

A JOINT PROJECT OF CSPO AND CATF

Made Possible Through the Support of the  
Bipartisan Policy Center's National Commission on Energy Policy

March 2009

# Energy Innovation From the Bottom Up

WORKSHOP BACKGROUND PAPER: PHOTOVOLTAICS

BY JOHN ALIC



The Consortium for Science, Policy, and Outcomes  
Arizona State University  
1701 K Street, NW  
Washington, DC 20006  
[www.cspo.org](http://www.cspo.org)



Clean Air Task Force  
18 Tremont Street  
Boston, MA 02108  
[www.catf.us](http://www.catf.us)

# Photovoltaics

Background Paper for March 13, 2009 Workshop | by John Alic

More than 250 companies worldwide make or sell solar photovoltaic (PV) cells or assemblies, which convert sunlight directly into electricity. One in ten of these companies manufactures in the United States. Production has been growing at double-digit rates worldwide since the 1970s, albeit from a small base, and global sales in 2007 totaled \$17 billion, about 10 percent in the United States. Production and sales take place in open, competitive markets. At the same time, these markets, like essentially all energy markets in the United States and elsewhere, have been shaped by government poli-

cies. Germany, in cloudy northern Europe but with lucrative government financial incentives, accounted for nearly half of 2007 world sales. In the United States, manufacturers and investors complain about the risks caused by policy instability since the twin energy shocks of the 1970s (Table PV-1), pointing out that when incentives come and go unpredictably long-term planning becomes a guessing game.<sup>1</sup>

PV cells are fabricated from semiconducting materials such as silicon, as are transistors and integrated circuits (ICs). While the

**Table PV-1. Selected Policy Incentives for PV Technology in the United States.**

- **R&D.** Since the late 1970s, PV-related federal R&D spending has totaled perhaps \$3 billion. In recent years most of the money has come from the Department of Energy, although the Defense Department, the National Science Foundation, and the National Aeronautics and Space Administration also fund PV R&D.
- **Procurement.** State governments and the federal government have sometimes appropriated funds for PV purchase and demonstration, including installations on non-government buildings.
- **Tax credits.** Federal tax credits for business PV purchases date from the Energy Tax Act of 1978 and, with some interruptions, have continued since (e.g., under the Energy Policy Act of 1992). For residential installations, federal tax credits have been as high as 40 percent (from late 1970s to 1985). The Emergency Economic Stabilization Act of 2008 set both business and residential investment credits at 30 percent. States have also provided solar energy tax credits (e.g., 25 percent in California during the 1980s).<sup>a</sup>
- **Loan programs.** In the 1980s, the Solar Bank provided low-interest loans for PV installations, as did some state programs. The 2005 Energy Policy Act authorized loan guarantees, but none have been extended.
- **Utility buyback requirements.** In place since passage of the 1978 Public Utility Regulatory Policies Act.

<sup>a</sup> The renewable energy electricity production tax credit (instituted in 1992 at 1.5 ¢/kilowatt-hour and now 2.1 ¢/kWh) has had essentially no impact on solar energy, since the credit applies only to electricity that is sold and since utilities or other taxpayers cannot claim both a production credit and an investment credit and the latter is usually more advantageous. For similar reasons, renewable portfolio standards, instituted by more than half the states since the mid-1990s, have provided little incentive for PV systems.

Sources: William M. Pegram, "The Photovoltaics Commercialization Program," *The Technology Pork Barrel*, Linda R. Cohen, et al. (Washington, DC: Brookings, 1991), pp. 321-363; *Renewable Energy: DOE's Funding and Markets for Wind Energy and Solar Cell Technologies*, GAO/RCED-99-130 (Washington, DC: General Accounting Office, May 1999); Fred Sissine, Lynn J. Cunningham, and Mark Gurevitz, *Energy Efficiency and Renewable Energy Legislation in the 110th Congress*, Report RL33831 (Washington, DC: Congressional Research Service, November 13, 2008); Fred Sissine, *Renewable Energy: Background and Issues for the 110th Congress*, Report RL34162 (Washington, DC: Congressional Research Service, December 10, 2008).

<sup>1</sup> For U.S. PV production figures, see "Solar Photovoltaic Cell/Module Manufacturing Activities 2007," Department of Energy, Energy Information Administration, Washington, DC, December 2008, <[www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv.pdf](http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv.pdf)>. PV output growth is often reported in terms of rated power, rather than revenues. Information on the world market, for manufacture, sales, and project expenditures (e.g., including installation costs and equipment such as inverters to convert direct to alternating current) is scattered and sometimes inconsistent. According Solarbuzz LLC, a market research firm, 2007 PV sales in Germany accounted for 47 percent of a world total of \$17.2 billion. "Marketbuzz™ 2008: Annual World Solar Photovoltaic Industry Report," March 17, 2008, <[www.solarbuzz.com](http://www.solarbuzz.com)>.

same basic physical principles govern both PV and microelectronics technologies, and the two industries began about the same time, microelectronics grew much more rapidly. Table PV-2 summarizes the reasons.



**Table PV-2. The PV Industry and Market Compared to Microelectronics.**

<b>ORIGINS</b>	Both industries date from the period of a decade or so following World War II. AT&T Bell Laboratories demonstrated the transistor in 1948 and the PV cell in 1954. ICs, which combine several transistors (now hundreds of millions) on a single chip, followed in late 1950s, commercialized by Texas Instruments and Fairchild Semiconductor.
<b>INITIAL DEMAND AND EARLY GROWTH</b>	Government procurement fueled early innovation in both industries, but IC demand grew faster to supply the Minuteman missile program and the Apollo project; by most accounts, these purchases, soon followed by other military programs, were a greater stimulus for innovations in microelectronics than R&D support.
<b>TECHNOLOGICAL COMPETITION AND VARIETY</b>	<p>The essential contrast between microelectronics and PVs is simple enough. While there are many types of PV cells, all perform the same basic function: conversion of light into electricity. As circuit components, semiconductor devices perform many different functions in both analog and digital circuits and firms began almost immediately to design and produce devices for different end markets. Sales to companies making transistor radios paved the way for sales to TV manufacturers at a time when sales of color TVs were exploding with the switch from black-and-white. Decades of swelling demand—for pocket and desktop calculators (some powered by PV cells), computers and peripherals of all types, and more recently for mobile telephony, MP3 players, and other essentially disposable products—fostered innovation and growth. Sometimes whole new end-product markets appeared almost overnight. Many or most of these would be quite impossible without inexpensive, high-density ICs. This is the primary reason why sales of semiconductor devices, now about \$250 billion annually (worldwide), grew so much faster than sales of PV devices and systems, which compete with other energy conversion more-or-less directly and often at a cost disadvantage (engine-driven generators for off-grid power, wind turbines and solar thermal for grid-connected applications).</p> <p>A further contrast stems from the physics of energy conversion. While IC chips will ultimately be limited by quantum mechanics, the ceiling has yet to be approached even as performance has improved by some nine orders of magnitude (e.g., as indicated by Moore's Law). For PVs, thermodynamics dictates that energy will be lost (as waste heat) in any conversion from sunlight to electricity: efficiency cannot reach or even approach 100 percent, and even in the laboratory has yet to reach half that level. Only in the earliest years of PV technology was an improvement by a single order-of-magnitude possible (and quickly achieved as efficiencies passed 10 percent). Nothing like the advances achieved with IC technology are even conceivable: the PV industry operates under fundamentally different constraints than microelectronics, even though each is built on knowledge foundations rooted in semiconductor physics.</p>
<b>INDUSTRY STRUCTURE</b>	Big companies, notably AT&T, owner of Bell Laboratories, made major contributions to early innovation in both industries. In microelectronics, large diversified firms were major forces into the 1970s and today IBM remains a rich source of IC technology. Other firms, such as Intel, began as startups (Intel as a spinoff from Fairchild, itself a spinoff from the firm established in 1956 by William Shockley, co-inventor of the transistor) and grew to become multinationals in their own right. Small firms (as also in biotechnology) have generated many PV innovations too, but most of those that have not been acquired remain small. In 2007, the two dozen companies making and selling PV cells or modules in the United States reported revenues totaling \$1.7 billion, about the level of U.S. microelectronics sales in 1975.

While sunlight is free and maintenance costs very low, PV systems themselves are expensive, largely because of the costs of materials and fabrication. (Table PV-3 describes the principal types of PV cells and systems.) The most efficient cell types (efficiency is simply the fraction of energy in incident light that is converted into electrical energy) remain prohibitively expensive except for specialized applications such as spacecraft power. Table PV-4 compares efficiencies for various cell types. Higher efficiency means less cell area is needed for a given output, but more efficient cells may cost many times more. Recent large improvements in the tradeoff between cost and efficiency for thin-film cells led to a doubling of sales from 2006 to 2007 as new production capacity came online.

The costs of the PV-generated electricity, like the prices utilities charge their customers, reflect government policies

and programs of many types. In effect, the United States has subsidized all forms of electric power. The federal government has built dams for hydroelectric power and subsidized nuclear electricity through R&D programs, the Price-Anderson Act's insurance provisions, and take-back arrangements for spent fuel. Coal reaches power plants over historically subsidized railway lines. Since PV-generated electricity is not sold, except through utility buy-backs, there is no price, and cost estimates necessarily reflect accounting assumptions (e.g., for depreciation and useful life, often taken to be around 30 years, and capacity factor, a function of available sunlight, hence geographic location). The market research firm Solarbuzz puts current costs in Sunbelt states at about 37 ½ cents per kilowatt-hour (kWh) for residential installations and slightly more than 21 ¢/kWh for industrial installations, well above utility

**Table PV-3. PV Technologies Summarized.**

**Crystalline** cells, which represent a declining but still dominant share of PV output, around four-fifths, are fabricated from specially grown single crystals of a semiconductor material, usually silicon. All atoms in these crystals share a common three-dimensional spatial orientation and their preparation, together with the raw material, accounts for most of the total cost of production. While these costs have declined at a rate of about 20 percent for each doubling of volume since commercial-scale production began in the 1970s, at some point the rate of improvement is bound to slow.

In **polycrystalline** cells, the orientation of atoms changes across grain boundaries. Although such cells are less costly to make, the boundaries disrupt current flow, to the detriment of efficiency.

**Amorphous** cells, of silicon or other semiconducting material (e.g., compounds such as cadmium telluride) have no grain boundaries to interfere with the flow of electricity, but, unlike in crystalline cells, the atoms are randomly arranged, again detracting from efficiency.

**Thin film** cells can be inexpensively fabricated by depositing amorphous layers through processes something like spraying or printing. They can also be made from **organic** semiconductors. Potentially inexpensive, organic thin films, to this point, have suffered rapid degradation with exposure to sunlight, whereas most other PV materials lose only a little performance as they age and have expected lifetimes of several decades.

**Stacked or layered** cells make use two or more materials sensitive to different portions of the solar spectrum. No known semiconductor captures more than a fraction of the relatively broad range of frequencies in sunlight; by passing that light sequentially through several materials, a greater fraction of the incident energy can be converted to electricity. At the current state of development, stacked cells cost one hundred to several hundred times more than single-layer cells and have found applications only in spacecraft.

While **optical concentration** by means of mirrors or lenses (typically fresnel lenses) reduces cell area for a given output, less efficient and more costly semiconductors may be needed to withstand the temperatures generated. The optics also raise non-cell costs.

Much research in recent years has explored devices tailored at very fine scale (e.g., through nanotechnology) to create arrays of localized features such as "quantum dots" or "quantum wells." In effect, these trap light, confining it for the conversion process. Such **heterostructures** promise high efficiency through capture of a greater percentage of the energy in sunlight, but so far they remain difficult and costly to fabricate even for laboratory experiments.

pricing, which has recently averaged about 10 ½ ¢/kWh for residential customers and 6 ½ ¢/kWh for industrial customers.<sup>2</sup> Since peak prices charged by utilities may be several times higher than these averages, PV investments can be attractive for some customers, especially since peak-load periods typically overlap periods of peak sunlight (e.g., in midday when air conditioning loads are high).

The cost-price gap has come down over the years, but high costs remain the primary reason why PV systems account for no more than around 0.05 percent of U.S. electricity output (and of course a smaller share of total energy consumption).<sup>3</sup> Standalone systems (sometimes in remote locations), unconnected to the grid, make up most of the existing capacity, although grid-connected installations have expanded rapidly over the past several years.<sup>4</sup>

Sunlight reaching Earth carries more than enough energy to supply almost any conceivable need. Yet even with quite high levels of PV efficiency, collecting and converting that energy on a large scale requires large areas and large investments (concentrators reduce the area but not necessarily the investment). The largest PV system built so far in the United States, completed in 2007 at Nellis Air Force Base, Nevada, has a rated capacity of 14 megawatts, occupies 140 acres, and cost an announced \$100 million.<sup>5</sup> By contrast, current-generation coal-fired plants are typically rated at 500 megawatts and above. Regardless of future cost declines and efficiency improvements, many more years will pass before PV installations could displace any very substantial amount of fossil fuel-burning generating capacity.<sup>6</sup> That will not happen without continuing technological advances. At the same time, there are many possible pathways for continuing innovation, as Tables PV-3 and PV-4 suggest, through advances in materials (e.g. compound and organic semiconductors), fabrication processes, and cell configurations (e.g., by means of microstructural and nanostructural engineering).

**Table PV-4. PV Efficiencies, ca. 2008.**

	PRODUCTION CELLS	LABORATORY RESEARCH
<b>Single crystal silicon</b>		24 percent
wafer	17 percent	
cast	14 percent	
ribbon	12 percent	
<b>Thin-film</b>		
silicon	8 percent	
cadmium telluride	12 percent	17-19 percent
organic (tandem)	< 6 percent	> 6 percent
<b>Stacked (multi-layer)</b>	~ 30 percent	> 40 percent
<b>Optical concentrator</b>	35 percent	~ 40 percent

Sources: Production cells - "Solar Photovoltaic Cell/Module Manufacturing Activities 2007," Department of Energy, Energy Information Administration, Washington, DC, December 2008, <[www.eia.doe.gov/cneaf/solar/renewables/page/solarreport/solarpv.pdf](http://www.eia.doe.gov/cneaf/solar/renewables/page/solarreport/solarpv.pdf)>, Table 3.8, p. 15; laboratory devices - Antonio Martí and Antonio Luque, *Next Generation Photovoltaics* (Bristol, UK: Institute of Physics, 2004); "Basic Research Needs for Solar Energy Utilization," Department of Energy, Office of Science, 2005, <[www.sc.doe.gov/bes/reports/files/SEU\\_rpt.pdf](http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf)>; Robert F. Service, "Can the Upstarts Top Silicon?" *Science*, Vol. 319, February 8, 2008, pp. 718-720; "Frontiers of Science Tackles Renewable Energy," *Salt Lake Tribune*, January 27, 2009. Efficiency benchmarks can also be found in several of the draft "solar technology roadmaps" prepared by the Energy Department in 2007 and available at <[www1.eere.energy.gov/solar/solar\\_america/planning.html](http://www1.eere.energy.gov/solar/solar_america/planning.html)>.

<sup>2</sup> Estimated costs for commercial PV installations (e.g., on office buildings) are intermediate. "Solar Electricity Prices," February 2009, <[www.solarbuzz.com](http://www.solarbuzz.com)>. Utility pricing from "Annual Energy Outlook 2009: Early Release Overview," Department of Energy, Energy Information Administration, Washington, DC, January 2009, <[www.eia.doe.gov/oiaf/aeo/index.html](http://www.eia.doe.gov/oiaf/aeo/index.html)>, Table A8.

<sup>3</sup> Estimated based on "Annual Energy Outlook 2009: Early Release Overview," Tables A8 and A16.

<sup>4</sup> In 2007 only about 50,000 utility customers were feeding excess self-generated power back to the grid for billing credits. Most of these customers were in California and most of the electricity came from PV systems. "Electric Power Industry 2007: Year in Review," Department of Energy, Energy Information Administration, Washington, DC, January 21, 2009, <[www.eia.doe.gov/cneaf/electricity/epa/epa\\_sum.html](http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html)>, p. 14.

<sup>5</sup> "Biggest U.S. Solar Panel Farms Open in Nevada, Colo," *Reuters*, December 18, 2007. The Colorado project, built for SunEdison, has a rated capacity of 8 megawatts.

<sup>6</sup> *International Energy Outlook 2008* (Washington, DC: Department of Energy, Energy Information Administration, September 2008), p. 49, forecasts an increase in China's coal-fired generating capacity from 299 gigawatts (GW) in 2005 to 735 GW in 2030. Taking a round number increase of 400 GW, this would correspond to a PV investment of roughly \$5 trillion at current pricing of about \$3 per peak-power watt (the \$1.2 trillion figure for equivalent peak power must be multiplied by around four times to account for variation in output with cloud cover and darkness; by contrast, modern coal-fired power plants exhibit availabilities, after allowances for scheduled maintenance and unexpected outages, of perhaps 85 percent).

A JOINT PROJECT OF CSPO AND CATF

Made Possible Through the Support of the  
Bipartisan Policy Center's National Commission on Energy Policy

April 2009

# Energy Innovation From the Bottom Up

WORKSHOP BACKGROUND PAPER: AIR CAPTURE  
BY JOHN ALIC



The Consortium for Science, Policy, and Outcomes  
Arizona State University  
1701 K Street, NW  
Washington, DC 20006  
[www.cspo.org](http://www.cspo.org)



Clean Air Task Force  
18 Tremont Street  
Boston, MA 02108  
[www.catf.us](http://www.catf.us)

# Direct Removal of Carbon Dioxide from the Atmosphere

Background Paper for April 17, 2009 Workshop | by John Alic



After fluctuating for centuries in the range of 280 parts per million (ppm), the global average concentration of carbon dioxide (CO<sub>2</sub>) in Earth's atmosphere has reached 385 ppm. Concentration is continuing to increase at about 0.6 percent annually and will likely exceed 500 ppm, or 0.05 percent, before mid-century.<sup>1</sup>

The consequences of rising levels of CO<sub>2</sub> on atmospheric behavior could be mitigated by some combination of three alternatives: (1) attempting to directly regulate Earth's temperature without regard to CO<sub>2</sub> and other greenhouse gases (GHGs), an approach often referred to as geoengineering; (2) reducing releases of CO<sub>2</sub> and other GHGs at their points of origin, which implies capture and sequestration of CO<sub>2</sub> from sources including coal-burning power plants, some 1500 of which produce nearly half of the nation's electricity and over one-third of its CO<sub>2</sub> emissions, or large-scale reduction in fossil fuel consumption, or both; (3) continuing to allow release of CO<sub>2</sub> from at least some sources while removing compensating tonnages from the atmosphere. Although the third alternative, "air capture," would almost certainly cost more on a per-ton basis than removal of CO<sub>2</sub> from power plant flue gases, it appears

to be the only practical means, other than fuel switching, of dealing with CO<sub>2</sub> emissions from small-scale sources, especially mobile sources such as road vehicles and aircraft. In some scenarios, then, air capture might be implemented in conjunction with post-combustion capture (PCC) of CO<sub>2</sub> from power plants.<sup>2</sup>

Although technological pathways for air capture have only begun to be explored, such pathways certainly exist: indeed, air capture, purely as a technology, is by all indications no more difficult than PCC, and in at least some respects would appear to be simpler. The essential difference is that much larger volumes of gas must be treated because of the low concentration of CO<sub>2</sub> in ambient air, 200 to 300 times less than in flue gases from coal-burning power plants, which means that very large tonnages of air must be treated to extract appreciable amounts of CO<sub>2</sub>, a constraint that appears likely to drive costs above those for PCC.

Most or all of the technical work on air capture has explored processes that make use of well-understood chemical reactions, such as those that occur when air is circulated through a mist or spray of water carrying dissolved sodium hydroxide. This takes up the CO<sub>2</sub> and, as in PCC systems, the solution can then be

<sup>1</sup> *International Energy Outlook 2008* (Washington, DC: Department of Energy, Energy Information Administration, September 2008), p. 90. Emissions of CO<sub>2</sub> are rising several times faster than concentration, at about 2.1 percent annually.

<sup>2</sup> For a brief introduction to air capture, see Nicola Jones, "Sucking Carbon Out of the Air," *Nature News*, December 17, 2008, < [www.nature.com/news/2008/081217/full/news.2008.1319.html](http://www.nature.com/news/2008/081217/full/news.2008.1319.html) >. Also Robert Kunzig and Wallace Broecker, "Clearing the Air," *New Scientist*, January 10, 2009, pp. 34-37. For technical treatments: Klaus S. Lackner, Patrick Grimes, and Hans-J. Ziock, "Capturing Carbon Dioxide from Air," First National Conference on Carbon Sequestration, Pittsburgh, PA, May 14-17, 2001, <[www.netl.doe.gov/publications/proceedings/01/carbon\\_seq/carbon\\_seq01.html](http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/carbon_seq01.html)>; Joshua K. Stolaroff, "Capturing CO<sub>2</sub> from Ambient Air: A Feasibility Assessment," Ph.D. thesis, Carnegie Mellon University, Pittsburgh, PA, 2006; and Joshua K. Stolaroff, David W. Keith, and Gregory V. Lowry, "Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spay," *Environmental Science and Technology*, Vol. 42, 2008, pp. 2728-2735.

renewed and the separated CO<sub>2</sub> compressed for sequestration. Sorbent regeneration and CO<sub>2</sub> compression would, again as for PCC, consume considerable energy. Unlike PCC installations, which would be built on the sites of power plants, air capture would impose no constraints on equipment size or location. Should one of the candidate technical approaches be implemented, standard units could be mass produced and sited so as to minimize system-wide operating costs. Possibilities include: atop geological formation suited to sequestration; near otherwise unusable supplies of energy that could be tapped for process heat (e.g., oil fields where natural gas is now flared for lack of market access); in windy areas, to take advantage of natural air circulation (rather than electrically powered fans).

In contrast to the industrial experience base for PCC, which is modest but provides a starting point, the only existing installations for removal of CO<sub>2</sub> from ambient air have been designed and built for environmental control in closed systems such as submarine hulls. Otherwise, work on air capture has been limited to feasibility studies, laboratory experiments, and small-scale rig tests, mostly conducted by university groups and small startup firms. So far, there has been little sign of interest by firms with substantial technical and financial resources and a knowledge base in analogous technological undertakings. Nor have government agencies, in the United States or abroad, conducted significant internal work or provided substantial external funding for technical and cost studies. As a result, cost and performance projections are highly uncertain compared even to those for PCC. (While detailed engineering studies by no means remove uncertainty concerning energy penalties and costs, they do narrow the range.) The questions, nonetheless, appear to have more to do with the conceptual design of alternative systems than with research (because, e.g., the chemistry for air capture is well understood, again as for PCC).

In principle, system designs might take any of a wide range of alternative configurations (e.g., for moving the air, for exposing it to the sorbent and regenerating the sorbent).

Engineering organizations routinely generate many such alternatives, evaluate them through calculations, modeling, and simulation, supported as necessary by experiment and testing, and choose the more attractive for more extensive analyses (e.g., to pin down key variables such as operating temperatures and rates of fluid flow and heat transfer). This work can be expensive and may take several years, the more so as the agenda moves on to field tests and, for consumer products, market trials, even though the usual objective is a satisfactory design, not some sort of optimum (which is generally impossible to define).<sup>3</sup> After product or system introduction, incremental development normally continues, based in part on feedback from service experience, as illustrated by improvements to sulfur dioxide scrubbers fitted to coal-burning power plants in the United States since the 1970s. For these scrubbers, equipment suppliers had acceptable designs in sight if not in hand when implementation began, and the technical agenda was largely one of improvement. For air capture, the process of converging on acceptable designs has not begun; indeed, the full range of alternative possibilities has yet to be explored. Thus a considerable period of technical exploration lies ahead, depending on policy decisions.

To the extent governments viewed air capture as a public works undertaking (rather than an energy-related technology), the customers for systems and equipment might include public agencies (perhaps including state or local bodies, such as those that carry out or oversee water treatment, waste collection and disposal), public-private partnerships, or private firms operating under government contract. Among the federal agencies that might be assigned responsibilities, the Army Corps of Engineers has longstanding experience with public works projects, including bid solicitation and evaluation, contract monitoring, and project management. Many other institutional arrangements might also be considered. Perhaps the chief danger, from a policy perspective, is to avoid the sort of opportunism that sometimes accompanies construction and service contracts.<sup>4</sup>

<sup>3</sup> As a summary slide from an MIT course on "Multidisciplinary System Design Optimization" put the matter: "In practice, optimization can be very difficult to implement... and it can be difficult (impossible) to verify that a solution is truly optimal" <[ocw.mit.edu/OcwWeb/web/home/home/index.htm](http://ocw.mit.edu/OcwWeb/web/home/home/index.htm)>. System design therefore remains a matter of compromise and depends ultimately on technical and perhaps commercial judgment.

<sup>4</sup> "According to Transparency International... the construction industry is the most corrupt in the world." Mina Kimes, "Flour's Corporate Crime Fighter," *Fortune*, February 16, 2009, p. 26.

A JOINT PROJECT OF CSPO AND CATF

Made Possible Through the Support of the  
Bipartisan Policy Center's National Commission on Energy Policy

March 2009

# Energy Innovation From the Bottom Up

WORKSHOP BACKGROUND PAPER: POST-COMBUSTION CAPTURE

BY JOHN ALIC



The Consortium for Science, Policy, and Outcomes  
Arizona State University  
1701 K Street, NW  
Washington, DC 20006  
[www.cspo.org](http://www.cspo.org)



Clean Air Task Force  
18 Tremont Street  
Boston, MA 02108  
[www.catf.us](http://www.catf.us)

# Post-Combustion Capture of Carbon Dioxide

Background Paper for March 27, 2009 Workshop | by John Alic



Burning a ton of coal releases some two tons of carbon dioxide, CO<sub>2</sub>, the major greenhouse gas (GHG). Each year the coal-burning power plants that generate nearly half of the electricity consumed in the United States emit some 2 ½ billion tons of CO<sub>2</sub>. These power plants, fewer than 1500 boiler-turbine-generator units located on perhaps 500 sites, account for more than 35 percent of the nation's CO<sub>2</sub> emissions and, on a CO<sub>2</sub>-equivalent basis, 27 percent of all U.S. GHG emissions.<sup>1</sup>

Coal's prevalence in the U.S. energy mix is a direct consequence of its abundance relative to other fossil fuels. The United States has large coal reserves that can be cheaply mined, as do China and India. Over the next century, much of the world's low-cost coal will probably be burned. While combustion of any fossil fuel releases GHGs, it is much harder to envision capturing CO<sub>2</sub> from hundreds of millions of cars and cookstoves than it is to imagine capturing and storing, probably in underground reservoirs such as those that have held oil and gas undisturbed for millions of years, the CO<sub>2</sub> from power plants numbering in the thousands. This is technically possible. But the costs appear to be high and they would show up on the electrical bills of homeowners and businesses everywhere.

Because coal contains about two-thirds carbon by weight, coal-fired power plants emit a gas stream that consists mostly of nitrogen and CO<sub>2</sub>, along with some water vapor and uncombined oxygen. While ordinary air contains less than 0.05 percent CO<sub>2</sub> by volume, flue gases contain some 12 percent to 15 percent CO<sub>2</sub>. It is this "extra" CO<sub>2</sub>—perhaps 10,000 tons per day from a typical 500 megawatt (MW) power plant—that contributes to the greenhouse effect.

There are four main pathways for reducing power plant emissions, as summarized in Table PCC-1. Only the post-combustion capture (PCC) alternative, in the rightmost column, will be considered during the course of this project, on the basis that PCC is technically proven (albeit not at power plant scale) and flexible (e.g., with the possibility of modular "end of pipe" installations for demonstration and scale-up and as retrofits to existing plants). Storage or sequestration of CO<sub>2</sub>, which amounts to putting carbon back where it came from after the available energy has been extracted, is a separable concern, and will likewise be left out of account; uncertainties concerning sequestration appear to be matters for scientific and technical inquiry (e.g., concerning possible leakage mechanisms and rates) more than innovation.<sup>2</sup>

<sup>1</sup> In 2007, coal-fired plants generated 48.5 percent of U.S. electrical power, followed by natural gas (21.6 percent) and nuclear (19.4 percent) plants. Coal-fired generating capacity has declined slightly in recent years, with new construction (two plants opened in 2007) falling behind retirements (21 plants, mostly small, closed in 2007). See, in general, *Electric Power Annual 2007* (Washington, DC: Department of Energy, Energy Information Administration, January 2009).

<sup>2</sup> Alternatives to underground storage have been proposed (including reduction of carbon to solid form), and some CO<sub>2</sub> might also be sold to industrial customers. The Department of Energy (DOE) began supporting work on CO<sub>2</sub> capture and storage in 1997, spending about \$1 million that year. Funding has climbed since, with the cumulative total now approaching \$500 million, but the majority of the money has gone, not for technology development, but for geological studies. In 2008, DOE budgeted \$14.3 million for capture technology and \$68 million (nearly 60 percent of capture-and-storage R&D totaling \$119 million) for regional partnerships to explore prospects for underground storage, including over two dozen small-scale demonstrations. Tax credits are also available for capture-and-storage investments and DOE also has loan guarantee authority, but in the absence of pending regulations there has been no reason for private parties to make such investments. Larry Parker, Peter Folger, and Deborah D. Stine, *Capturing CO<sub>2</sub> from Coal-Fired Power Plants: Challenges for a Comprehensive Strategy*, Report RL34621 (Washington, DC: Congressional Research Service, August 15, 2008), pp. 21-22.

**Table PCC-1. Alternatives for Reducing Emissions from Coal-Burning Power Plants.**

	<b>FUEL SWITCHING</b> (REPLACE COAL AS ENERGY SOURCE)	<b>PRE-COMBUSTION CAPTURE</b> (REMOVE CARBON FROM COAL BEFORE COMBUSTION)	<b>OXYFUEL</b> (REMOVE NITROGEN FROM AIR BEFORE COMBUSTION)	<b>POST-COMBUSTION CAPTURE</b> (REMOVE CO <sub>2</sub> AFTER COMBUSTION)
<b>DESCRIPTION</b>	Shift to renewables, nuclear power, natural gas. <sup>a</sup>	Gasify coal and separate out carbon, leaving a fuel consisting principally of hydrogen.	Burn coal in nearly pure oxygen leaving flue gases consisting of nearly pure CO <sub>2</sub> to facilitate separation.	Separate CO <sub>2</sub> from other constituents of flue gas, principally nitrogen.
<b>ADVANTAGES</b>	Avoids environmental, health, and safety risks associated with mining, transporting, and burning coal.	Integrated gasification combined cycle (IGCC) plants operate at higher efficiencies than alternatives, reducing fuel costs and CO <sub>2</sub> emissions directly.	Separation of nitrogen from air before combustion takes less energy than separating CO <sub>2</sub> from flue gases after combustion.	Could in principle be retrofitted to existing plants. Modular, facilitating scale-up and incorporation of technical improvements.
<b>DISADVANTAGES</b>	High investment costs, long switchover time.	First costs likely to be higher than some alternatives. Limited experience; considered unproven. <sup>b</sup>	Under development but not yet demonstrated. Requires boiler modifications, perhaps extensive. A post-combustion separation step may still be necessary and CO <sub>2</sub> must in any case be compressed and transported for sequestration.	Separation and compression of CO <sub>2</sub> energy-intensive, reducing net electrical output. Available separation processes proven on small scale but not at large power plants.

<sup>a</sup> Natural gas plants emit less CO<sub>2</sub> than coal-fired plants because gas contains less carbon per unit of energy. They can be built more quickly and cheaply than coal-fired plants and produce fewer regulated pollutants such as sulfur dioxide and mercury. In recent years, utilities have generally preferred to build them, especially for adding peaking capacity. Combined cycle plants pair a gas turbine operating at high temperature with a lower-temperature steam turbine for efficiencies in the range of 50 percent, substantially greater than alternatives.

<sup>b</sup> IGCC plants operate much like natural gas-fired combined cycle plants except that the fuel is gasified coal. Because gasification adds considerable cost and complexity, only a few of these plants have been constructed. The Department of Energy has funded work on coal gasification since the late 1970s and when R&D on carbon sequestration began in 1997 again focused on IGCC. On the reasons and results, see *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978-2000* (Washington, DC: National Academy Press, 2001), pp. 174-177, and *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two)* (Washington, DC: National Academy Press, 2007), pp. 132-149.

Chemists and chemical engineers know a great deal about carbon and oxygen, two of nature’s fundamental building blocks, and about CO<sub>2</sub>: flue gases are hardly exotic, and separating out the constituents of gas mixtures is a familiar industrial process. Proprietary amine-based “scrubbing” processes for separating CO<sub>2</sub> from nitrogen, simple in concept and straightforward in practice, have been available for decades (Box PCC-1).<sup>3</sup> The problems are those of scale and costs. Although improved separation technologies may bring down costs, there is so much carbon in coal, hence so much CO<sub>2</sub> emitted by power plants, that bulky and expensive equipment will be needed for almost any PCC process.

Although sulfur dioxide scrubbers have been widely retrofitted to existing coal-fired power plants, a 500 MW plant that might produce 10 tons per hour of sulfur dioxide (depending on the sulfur content of the coal burned) could easily emit some 500 tons per hour of CO<sub>2</sub>. Flue gases leave the boiler at approxi-

mately atmospheric pressure, which means they occupy a large volume and require large tanks or towers (and piping and ductwork, pumps and compressors, heaters and heat exchangers). (The slower the reaction rates, the larger the tanks must be.) Big pieces of equipment carry big price tags, perhaps totaling half a billion dollars or more (and some existing plants might not have enough space). Operating costs will be high too, depending on process details and energy requirements. With available technology, CO<sub>2</sub> capture and compression would consume a substantial portion of the plant’s electrical output. The costs of electricity would rise and some rate-payers might find their bills had doubled.

Cost estimates even for amine separation are uncertain, since no utility-scale installations with high capture fractions have been built.<sup>4</sup> The usual rule for almost any sort of large technical project seems to be initial optimism followed by schedule extensions and cost overruns. The requisite for

<sup>3</sup> In introducing separation technologies, Bert Metz, et al., *IPCC Special Report on Carbon Dioxide Capture and Storage* (Cambridge, UK: Cambridge University Press, 2005), notes that “further details are available in standard textbooks” (p. 109). This volume provides an accessible introduction to alternatives for removing and sequestering carbon or carbon dioxide from coal and other fossil fuels. On amine scrubbing, also see R. Notz, N. Asprion, I. Clausen, and H. Hasse, “Selection and Pilot Plant Tests of New Absorbents for Post-Combustion Carbon Dioxide Capture,” *Chemical Engineering Research and Design*, Vol. 85, Part A, 2007, pp. 510-515.

<sup>4</sup> Costs per ton of CO<sub>2</sub> extracted seem likely to reach a minimum in the range of 85 percent to 95 percent capture. Such costs can be expressed in two ways, as cost per ton of CO<sub>2</sub> captured or cost per ton of avoided emissions. The two differ, with avoided costs larger. This is because both separation and subsequent compression of CO<sub>2</sub> consume considerable power, which must be made up either from the plant’s own output or from some other source. The consequence is an added increment of CO<sub>2</sub> to be captured and stored, or an added amount of power to be purchased, and, since the same total cost is spread over both the tonnage of CO<sub>2</sub> captured and the tonnage avoided, the latter will always be greater.

reasonably accurate planning estimates is a baseline of similar projects with similar technologies: automakers design new models continually and rarely err by large amounts; Airbus designs new planes at lengthy intervals, technical experience carries over only partially, and deliveries of the new A380 began two years late. Since there is little experience with PCC, cost estimates must be considered unreliable. While utilities, engineering and construction firms, and equipment vendors know how to plan and build pulverized coal plants and can predict operating costs with good accuracy, they do not, as yet, know how to plan, design, build, and operate plants equipped for large-scale CO<sub>2</sub> capture.<sup>5</sup> Further uncertainties stem from the incentives of vendors to

present optimistic estimates and the incentives of utilities to express pessimism (e.g., to stall or delay regulatory mandates or win rate increases large enough to cushion against cost overruns).

With such qualifications noted, Table PCC-2 presents two sets of estimates, prepared by the Department of Energy (DOE) on the basis of engineering studies for retrofitting an existing coal-fired plant and for a new “greenfield” plant, with and without what is described as “advanced amine-based capture technology.” Although the incremental costs for the new plant are somewhat less, in both cases electricity costs rise by an amount comparable to generating costs for a typical pulverized coal plant, put by DOE at 6.4 ¢/kilowatt-hour (kWh).

### Box PCC-1. Chemical Separation as Business and Technology.

A number of firms market proprietary technologies—basically, know-how—for separating CO<sub>2</sub> from other gases. Because many chemical processes are quite sensitive to variables ranging from temperature and pressure to catalysts, knowledge that has been developed and validated (e.g., through demonstration) can be packaged and sold, for instance on a royalty basis. Innovating firms may also earn profits from equipment sales or through strategic alliances and joint ventures. In some cases, process details remain secret (being invisible, they are difficult to reverse engineer); in others, patents protect chemical compositions.

In most such arrangements, company-to-company negotiations, rather than some sort of market, determine the value assigned to “technology.” Buyers seek assurances that the technology will meet their expectations and recourse if it does not; sellers aim to protect against buyers who might try to innovate around the proprietary product or process, perhaps to emerge as a competitor. For policymakers, the confidential nature of many transactions elevates levels of uncertainty (e.g., concerning technical performance and costs) relative to, for instance, photovoltaic systems sold in competitive markets.

The best-developed PCC technologies, those for amine scrubbing, have been available for many years in several proprietary variants. The applications, however, have been small in scale—e.g., for beverage carbonation, for producing soda ash.

Amine separation works something like sulfur dioxide scrubbing. All coal contains up to a few percent sulfur, which combines with oxygen during combustion to form sulfur dioxide, the cause of acid rain. In scrubbers the sulfur dioxide reacts chemically with another substance, typically limestone in the form of a slurry, forming a solid that can be disposed of. Utilities began installing sulfur dioxide scrubbers several decades ago; with experience, costs have come down and performance improved.

Amine scrubbers, somewhat similarly, would pass flue gases through a solution of an amine compound, generally in water, to absorb (i.e., dissolve) CO<sub>2</sub>. (Amines are organic compounds related to ammonia; ammonia is itself an alternative sorbent and demonstrations of ammonia scrubbing are underway.) In a subsequent downstream stage the CO<sub>2</sub> is removed (“stripped”), leaving a relatively pure gas to be compressed for transport and storage. The amine solution is meanwhile regenerated for reuse. While many other separation technologies have been proposed, amine absorption is the only alternative for which substantial industrial experience exists.

<sup>5</sup> The operating record of nuclear power plants for instance, has improved steadily since the 1970s. In that decade, capacity factors—the fraction of time a plant is online, delivering electricity—averaged 60 percent; in 2007, the average reached 92 percent, higher than for coal-fired plants. *Nuclear Power in an Age of Uncertainty* (Washington, DC: Office of Technology Assessment, February 1984), p. 89; *Electric Power Annual 2007*, Table A6, p. 102.

**Table PCC-2. Cost Estimates for Amine-Based Post-Combustion Capture.**

	RETROFIT		NEW PLANT	
	NO CAPTURE	90% CAPTURE	NO CAPTURE	85% CAPTURE
Net Electrical Output (megawatts)	434 MW	303 MW	550 MW	550 MW
Net Operating Efficiency (percent)	35 %	24.5 %	36.8 %	24.9 %
Estimated investment (first) cost (millions of dollars)	—	\$ 400	\$ 850	\$ 1590
Estimated cost per ton of CO <sub>2</sub>				
Captured	—	\$ 54	—	\$ 44
Avoided	—	\$ 81	—	\$ 68
Estimated increase in cost of electricity (¢/kWh-hour)	—	6.9 ¢	—	5.5 ¢

Notes: All cases pulverized coal, no superheat. Steam conditions: retrofit - 2500 psi, 1000 F; new plant - 2400 psi, 1050 F. Efficiencies based on higher heating value. The retrofit case is Conesville #5, operated by American Electric Power in Conesville, Ohio. Cost estimates assume 85 percent capacity factor; 2006 dollars for retrofit case, 2007 dollars for new plant.

Sources: "Carbon Dioxide Capture from Existing Coal-Fired Power Plants," DOE/NETL-401/110907, November 2007; "Cost and Performance Baseline for Fossil Energy Plants," DOE/NETL-2007/1281, August 2007, both Department of Energy, National Energy Technology Laboratory, <www.netl.doe.gov>.

As the figures in Table PCC-2 suggest, coal-burning power plants ordinarily operate at efficiencies of up to about 35 percent.<sup>6</sup> Higher efficiencies are technically possible, which would reduce CO<sub>2</sub> emissions directly, but first costs rise at rates that in the past were often taken to exceed the savings in fuel costs. Capture and storage of CO<sub>2</sub>, no matter how this might be accomplished, will have the effect of reducing efficiencies and increasing generating costs. There are two primary reasons. In most processes so far envisioned, some of the steam from the boiler will be bled off for process heat (with amine separation, most of this heat is needed to strip the CO<sub>2</sub> from solution) and will no longer be available for driving the turbine and generating electricity. (In retrofits the turbine may be operated well off of its design point, resulting in further losses.) Second, a portion of the electrical output will be consumed in powering capture and storage equipment, principally compressors and pumps. In almost any alternative, CO<sub>2</sub> will be compressed in multiple stages to perhaps 2000 psi before transport; this alone will constitute a large "parasitic" load, dozens of megawatts for a plant of typical size.<sup>7</sup> In the retrofit case in Table PCC-2, these (and other minor) losses reduce the plant's generating capacity from the original rating of 434 mw to an estimated 303 mw.

Table PCC-2 assumes that retrofitting is a practical option. That may not be true at all sites. Figure PCC-1 indicates how much land area separation equipment can occupy. The illustration shows a hypothetical 800 MW plant with amine separation: even assuming "significant advances in volume reduction for absorbers and desorbers," site acreage roughly doubles.

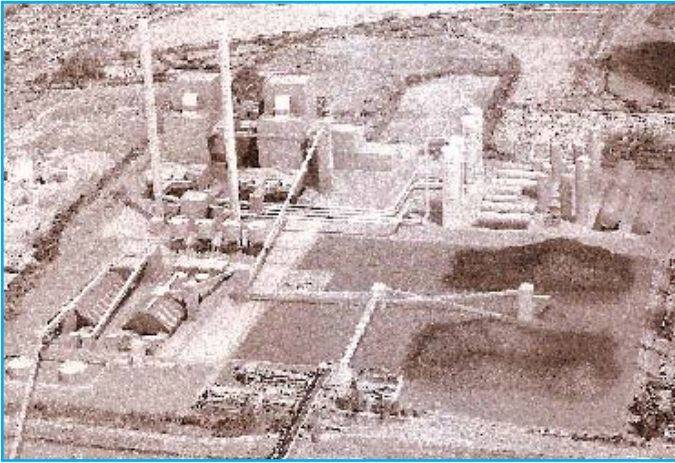
Capture costs can be reduced in two complementary ways: by developing alternative forms of CO<sub>2</sub> separation that consume less energy as steam and electrical power (e.g., through chemical processes with lower heats of reaction and more efficient CO<sub>2</sub> compressors) and by increasing baseline power plant efficiency, raising the plant's pre-capture electrical output per unit of CO<sub>2</sub> emitted.

A great many alternatives to amine or ammonia absorption are under study. The possibilities include long lists of possible solvents, including many amine compounds and combinations of amines that have yet to be examined, membranes that would preferentially pass CO<sub>2</sub>, porous solids to adsorb it, and distillation. There are also multiple routes to increased power plant efficiency, most of them well known. In the past, high costs have slowed their adoption.

<sup>6</sup> According to *The Future of Coal: Options for a Carbon-Constrained World, An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2007), "The U.S. coal fleet average generating efficiency is about 33%, although a few, newer generating units exceed 36% efficiency" (p. 17).

<sup>7</sup> For the retrofit case in Table PCC-2, compression (and associated cooling) of the CO<sub>2</sub> requires an estimated 45 MW; adding in other auxiliary power requirements, mostly for pumps, brings the total to 55 MW, nearly 13 percent of the plant's pre-capture output. Improvements in compressor design may reduce electrical loads somewhat (although large compressors and the electric motors that drive them are already quite efficient), and a plant designed from the outset for capture would probably have lower parasitic steam losses.

Figure PCC-1.



Artist's rendering of a hypothetical 800 MW power plant with amine-based CO<sub>2</sub> capture. The separation and stripping equipment is on the right (vertical towers), the rest of the plant on the left (two tall stacks).

Source: Richard Hotchkiss, "Carbon Dioxide Capture and Storage from Coal Fired Power Plants," Coal Research Forum, Rugeley, UK, June 20, 2007.

Policies that encouraged or required CO<sub>2</sub> capture would alter the cost calculations of utilities, making investments in efficiency more attractive. Efficiency depends quite directly on steam temperature and pressure. Working temperatures and pressures are kept well below those achievable in principle because materials costs rise rapidly for pressure vessels, piping, and other equipment that must operate reliably for three, four, or five decades at high temperatures and loads. Placing a price on CO<sub>2</sub> would move design points for steam power plants to higher temperatures and pressures and would probably also encourage the adoption of alternatives to conventional steam power plants.<sup>8</sup>

There are no technical reasons, only economic and political reasons, why coal-fired power plants could not be fitted for 90 percent CO<sub>2</sub> capture and still operate nearly as efficiently as today's average plants without capture. With learning over time and standardization, costs should come down. Modules might be added to raise capture fractions in stages, to manage technical risks and moderate rates of cost and price increase. Pricing CO<sub>2</sub> at a high enough level would lead utilities to retire inefficient older plants, retrofit their more efficient plants if otherwise practical, and choose high-efficiency designs for new construction.

<sup>8</sup> Metz, et al., *IPCC Special Report on Carbon Dioxide Capture and Storage*, pp. 113-170, reviews many other possibilities.