, two were marginal, and two were not cost-effective. Although the study's engineering-economic model was based on nominal 90% CO_2 capture from a new "ultra-supercritical" (USC) PC plant (750 MW, 4200 psia/1110ºF/1150ºF), many of the options examined could equally be applied to a retrofit design at sites with adequate available space.

To be deemed economically feasible, a modification had to have a positive net present value for capital plus 7 years of O&M costs relative to the base-case design. Other complex real-world factors, such as the impact of a modification on plant availability, were not included in the analysis.

The four potentially cost-effective improvements were:

- Using a high concentration amine solvent solution (if suitable corrosion inhibitors are available)
- “Split flow” regenerated solvent return (lean and semi-lean) to the CO_2 absorber
- Flashing of reboiler condensate and feeding it to the CO_2 stripper
- Solvent reboiling with heat from the CO_2 compressor discharge.

The next phase of work in EPRI’s post-combustion CO_2 capture and compression heat integration and optimization studies will examine integration options with the USC PC plant (the eight modifications previously examined were integration options *within* the CO_2 capture and compression systems). Evaluators will model both an optimized MEA-based post-combustion capture system and an MHI KS-1 (sterically hindered amine) system retrofitted to the same state-of-the-art (1100°F series) PC plant. Relative technical and economic comparisons of the two designs will be made. Although results will be most relevant to the design of new USC PC plants, findings are expected to also suggest economic approaches to retrofit post-combustion CO_2 capture to older units with lower steam conditions and poorer emissions control equipment. Plant integration approaches being considered for this phase of the study include:

- Heat recovery from the capture plant’s condensate return to heat feedwater, thereby reducing the effect on the low-pressure power turbine (i.e., net steam loss) of steam extraction for solvent regeneration (see Figure 4)
- Heat recovery from the CO_2 compressors and intercoolers to heat feedwater, thereby reducing the effect on the low-pressure power turbine (i.e., net steam loss) of steam extraction for solvent regeneration (see Figure 4)
- Cooling system optimization to minimize the need for additional cooling tower cells and additional water consumption as a result of capture and compression equipment
- The use of steam turbine drives for the CO_2 compressors rather than motor drives—this approach may be beneficial if electrical distribution infrastructure is limited and steam loss from the low-pressure power turbine can be accommodated
- “House power” transformer and high-voltage power distribution integration options, use of excess capacity in existing motor control centers, etc.
- Layout optimization to minimize hot piping lengths and pressure drops on all equipment

  As with the eight candidate capture system integration options, this set of plant integration options is not considered by EPRI to be a definitive set of alternatives, but rather an initial set useful for understanding the types of optimization measures likely to prove cost-effective.

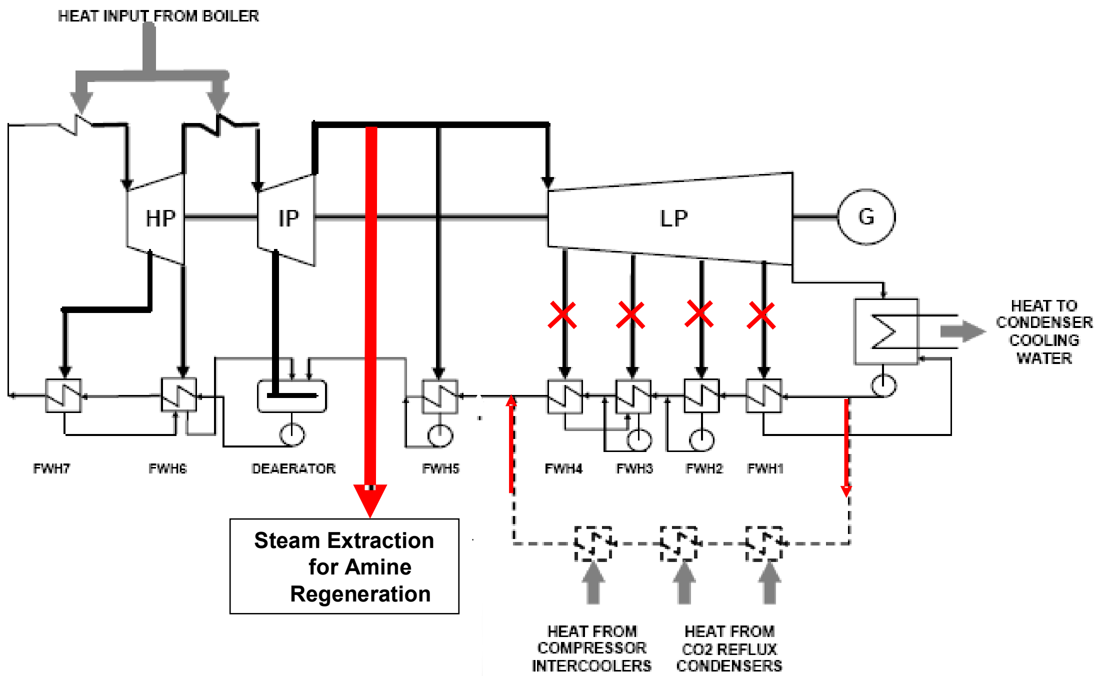


Figure 4
Example Heat Integration Opportunity—Feedwater Heating by Heat Recovery from CO_2 Capture and Compression Equipment to Offset Steam (Power) Loss in the Low-Pressure Turbine (adapted from diagram by Imperial College London)

Influence of Regulatory Structures on CO_2 Capture System Design Optimization

Regulatory rules on the operation of CO_2 capture equipment—especially whether it will be permissible to turn off the capture equipment during periods of peak power demand to maximize MW output (presuming annual CO_2 caps are still met)—could have a significant influence on optimal capture system design. EPRI is examining the design ramifications of this issue, namely the ability to provide operating flexibility in the combined power plant and capture plant system, from both a "societal value" economics perspective and an engineering options perspective. As with the aforementioned heat and mass integration optimization studies, such analyses are not specific to CCS retrofits—indeed, retrofits usually offer fewer design options than new plants—but many conclusions are equally applicable to retrofit applications.

Initial results confirm expectations that the greatest technical challenges lay in areas where mass and energy flows change the most between without-capture and with capture operation—the low-pressure steam turbine and the condensate and cooing systems. One possibility being investigated by Imperial College London is clutchable low-pressure turbines (i.e., the ability to turn on/off flow to one turbine in a two-turbine configuration.

Even in situations where regulators may not allow flue gas to routinely be emitted untreated, EPRI is examining alternate approaches that allow temporary boosts in maximum power output, such as solvent storage vessels (during peak periods, the reboiler would shut down and the stripper bypassed; stored lean solvent would be fed to the absorber and rich solvent would be stored for later regeneration).

EPRI Collaborative Demonstrations for Scale-Up of CCS Technologies

EPRI is teaming with industry partners and, in some cases, governmental organizations to conduct several pilot-scale and pre-commercial-scale CO_2 capture and storage demonstration projects. These projects provide real-world validation of technology performance and added insight into CO_2 capture and compression design optimization approaches for both new plant and retrofit applications. Current projects include:

- With thirty-some other power companies, EPRI is managing/monitoring the test program for Alstom's 1.7 MW_e equivalent CO_2 capture pilot using a "chilled ammonia" solvent at We Energies' Pleasant Prairie Power Plant in southeast Wisconsin. As of early 2009, thorough commissioning of the system had taken place, with testing to begin in earnest by mid-2009.
- Two larger demonstrations will retrofit CO_2 capture units to treat slipstreams of flue gas from PC plants; the projects will compress and inject the captured CO_2 into underlying geologic storage reservoirs ("saline formations"), thus making them truly integrated CCS projects:
  - Drawing upon experience gained at the Pleasant Prairie pilot, Alstom and American Electric Power (AEP) are building a 20 MW_e equivalent chilled ammonia "product validation facility" at AEP's Mountaineer generating station along the Ohio River in West Virginia. A deep well (to strata suitable for CO_2 storage) had been drilled at the site as part of an earlier DOE project; a second CO_2 injection well was drilled in early 2009. Alstom will operate the capture plant for a year, and AEP will operate it for up to four additional years. Capture and storage of about 100,000 tons of CO_2 annually is expected.
  - In an analogous project, Southern Company will install and operate a CO_2 capture demonstration unit based on an advanced amine process at one of its plants in the Gulf Coast region. It plans to operate the unit for four years. The CO_2 injection and plume monitoring operations will be managed by EPRI as part of DOE's Southeast Regional Carbon Sequestration Partnership project. Storage will take place in a large deep saline formation prevalent throughout the area. EPRI will also monitor and report on performance of the capture plant over the course of the project. Capture and storage of about 150,000 tons of CO_2 annually is expected.

    Southern Company also intends to use the project to validate improved equipment designs, including a rectangular absorber, structured packing (to provide necessary gas-liquid contact in a more compact zone), continuous filtration, an absorber-top solvent recovery system, and heat integration measures.

EPRI Results Help Shape the Future

Collectively, EPRI's CCS retrofit studies, CCS integration optimization studies, CCS operating flexibility analyses, and *integrated* post-combustion capture, CO_2 injection, and plume monitoring demonstration projects represent the type of accelerated real-world RD&D that is urgently needed to ensure that CCS technologies can be applied to coal-fired power plants—whether new or existing—in the requisite numbers to achieve the PRISM-forecast reductions in electricity-related CO_2 emissions.

The examination of CCS retrofit opportunities should not detract from companion RD&D to boost the efficiency of new and existing coal-based plants (e.g., advanced high-temperature materials for new plants; heat recovery opportunities for existing plants) because higher power block efficiencies help reduce the required size (and hence the cost and energy penalty) of CO_2 capture and compression equipment.

In conjunction with other elements in the PRISM's *full portfolio*, RD&D on CCS retrofits will help ensure that the electric power sector continues to meet society's demand for affordable, reliable, environmentally responsible electricity.