Natural Resources Research, Vol. 19, No. 1, March 2010 (© 2010)
DOI: 10.1007/s11053-010-9111-3

Subsurface Sequestration of CO_2 in the U.S: Is it Money Best Spent?

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Received 7 December 2009; accepted 20 January 2010
Published online: 5 February 2010

The continuously decreasing average coal rank (heating value), inadequate investment, and ever stricter air-emission controls have caused the average efficiency of electricity generation from coal in the U.S. to plummet to a mere 32% by the year 2008. The U.S. gas-fired powerplants are 30% more efficient than the coal-fired ones, with average efficiency of 43% in 2008. Replacing each 1,000 MW_e generated by an average coal-fired powerplant with an average gas-fired powerplant would avoid *today* 7 million tonnes of CO_2 emissions, 1.2 million tonnes of toxic ash, and significant issues with water contamination. The parallel upgrades to the more efficient supercritical steam turbines would decrease current emissions by up to 50% (from the current average plant efficiency of 32% to over 45%). The CO_2 captured in the new combined-cycle powerplants might be used to enhance oil recovery in local fields, where feasible. The CO_2 enhanced oil recovery (EOR) can never become the main sink for the gigantic CO_2 volume generated each year by electric powerplants. Currently, EOR could absorb only 1% of that volume.

KEY WORDS: Electrical power generation, coal, natural gas, generation efficiency, coal ash, water contamination, Clean Air Act, ultra supercitical steam, avoided carbon dioxide emissions.

INTRODUCTION

The purpose of this paper is to compare carbon capture and sequestration (CCS) with (i) switching from coal-fired to natural gas-fired powerplants and (ii) increasing efficiency of electricity generation from coal-fired powerplants by raising the steam pressure and temperature. Options (i) and (ii) eliminate permanently a substantial part of carbon dioxide emissions from electricity generation by increasing efficiency, while option (i) also avoids the generation of solid ash and mineral waste from coal. In contrast, CCS increases both carbon dioxide and solid waste emissions from electricity generation and requires the development of a spurious expensive infrastructure, whose sole purpose would be to hide the increased emissions in the subsurface "forever".[3] Table 1 is a snapshot of electricity generation in the U.S. in the year 2008. Note that natural gas generated about 45% of electricity, but only 17% of CO_2 emissions and *no* solid emissions. Thus, in 2008 alone, the natural gas-fired powerplants in the U.S. *avoided* $2.52 \times 0.88/2 - 0.436 = 0.67$ billion tonnes of CO_2 emissions and 127 million tonnes of toxic coal ash sludge.

COAL-FIRED AND GAS-FIRED POWERPLANTS IN THE U.S. AND EUROPE

The basic unit of electrical power output is 1,000 MW_e = 1 GW_e. This amount of electrical

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[3]With little assurance that this "forever" will last longer than a couple of decades, before the stored CO_2 starts leaking into the overlying aquifers.

power is generated by a single large modern coal-fired powerplant. We define this unit as 1 PPE = 1 Power Plant Equivalent. Table 1 shows that the U.S. now has 227 PPEs that are coal-fired and 100 PPEs that are gas-fired. The net energy efficiency of a powerplant is defined as:

$$\eta_e = \frac{\text{Electricity generated in one calendar year (J)}}{\text{Heat of burning fuel in one year (J)}} \quad (1)$$

Table 1. Summary of Electricity Generation in the U.S. in the Year 2008

Quantity	Coal	Gas
Fuel used	975	153[a] megatonnes (Mt)
Fuel heating value	23.1	46.6 GJ/tonne
CO_2 emissions	2.52	0.421 gigatonnes (Gt)
Solid waste	288	0 Mt
Generation efficiency[b]	32	43%
Electricity generated	2	0.88 GWh
Electric power generated	227	100 GW_e

[a]6.7 trillion standard cubic feet of natural gas with the standard density of 0.84 kg/m^3 at 0°C and 1 atm, or 0.79 kg/m^3 at 15.56°C and 1 atm, see Table 11 in Patzek (2004). The average natural gas here has the molecular weight of 18.8 g/mol. The range of densities of natural gases is 0.7–0.9 kg/m^3 at 0°C.
[b]See Eq. 1.

Thus "district heat" (low quality steam and/or hot water for heating) is excluded in these calculations.

The net energy efficiencies of several European coal-fired powerplants and all U.S. coal-fired and natural gas-fired powerplants are shown in Figure 1. The U.S. efficiencies were calculated from the thousands of megawatthours of electricity generated from coal and natural gas, reported by the U.S. DOE EIA (Report DOE/EIA-0226), the coal BTUs reported to generate electricity (Report DOE/EIA-0226), and the millions of standard cubic feet (MMscf) of natural gas burned to generate electricity (n3045us2a.xls). All these data are posted on the DOE EIA website and are readily accessible. The average heating value of natural gas in U.S.

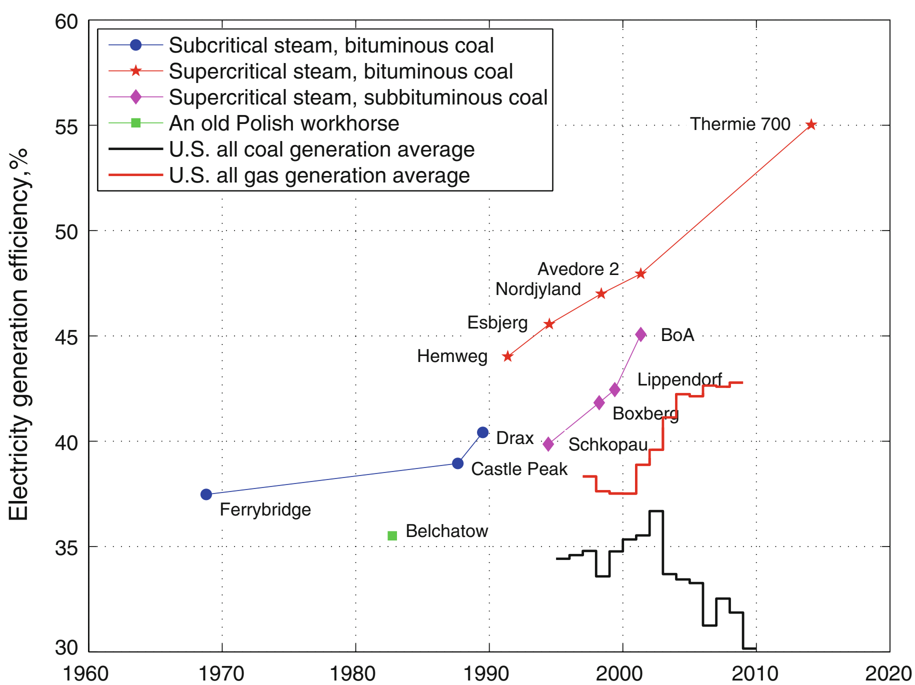

Figure 1. Net efficiency of generating electricity from coal- and natural gas-fired powerplants. Note the dismal overall energy efficiency of electricity generation from coal in the U.S. decreased by the many small, inefficient and obsolete powerplants. The U.S. natural gas-fired powerplants have efficiencies in the range of good subbituminous coal-fired powerplants in Europe. The European coal-fired powerplant data are from Figure 1.5 in Pawlik and Strzelczyk (2009). The overall efficiency of U.S. electricity generation has been calculated from the DOE EIA files epmxlfile4_1.xls (Report DOE/EIA-0226) for coal, and n3045us2a.xls for natural gas. All DOE files were accessed on October 20, 2009.

pipelines was assumed to be 1050 BTU/scf = 46.6 MJ/kg (Foss, 2004). On average, the U.S. coal-fired powerplants lag far behind the European ones in energy efficiency.

Over the last decade, net energy efficiency of electricity generation from coal in the U.S. has been dismal and decreasing, because of lack of investment[4] and stricter regulations on the flu-gas emissions that continued to diminish plant efficiency. Around 920 U.S. coal plants—78% of the total—are small (generating less than half a gigawatt), antiquated and horrendously inefficient. Their average age is 45 years, with many over 75. They tend to be located amidst dense populations and in poor neighborhoods to lethal effect. These outdated plants burn 20% more coal per megawatt hour than modern large coal units and are 60 to 75% less fuel-efficient than combined cycle gas plants. They account for only 21% of America's electric power but almost half of the sector's emissions.[5]

Net energy efficiency of natural gas-fired powerplants in the U.S. is significantly (at least 33% and perhaps as much as 50%) higher than that of the coal-fired powerplants, see Figure 1. The share of natural gas in electricity generation in the U.S. has been increasing steadily, see Figure 2, reaching 45% of the coal-fired electricity production in 2008 and 50% in the first five months of 2009.

Remark 1 By increasing average efficiency of coal-fired electricity generation in the U.S. from the current 32% to 42%, we could permanently eliminate 1/3 of the current U.S. CO_2 emissions from coal. By going deeper into the supercritical steam region—to attain a 45% average efficiency—1/2 of the CO_2 emissions in the U.S. would be eliminated permanently. This solution is immediately technically feasible, but would require action and investment. □

EMISSIONS FROM ELECTRICITY GENERATION

Because of their low energy efficiency, see Figure 1, and low-rank coals used (23 MJ/kg coal in 2009, on the average[6]), the U.S. coal-fired powerplants generate excessive amounts of carbon dioxide,[7] see Figure 3, mineral matter and ash, see Figure 4, and contaminated water,[8] see Figure 5.

Records indicate that powerplant landfills[9] and other disposal practices have polluted groundwater in more than a dozen states, contaminating the drinking water in some towns with toxic chemicals.

[4]Perversely, the American utility companies have been discouraged from modernizing old powerplants that were grand-fathered under the Clean Air Act of 1970, amended in 1990 (www.epa.gov/air/caa/). Let us calculate the cumulative CO_2 and ash emissions from coal-fired powerplants between 1995 and 2009, and subtract the 1995 values multiplied by the number of elapsed years minus 1. The result is the contribution of the Clean Air Act to the incremental total emissions of 14 million tonnes of CO_2 and 2.2 million tonnes of coal ash per coal-fired PPE. The approximate total incremental emissions from all U.S. coal-fired power plants are then 3 billion tonnes of CO_2, 500 million tonnes of ash, and a commensurate incremental contamination of water and soil. Over the same time period, the CO_2 enhanced oil recovery in the U.S. injected at best 0.5 billion tonnes of CO_2. A recent Harvard Center for Risk Analysis study of nine old power plants in the Chicago area has provided federal lawmakers with new justification for ending the grandfather clause in the federal law—as has been proposed under H.R. 2900 (the Waxman-Boehlert Clean Smokestacks Act) and S. 1369 (the Jeffords-Lieberman Clean Energy Act)—both of which would put in place timelines for older facilities to apply Best Available Control Technology to substantially reduce emission rates.

[5]*How to End America's Deadly Coal Addiction* by Robert F. Kennedy, Jr. Published in the *Financial Times*, July 19, 2009.

[6]Calculated from the Report DOE/EIA-0226, accessed on October 20, 2009. The average coal heating value of 23 MJ/kg means that U.S. coal-fired powerplants are fed increasingly with the subbituminous coal from the U.S. West (Croft and Patzek, 2009; Patzek and Croft, 2009).

[7]Using the standard heat of combustion of carbon to carbon dioxide, equal to 32.8 MJ/kg of elemental carbon C. *Source*: Table 5-76 in Lide (1994).

[8]"For years, residents here complained about the yellow smoke pouring from the tall chimneys of the nearby coal-fired powerplant, which left a film on their cars and pebbles of coal waste in their yards. Five states including New York and New Jersey sued the plant's owner, Allegheny Energy, claiming the air pollution was causing respiratory diseases and acid rain. So three years ago, when Allegheny Energy decided to install scrubbers to clean the plant's air emissions, environmentalists were overjoyed. The technology would spray water and chemicals through the plant's chimneys, trapping more than 150,000 tons of pollutants each year before they escaped into the sky. But the cleaner air has come at a cost. Each day since the equipment was switched on in June, the company has dumped tens of thousands of gallons of wastewater containing chemicals from the scrubbing process into the Monongahela River, which provides drinking water to 350,000 people and flows into Pittsburgh, 40 miles to the north." *Source*: Charles Duhigg, *Cleansing the Air at the Expense of Waterways*, *NYT* October 13, 2009, Section A. For the thousands of Clean Water Act violations by the coal-fired powerplants see the web version at www.nytimes.com.

[9]An EPA list of 574 coal ash sites is at www.earthjustice.org/library/references/09ccw-survey-summary-results.pdf.

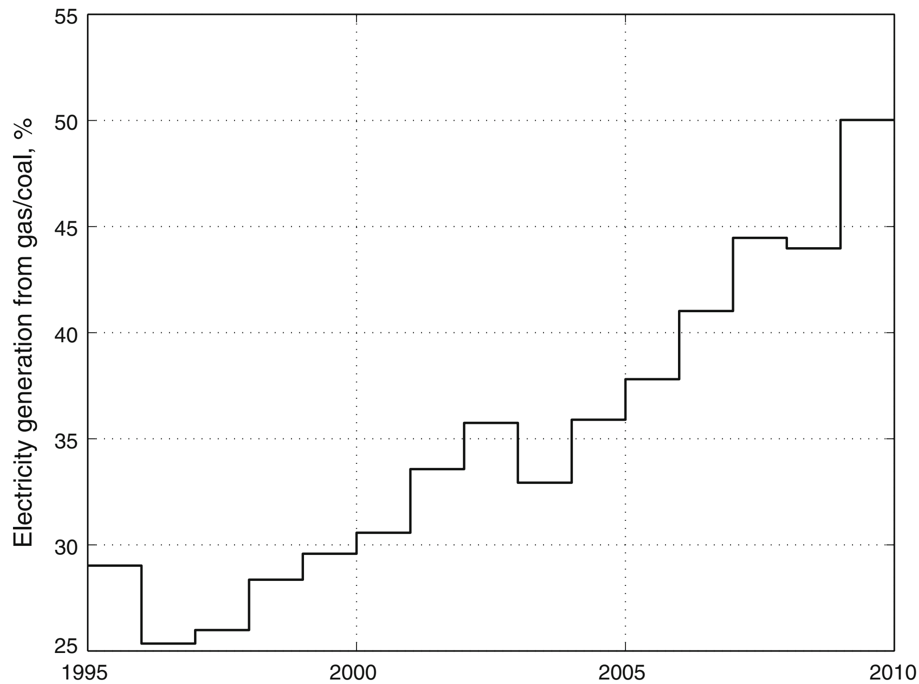

Figure 2. The fraction of electricity generated from gas-fired powerplants in the U.S., relative to coal-fired electrical powerplants. Note that in 2008, the last full year of data, the gas-fired powerplants generated 45% of the electricity generated by the coal-fired powerplants.

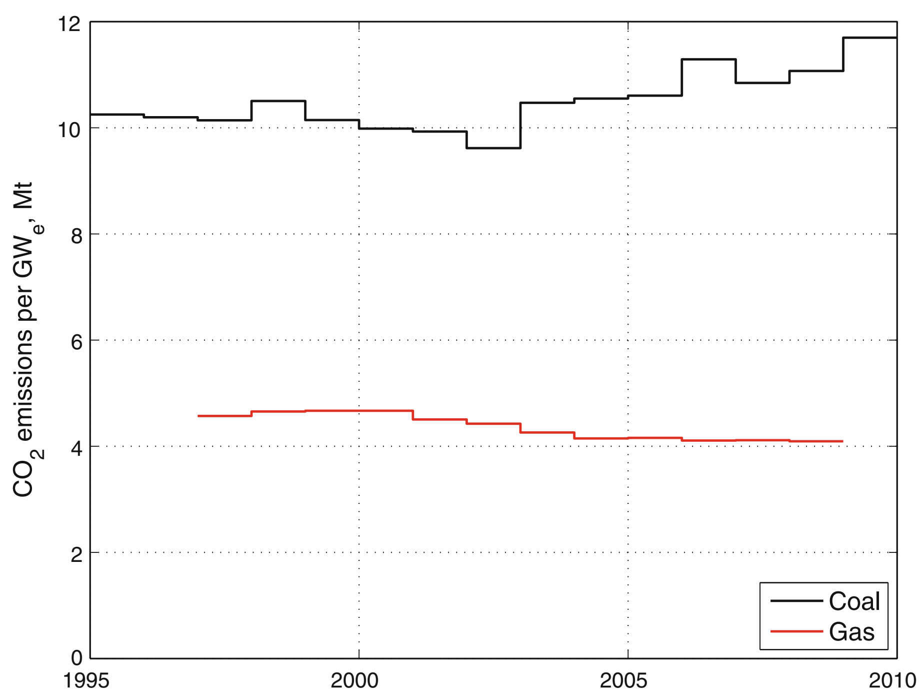

Figure 3. The carbon dioxide emissions per 1 PPE (1,000 MW_e) from the coal-fired and gas-fired electrical powerplants in the U.S..

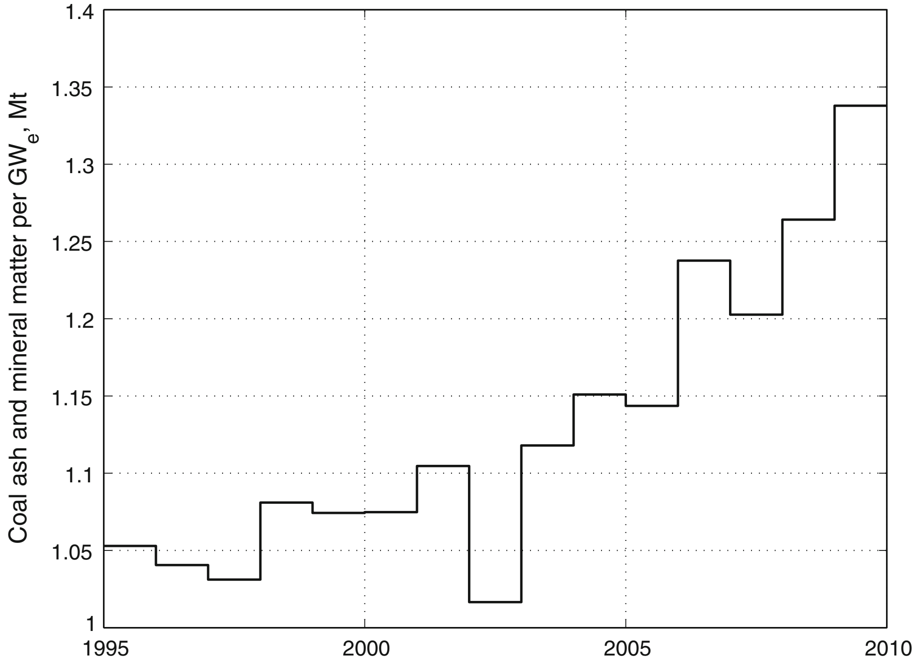

Figure 4. The megatons of coal ash generated by 1 coal-fired PPE in the U.S. Note that in 2008, on the average, over 1.25 million metric tones of coal ash and mineral matter were generated for each 1 PPE from coal.

A 2007 report published by the E.P.A. suggested that people living near some powerplant landfills faced a cancer risk 2000 times higher than federal health standards.

The average carbon dioxide emissions from the coal-fired powerplants in the U.S. have been calculated annually as:

$$\frac{\text{Mega tonnes of } CO_2}{1,000\ \text{MW}_e} = \text{Mass of coal burned in one calendar year (kg coal)} \times \frac{\text{Average heating value (HHV) of coal in a given year (MJ/kg coal)}}{32.8\ \text{MJ/kg C}} \times \frac{44}{12} \times \frac{1,000 \times 24 \times 365}{\text{Coal MWh in one calendar year}} \times \frac{1\ \text{Mt}}{10^9\ \text{kg}} \tag{2}$$

44/12 is the ratio of molecular weights of CO_2 and C. By not accounting for the contribution of hydrogen to the coal's HHV, Eq. 2 exaggerates somewhat the calculated CO_2 emissions.

The average carbon dioxide emissions from the natural gas-fired powerplants in the U.S. have been calculated annually as:

$$\frac{\text{Mega tonnes of } CO_2}{1,000\ \text{MW}_e} = \text{Mass of gas burned in one calendar year (kg gas)} \times \frac{44}{16} \times \frac{1,000 \times 24 \times 365}{\text{Gas MWh in one calendar year}} \times \frac{1\ \text{Mt}}{10^9\ \text{kg}} \tag{3}$$

44/16 is the ratio of molecular weights of CO_2 and CH_4, which is the main component of natural gas.

To convert the standard cubic feet of natural gas reported by EIA to kilograms, the standard density of natural gas of 0.79 kg per standard cubic meter has been used, see Table 1.

Figure 5. The December 22, 2008, failure of the coal ash slurry dump near the Kingston Fossil Plant in Harriman, Tennessee, was the largest industrial disaster in many decades. Four million m^3 of sludge were released. Coal ash is composed primarily of oxides of silicon, aluminum, iron, calcium, magnesium, titanium, sodium, potassium, arsenic, mercury, and sulfur plus small quantities of uranium and thorium. Some of the uranium is U235, which together with thorium are fissile radioactive materials. Fly ash is primarily composed of non-combustible silicon compounds (glass) melted during combustion. Tiny glass spheres form the bulk of the fly ash. Stored coal ash slurries eventually threaten water supplies, human health, and local ecosystems. *Photo*: Wade Payne/ Greenpeace, via Associated Press.

The amount of mineral matter and ash has been calculated as:

$$\frac{\text{Mega tonnes of ash}}{1,000\,\text{MW}_e} = \text{Mass of coal burned in one calendar year (kg coal)} \times \left(1 - \frac{\text{Coal HHV}}{32.8}\right) \times \frac{1,000 \times 24 \times 365}{\text{Gas MWh in one calendar year}} \times \frac{1\,\text{Mt}}{10^9\ \text{kg}} \quad (4)$$

AVOIDING EMISSIONS

By simply replacing an average U.S. coal-fired powerplant with an average gas-fired plant, we can avoid almost 7 million tonnes of CO_2 per 1 PPE, see Figure 6. These savings are staggering, when we consider that in 2009 there were 227 PPEs that burned coal. In 2007, an average gas-fired powerplant saved about 62% of the emissions of a coal-fired powerplant in the U.S., see Figure 7. Note that this replacement would also save about 1.2 million tons of ash and sludge per 1 PPE.

Remark 2 The simplest and most cost-effective way of decreasing CO_2 emissions from coal-fired powerplants is to replace them with gas-fired powerplants. □

ADDING EMISSIONS AND HIDING THEM

Suppose that CO_2 could be separated and captured at the existing coal-fired powerplants. Also, suppose that this CO_2 could be compressed to a supercritical state, piped to a desirable oil field or saline water aquifer, and injected there through multiple wells, the number of which would increase with time. None of this technology is available today at scale, but suppose that every technical, geological, and economic obstacle will be removed. Given these assumptions, carbon capture and storage will increase coal consumption in a powerplant by 25 to

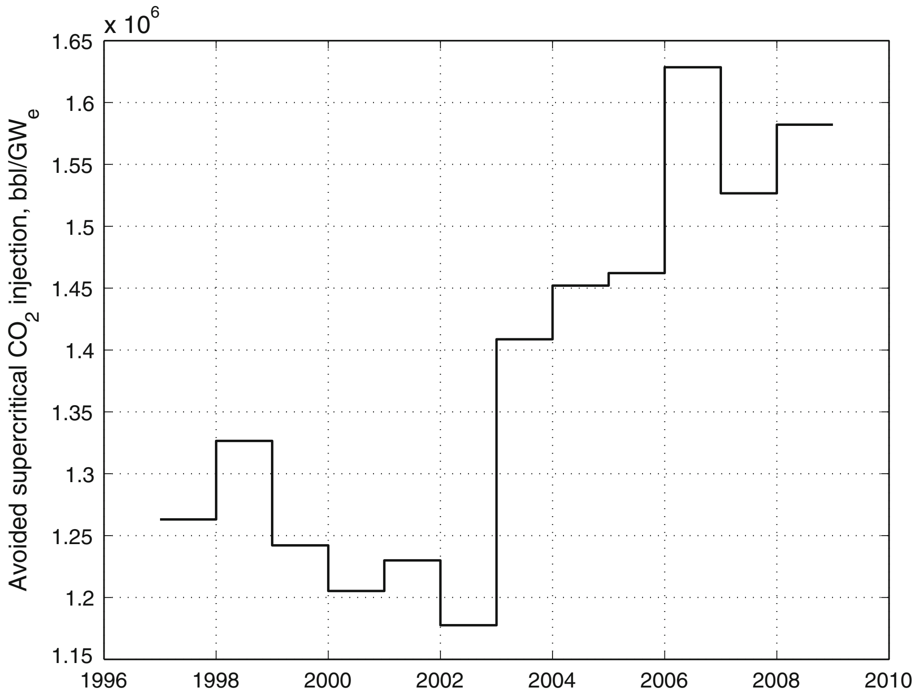

Figure 6. The carbon dioxide emissions *avoided* by replacing the generation of the average U.S. coal-fired PPE with a natural gas-fired PPE. In 2008, we would avoid 7 million tons of CO_2 by producing 1,000 MW_e from an average gas-fired powerplant, when replacing an average coal-fired plant.

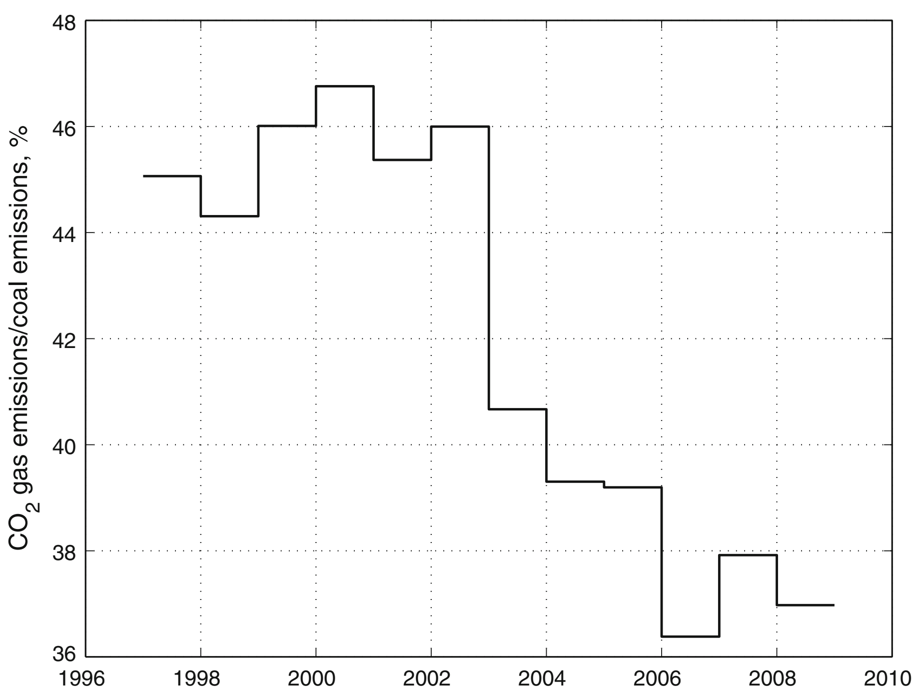

Figure 7. The ratio of the overall carbon dioxide emissions per 1 PPE from the U.S. gas-fired and coal-fired electrical powerplants. Note that in 2008, the generation of 1 PPE from an average gas-fired powerplant resulted in only 37% of the CO_2 emissions from an average coal-fired plant.

40% (Metz and others, 2005). Let us assume an increase of coal consumption by 1/3 (33%) on average. Since we also want to sequester emissions from the additional coal needed for sequestration, the total coal emissions will increase as the sum of an infinite geometrical series with the quotient of $q = 1/3$, and the increment will be

$$\Delta = \frac{1}{1-q} - 1 = \frac{3}{2} - 1 = \frac{1}{2} \tag{5}$$

Thus, CO_2 sequestration will ultimately increase CO_2 generation by 50%. In other words, for every two coal-fired PPEs, a third PPE will have to be built, to serve the energy required to sequester the CO_2 generated by all three powerplants. Of course, solid waste and water pollution from coal will also be created at a 50% higher rate. This estimate does not include the massive raw material and equipment requirements of CCS.

Remark 3 Given the assumptions in this paper, full CO_2 sequestration from coal fired powerplants is prohibitively energy-expensive and environmentally harmful. □

CO_2 INJECTION FOR ENHANCED OIL RECOVERY (EOR)

Another, "cheaper" option for the disposal of CO_2 captured in the coal-fired powerplants is CO_2 injection into mature oil fields to enhance oil recovery from these fields. The popular wisdom is that there is enough pore space in the suitable oil fields to allow for capture of most of the power-station CO_2. Let us examine this possibility in more detail.

In the U.S., CO_2 injection has accounted for the recovery of about 1.5 billion bbl of oil, and CO_2 sales to U.S. EOR projects reached an estimated 3 billion cubic feet per day (bcfd) in 2008, with about 83% of it coming from CO_2 source fields, according to a presentation[10] at the Third Annual Wyoming CO_2 Conference, Casper, Wyoming, June 23–24, 2009. The overall mass balance of CO_2 suggests that 17% of the CO_2 used in enhanced oil recovery (EOR) projects is recirculated[11] and 83% is newly produced CO_2 from natural sources piped into these projects. The latter natural CO_2 could be replaced with the CO_2 captured in coal-fired powerplants.

Let us assume that in 2008, daily injection of new CO_2 in the U.S. CO_2-based EOR projects was 2.4 billion of standard cubic feet per day. Let us also assume that this CO_2 is compressed from its standard density of 1.86 kg per standard cubic meter to a supercritical state with the average density of 700 kg per cubic meter of gas-filled reservoir pore space.[12] Then, at average reservoir conditions, the daily volume of injected new CO_2 is $2.4 \times 10^9 \times 0.3048^3/(700/1.86) = 181{,}000\ m^3/d$ = 28,700 reservoir barrels per day (bpd).

From Figure 3 it follows that one coal-fired PPE generated 11.2 million tons of CO_2 in the year 2008 (the last full year of data). This mass flow rate of CO_2 translates into $44{,}000\ m^3/d \approx 7{,}000$ bpd at the average reservoir conditions. With the full CO_2 sequestration, the required injection volume may increase by 50%, to 10,400 bpd (all numbers are rounded off to three significant digits).

The calculations of CO_2 sequestration based on the overall storage capacity of finite oil and gas reservoirs may be misleading. Regardless of the available maximum pore volume, the rate of CO_2 injection into these reservoirs will be the limiting factor. It is next to impossible to inject 10,000 bpd of new CO_2, each day—for decades—into a finite reservoir. The injection pressure may quickly exceed the maximum pressure needed to lift the overburden ("the fracture pressure"), and new CO_2 injection wells in far-away locations—with the accompanying pipelines—may be required.

Remark 4 In 2009, all newly produced CO_2 used to drive all enhanced oil recovery projects in the U.S. was equivalent to the emissions from 2.76 coal-fired PPEs with full CO_2 sequestration. In 2009, there were 227 such powerplant equivalents in the U.S., and their emissions with CO_2 sequestration requirements were 227/2.76 = 82 times larger than all new CO_2 injection needed for EOR, roughly a factor of 100. □

A factor of 100 is the difference between running (at 9 km/h) and flying a jet (at 900 km/h). Thus, the U.S. carbon dioxide projects will never be able to absorb the year-to-year emissions of the existing coal-fired

[10]Reported by Guntis Moritis, *Rocky Mountain EOR, Oil and Gas Journal*, August 10, 2009.

[11]Locally, CO_2 recirculation can be many times higher, but there have been substantial project expansions.

[12]The mean density of the supercritical CO_2 in 21 EOR projects in the U.S. was calculated to be 680 kg/m^3.

powerplants in the U.S. At best, after an expansion of U.S. CO_2 EOR projects by a factor of 10, CO_2 sequestration in oil fields, while useful, will remain a 10% solution.

CONCLUSIONS AND POLICY RECOMMENDATIONS

A 30 to 50% *permanent* reduction of CO_2 emissions from coal-fired powerplants in the U.S. is immediately and clearly feasible with the existing, off-the-shelf technology. Instead, we seem to be going in the opposite direction that will lead to a 30 to 50% increase of CO_2 emissions through carbon capture and geologic sequestration, as well as commensurate solid waste emissions and the ensuing water contamination.

The current CO_2 emissions from coal-fired electric powerplants in the U.S. could be cut permanently by at least 1 billion tons per year using the following approach:

1. Shut down the older powerplants and replace them with modern gas-fired powerplants.
2. Upgrade some of the larger coal-fired powerplants block-by-block to deeply supercritical steam.

Replacing the least-efficient 20% of electric power generation with options 1 and 2 would cut off 2/3 of 2.5 billion tons per year of CO_2 emissions, or 1.6 billion tons of CO_2 per year, or almost 1,000,000 barrels of supercritical CO_2 per day, each day for decades. The required large investment would revitalize some of the poorest neighborhoods in the U.S. and improve the dismal public health conditions there. But such sensible options do not seem to be on the table. Instead, we have focused all of our attention on CCS. A significant part of research funding available through U.S. DOE is focused solely on CCS, and other faster, cheaper and less energy-intensive solutions are not considered. As M. King Hubbert observed once: ‘‘Our ignorance is not so vast as our failure to use what we know.’’

ACKNOWLEDGMENTS

This paper has been reviewed by Dr. Larry Lake of UT Austin and Lucas J. Patzek, a Ph.D. candidate at the Washington State University in Pullman. Their numerous corrections and suggestions are gratefully acknowledged. Mr. Tom Halbouty, VP of Pioneer Natural Resources, has pointed out to me the possible role of the Clean Air Act in locking the low efficiency and high emissions from the electric power utilities in the U.S.

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