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Status and analysis of next generation post-combustion CO$_2$ capture technologies

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Abstract

Post-combustion CO$_2$ capture technologies tested above ~20 MWe on flue gas slip streams from coal-fired power plants are thus far exclusively aqueous solutions of amines or ammonia. These near-term technologies, when combined with compression to pipeline pressures, impose a ~25-30% load on a coal-fired power plant and nearly double the cost of electricity. Much of this increase is due to the relatively low CO$_2$ concentration and ambient conditions of flue gas, which poses an inherently difficult separation. Nonetheless, this relatively high energy and monetary cost provides an incentive for the development of next generation lower-energy and lower-cost capture processes. Since 2006, the Electric Power Research Institute (EPRI) has had an active program to review and conduct due diligence on emerging post-combustion CO$_2$ capture technologies. Using this knowledgebase, we critically review and analyze the status of the broad spectrum of next generation technologies, including solvents, adsorbents, membranes, and other capture processes. This effort spans some 125 post-combustion capture technologies and is part of EPRI's on-going effort to understand the landscape of CO$_2$ capture technologies, to identify research gaps, and to accelerate relevant research fields. We use the taxonomy of technology readiness level (TRL) to rank and classify the landscape of CO$_2$ capture technologies. We provide overview results of this ranking exercise and show how the findings will be used by EPRI and the utility industry to better identify opportunities to accelerate the development cycle and to anticipate the timing of major pilots and eventual commercial offerings. This analysis also leads us to several important insights, especially for capture technologies applied at power plant scales.

Keywords: Carbon Capture, Technology Readiness Level, TRL, Overview, Status, Post-Combustion

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1. Introduction

The need to improve and deploy CO_2 capture technology stems primarily from the need to reduce the approximately 25-30% parasitic load and 60-90% cost of electricity increase (COE) of near-term carbon capture and storage (CCS) technologies when applied to coal-fired power plants [1,2]. These near-term technologies mainly use aqueous solutions of amines or ammonia whose performance has been tested in small pilot units on coal-fired power plants. CCS is widely believed to be an important tool in helping to reduce CO_2 emissions from anthropogenic sources. Despite this view, there is a clear lack of progress at the pilot and larger scales in the past few years, largely resulting from the global economic downturn as well as the lack of progress on regulations to control greenhouse gas emissions. In the United States, the Environmental Protection Agency (EPA) has proposed rules for limiting CO_2 emissions for new fossil-fired power plants (as low as 454 kg CO_2/gross MWh or 1,000 lb CO_2/gross MWh) [3]. New natural gas combined cycle power plants can already meet the proposed emissions targets without adding CO_2 capture, and EPRI projects that under low-natural gas prices currently prevalent in the U.S., partial capture on coal-fired power plants using conventional CCS technologies are uneconomical without subsidy for CO_2 capture including sales of CO_2 for enhanced oil recovery [1,4,5]. Additionally, at least in the U.S., the price of natural gas is near historic lows and given the environmental pressures on coal-fired units, there is a shift towards using increasing amounts natural gas instead of coal for power production. This shift is significant, because CO_2 emissions from natural gas-fired power plants are about one-half that of coal-fired power plants, thereby reducing the net emissions from the power sector. Indeed, the United States has reduced its CO_2 emissions mostly due to the shift to natural gas in power production [6]. Because of these factors, the urgency for CCS on power plants from recent years has abated significantly. We note, however, that under most regulatory scenarios being considered, CCS will also eventually be required on natural gas-fired power plants, but there is almost no research being conducted on natural gas CCS. It is reasonable to expect that the technologies that capture CO_2 from coal-fired power plants could also be applied to natural-gas fired power plants, but the efficiencies, performance, and costs have only been explored at a high level.

2. Post-Combustion Capture Status

For later-stage projects, the Global CCS Institute reports that the total number of projects is 60 [7]. Many of these large projects often announcements, pre-FEED, or FEED studies, not projects with actual operational units, and are exclusively solvents, with less than a handful for power plants. The largest post-combustion capture project on a power plant is a 110 MWe capture process at the Boundary Dam Power Plant located in Saskatchewan, Canada, expected to begin commercial operation later this year.

For earlier-stage projects, research and development in capture has slowed over the past 3-4 years. Earlier stage technologies continue to exhibit a serial development pathway with discovery of novel chemistry, process engineering, and application to power plants following one another in lockstep. We believe such a serial approach is slow, often requires backtracking on the developing cycle, and can be ultimately more expensive. A more synergistic approach will be needed to develop breakthrough technologies and must involve close technical collaboration between chemists, process engineers, and power plant personnel to develop new capture chemistry used in a process that is well-integrated into a power plant [8,9]. We believe such an approach is the best option to developing breakthrough technologies, but with few notable exceptions, we do not observe many research groups acting in such a fashion. As a result, progress has been incremental for the known set of technologies with less than a handful of notable new technologies. Some adsorption and membrane technologies are currently being scaled up from lab and bench to small pilots in the ~1 MWe range in the U.S. [10,11]. In addition, a ~10 MWe adsorbent pilot is under construction in South Korea [12]. Results from these alternate technologies are anticipated in 2015-16.

Over the past 8 years, EPRI has analyzed over 125 post-combustion capture technologies, from early-stage concepts to late-stage processes. Our analysis was based on understanding the underlying principles of the technology, its chemistry as well as heat and mass balances, sometimes under non-disclosure agreements if required. We conducted such analysis to determine if we can appropriately accelerate promising technologies. As an overview, we also assigned a TRL value to each process we investigate as characterized in Table 1 [13]. In most cases, the determining the TRL is relatively straightforward since information was available publically or the developer would provide us

sufficient information. In some cases, the developer's current activities would straddle two TRLs in which case we assign the lower TRL.

Table 1. Technology Readiness Level. A capture process is assigned a TRL ranking according to the typical characteristics shown.

TRL	Typical Size	Typical Characteristics
1	Analysis on paper or small lab	**First Idea: Basic principles observed and reported** • Observation of material properties or other physical/chemical phenomena • Scientific research begins to be translated into applied research and development • Cost: Very low "unique" cost. Investment or cost is borne by scientific research programs or individual inventor.
2	Paper analysis or small lab	**Preliminary Design: Initial concept and/or application formulated** • Practical applications of basic physical principles are "invented" or identified. • Generalizations assumed for physical/chemical data not readily available. • Primarily an analytical step rather than a laboratory step. • Cost: Very low "unique" cost. Investment or cost is borne by scientific research programs.
3	Lab Tests	**Analytical and experimental critical function and/or characteristic proof-of-concept** • Initiation of active R&D for the specific application. • Detailed analytical studies to design the application and predict its performance. • Laboratory studies that physically verify the engineering/scientific assumptions of the analytical studies. • "Proof of Concept" stage • Cost: Low "unique" cost that is technology specific, e.g., $1 million
4	Bench-Scale Synthetic Gas	**Component validation in laboratory environment** • Component level assemblies are assembled from available "pieces" as a functional unit in a laboratory setting. • Test assemblies should be generally consistent with the eventual system but are relatively "low-fidelity". • Cost: Low to moderate "unique" cost, e.g., $3 million. Investment cost will be technology dependent, but probably several factors greater than cost to achieve TRL 3.
5	Bench-Scale Actual Flue Gas	**Component Validation: demonstration in a relevant environment** • Component level assemblies are designed and function independently as a unit. • Relevant environments are likely to be a laboratory or a small pilot plant that simulate operational environments. • One to several component technologies might be involved in the demonstration. • Cost: Moderate "unique" cost, e.g., $3 million. Investment cost will be technology dependent, but likely to be several factors greater than cost to achieve TRL 4.
6	~1 MWe Slipstream	**Integrated Demonstration: Prototype components in a relevant environment** • Prototype components are those whose designed and function essentially the same as expected for full scale deployment. • Full system integration is not required at this stage. • Relevant environments may include field power plant settings, or smaller pilot/test plant installations. • This maturation step is driven more by assuring management confidence than by R&D requirements. • Cost: Technology and demonstration specific but typically ~$20 million, a fraction of TRL 7 costs.

Table 1 - cont'd. Technology Readiness Level. A capture process is assigned a TRL ranking according to the typical characteristics shown.

TRL	Typical Size	Typical Characteristics
7	~25 MWe Slipstream	**Sub-scale Demonstration: Fully functional prototype in an operational environment.** • A fully functional prototype whose size/capacity more than ~5% of the capacity required for full scale implementation. • Include all components or unit processes expected at full scale. • Be deployed as an adjunct to an operating power plant. • Deploy an operations/control system of a scope comparable to full scale implementation of the technology. • Cost: Technology and demonstration specific but typically ~$150 million, a fraction of TRL 8 costs.
8	~150 MWe	**Full-scale Demonstration: Technology in its final form and under expected conditions.** • Demonstration size/capacity more than ~25% of the capacity required for full scale implementation. • Performance guarantees supportable by TRL 7 experience – capacity, material use/production, and energy use/production. • Cost: Technology specific but may be the highest cost for the technology deployment due to diseconomies of (smaller) scale and "first of a kind" costs, e.g., approaching $1 billion
9	~500 MWe	**Commercially Available: Deployment of the technology in its final form in normal commercial service** • Normal commercial service as characterized by full size/capacity • Enforceable performance guarantees – capacity, material use/production, and energy use/production. • Standard industry warrantees • Cost: Technology and capacity specific, often projected $1+ billion

We assigned a TRL value to each of the 125 post-combustion technologies investigated. All TRL levels were updated as of mid-2014. In general, there is limited access to technologies ranked TRL 1 since many are not yet focused on carbon capture *per se*, unless there's a specific attempt at doing so. These earliest stages of development may still be focused on basic science and understanding of new observations or insights. Often, they are also proprietary without any public information available. TRL 2 technologies start to have some focus on carbon capture, perhaps limited to calculations and a preliminary process concept. Like TRL 1 technologies, TRL 2 technologies generally have not progressed sufficiently to make information public. Hence, we do not report any TRL 1 technologies and very few in TRL 2, though we recognize there is ample early-stage concepts being developed at TRL 1 and 2 that could potentially be used for carbon capture.

Of the 125 processes investigated, absorption comprised 53 or about 43%, adsorption comprised 29 or about 23%, membranes comprised 18 or about 14%, with others such as mineralization and cryogenic comprised 25 or about 20%. The dominance of solvents is due to the fact that absorption is more widely practiced in the chemical process industries and has practical advantages at large scales. Unless radically different capture chemistries are investigated, only incremental advances in absorption solvents and processes are likely to continue. Adsorption and membrane technologies both require process development along with material development, and will require more development than absorption. Relative to our earlier studies [8,9,13], we observe increasing exploration of non-solvent technologies at earlier TRLs while the later TRL technologies continue to be solvent based.

Note that TRL is explicitly based on technical and performance criteria only, not an economic criterion. For carbon capture on power plants, however, scaling a technology to higher and higher TRLs incurs significant cost, often in the

billions of dollars at the highest TRLs. Hence it's reasonable to expect that the higher TRL technologies are also the most economic ones for that particular project.
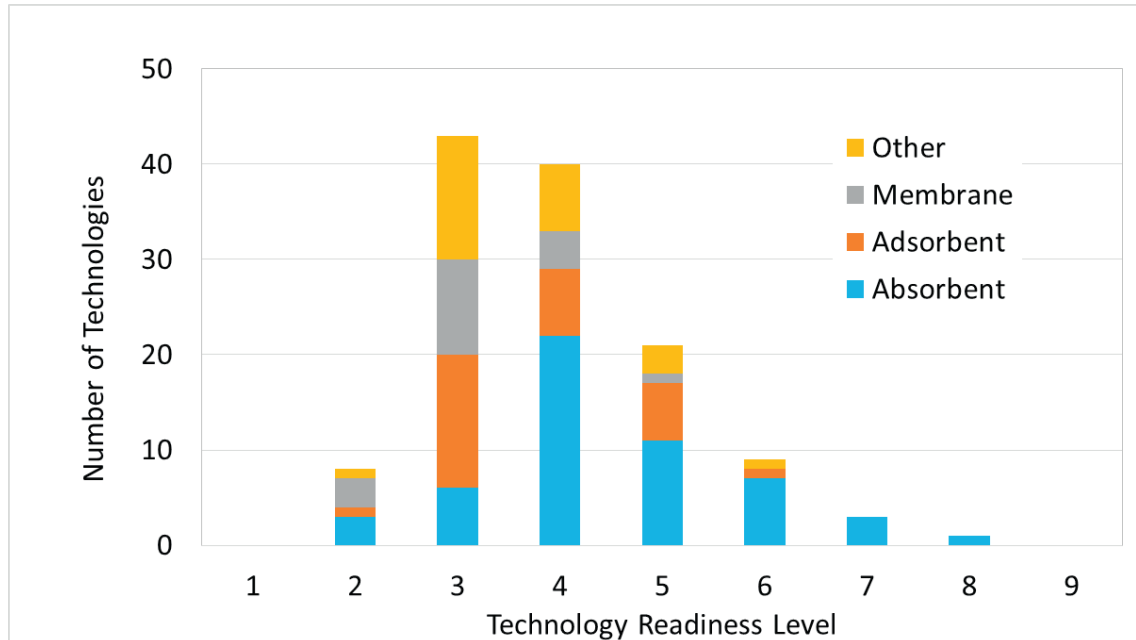

Figure 1. TRL Histogram of Post-Combustion Technologies. While most post-combustion technologies are absorption-based, an increasing number of early-stage technologies are not.

2.1. Absorption (Solvents)

Absorption processes are common in the chemical process industries, and there is significant commercial experience with their operation. This stems from the fact that absorption processes are generally less expensive for large-scale separations, easier to operate, and more robust than other processes. Additionally, compared to solids, solvents offer more opportunities to exploit chemical differences in components of a mixture in order to separate them. As a result, all of the more-developed CO_2 capture processes are solvent based.

In conventional solvents, the existing approach of reacting the acidic CO_2 with a basic nitrogen atom in aqueous solutions of amines, ammonia, and amino acids has largely continued. Process developers rarely disclose their specific chemistry, but most will identify the class of chemistry, e.g., primary amines, secondary amines, blends, etc. Though these chemistries have been widely studied already and keep advancing, they offer only incremental gains over each other. Additional incremental gains are offered by improvements in process design. Like improvements in the chemistry of the solvent, these process improvements also tend to be proprietary. Still, because of widespread use of absorption processes, even incremental advances are commercially significant.

Other solvents include non-aqueous ones such as ionic liquids or phase separation materials. They offer a potential advantage of reduced regeneration energy and are being developed at largely academic institutions or at small companies. The major challenges include little operational data of such systems at large scales (even in other industries), their potential cost, and a longer time needed to achieve commercial scale. There are vast numbers of such chemistries possible, as in the case of ionic liquids, and the challenge is often finding which subset to focus on. Water in flue gas can also sometimes reduce the performance of such non-aqueous solvents. Other challenges include high viscosity, slower kinetics, and potential high cost; overcoming these challenges is an ongoing research activity.

Remaining approaches to absorption, which have a longer path to commercialization, involve changing the absorption chemistry itself or using promoters (catalysts) to enhance the rate of absorption. One particular use of a promoter under development is the use of carbonic anhydrase as a catalyst to increase the kinetics of aqueous CO_2

reactions. All of these remaining approaches also aim to reduce the energy of regeneration, while some offer the additional advantage of potentially reducing the gas-liquid contactor volume.

2.2. Adsorption (Solids)

Adsorption is less commonly practiced in the chemical process industry. Because adsorption can be used in different process configurations, both adsorbent properties and process design can strongly influence the effectiveness of a separation. Consequently, developing adsorption processes for very large-scale CO_2 capture requires development of both adsorbent materials and corresponding processes. As was the case with ionic liquids in solvents, other types of materials are also being investigated at early stages for adsorbents.

Adsorbents being developed for CO_2 capture exhibit a variety of origins, characteristics, and chemistries. EPRI's own work has characterized a class of adsorbents in collaboration with University of California at Berkeley, Lawrence Berkeley National Labs, and Rice University [14]. Based on this work, we have identified several thousand potential new zeolites, zeolitic imidazolate frameworks, porous polymer networks, and metal organic frameworks that could lower the energy consumption of CO_2 capture.

Additional advances are being made in process design, and these could have as much impactas advances in novel materials. Virtually all of these process improvements are considered proprietary. Like absorption, a combination of materials and process improvements combined with close integration with a power plant is going to be needed to significantly advance adsorption technology. Unlike absorption, however, adsorption is not as widely used in chemical process industries at large scales and therefore large-scale operations may present additional challenges.

2.3. Membranes

Industrial-scale membrane separation processes are much less common than either absorption or adsorption. With few exceptions, such as reverse osmosis for desalination, large-scale membranes are not commonly used in the chemical process industries. For gas separations, only one utility-scale equivalent commercial membrane facility is operational: a UOP (Separex) membrane system that removes CO_2 from natural gas with a gas flow rate equivalent to the flue gas flow rate from a 450-MWe power plant [15]. Though this polymer is not suitable for separating CO_2 from flue gas, it does show that the general scale of existing membranes is within the range required for coal-fired power plants.

Membrane technologies advanced in the past two years for CO_2 capture. Examples include gelled ionic liquids, facilitated transport membranes, and hollow fibers designed specifically for use in gas-liquid contactors. These are not new technologies, but in general, they do represent continued progress in membrane research for CO_2 capture relative to previous years. Additional activity can be seen in process development with membranes. However, like absorbents and adsorbents, much of the membrane materials development and process development are proprietary.

Coal-fired power plants present some unique challenges for membranes. One challenge is that particulate matter can deposit on the membrane surface, decreasing its permeability or damaging it over time [16]. Another issue is that membranes deployed at utility-scales will likely be modular, using tens of thousands of membrane modules arranged in an array that distributes flue gas through the networked array. These types of challenges have not yet been addressed by membrane developers since they have not yet reached any meaningful scale. The DOE-NETL has funded membrane projects that will address these issues in 2014-15 at the National Carbon Capture Center.

2.4. Other

Technologies such as mineralization and cryogenic separation are far less common and in earlier stages of development relative to the scale required for power sector. Mineralization schemes can be energy intensive or otherwise rely on the supply of other chemicals that may inherently limit their wide-scale deployment [8,9]. Cryogenic processes can also be energy intensive, but offer potential for energy savings at the cost of increasing hardware costs. Remaining processes such as biological approaches or CO_2 utilization schemes have significant hurdles in wide-scale deployment due to scale of CO_2 emissions [9].

3. Research Pathway

The timeline for capture development can vary widely, determined primarily by funding, market, and regulatory drivers. In general technologies ranked TRL 1 are not yet focused on carbon capture itself, unless there's a specific attempt at doing so. These earliest stages of development may still be focused on basic science and understanding of new observations or insights. TRL 2 technologies start to have some limited focus on carbon capture, perhaps limited to calculations and a preliminary process concept. These early stages of research can sometimes take decades and thus need guidance from the start if they are going to be focused on carbon capture. However, these earliest stages of research are where breakthrough capture technologies are likely to emerge. We continue to believe that the emergence of breakthrough technologies will require close interdisciplinary collaboration between chemists who can synthesize appropriate separation materials, process engineers who can design processes using those materials, and power plant engineers who can integrate the process into the power plant [8, 9]. In the current landscape of CO_2 capture technology development, these groups work largely independent of each other.

Figure 2 shows an example development timeline based on observations made by us and others of solvents, adsorption, and membranes being developed for post-combustion carbon capture [10,11,17]. These timelines assume well-guided and well-funded R&D from the earliest stages of capture chemistry and process development. Given that our observations are necessarily for first-of-a-kind process, these timelines are likely to considerably shorten as carbon capture is increasingly deployed at each TRL. Test centers such as the U.S. DOE NETL National Carbon Capture Center facilitate such acceleration by testing and deploying many different technologies at between TRL 4-6, and help shorten the timeline. Nonetheless, a new concept from early stages to commercial stages at power plant scales is likely to take ~20 years on a well-funded and well-guided project pathway.
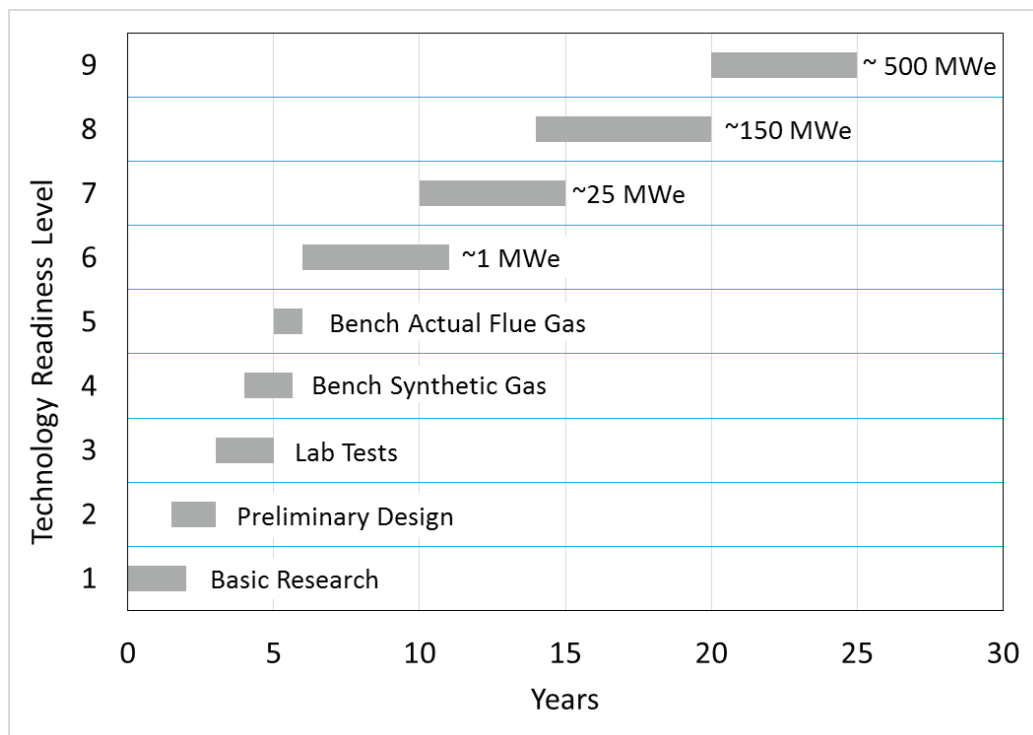

Figure 2. Timeline for Development of Post-Combustion Capture Processes. Basic research to commercial deployment at utility scales is likely to take ~20 years.

4. Summary

Knowledge and insights gained in this oversight effort form much of the basis for EPRI's post-combustion CO_2 capture R&D program. We use these insights to identify gaps, conduct internal and external research to fill those gaps, and guide the broader research community to focus research in a particular direction. Since 2006, EPRI participated in over 30 projects on post-combustion CO_2 capture spanning TRL 1-7 and involving absorption, adsorption, membrane, and other technologies. Results from the projects are distributed through reports issued by EPRI or its project collaborators.

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