Environ. Sci. Technol. **2010,** *44,* 4042–4045

Environmental Science & Technology
Viewpoint

Is Carbon Capture and Storage Really Needed?[1]

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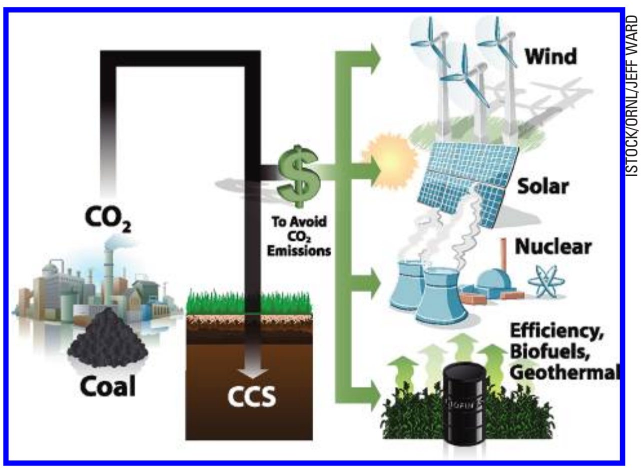
If CO_2 cannot be stored at profit, perhaps it is best to switch to low-carbon alternative energy post haste.



Two of the greatest contemporary global challenges are anthropogenic greenhouse gas emissions and energy sustainability. A popular proposed solution to the former problem is carbon capture and storage (CCS). Unfortunately, CCS has little benefit for energy sustainability and introduces significant long-term costs and risks. Thus, we propose the adoption of "virtual CCS" by directing the resources that would have been spent on CCS to alternative energy technologies. (The term "virtual" is used here because the concept described in this work satisfies the Merriam-Webster Dictionary definition of virtual: "being such in essence or effect though not formally recognized or admitted.") In this example, we consider wind and nuclear power and use the funds that would have been required by CCS to invest in installation and operation of these technologies. Many other options exist in addition to wind and nuclear power including solar, biomass, geothermal, and others. These additional energy technologies can be considered in future studies. While CCS involves spending resources to concentrate CO_2 in sinks, such as underground reservoirs, low-carbon alternative energy produces power, which will displace fossil fuel use while simultaneously generating revenues. Thus, these alternative energy technologies achieve the same objective as that of CCS, namely, the avoidance of atmospheric CO_2 emissions.

Carbon Capture and Storage. The Intergovernmental Panel on Climate Change released a report in 2005 summarizing the technologies available for CCS. The most promising of multiple options for capture is currently liquid absorption with a regenerable solvent. Advantages of this technology include high treatment capacity, high CO_2 stream purity (because of solvent selectivity for CO_2), and capacity for retrofit with older coal power plants (*1*). However, this method imposes a significant energy penalty for regeneration of the solvent, as well as solvent replacement cost, because the solvent degrades in the presence of acid-forming gases. Also, retrofitting a coal power plant is more expensive than integrating a capture system into a newly built plant, thus adding to the cost (*2*). The retrofit cost factor is important since 785 GW of coal and natural gas plants were operational in the U.S. in 2007, with planned additions of 10.9 to 16.8 GW each year until 2012 (*3*). Thus, retrofit may be more common in the U.S. in the coming years than building coal power plants integrated with CCS. Capture methods including adsorption, membranes, and other novel approaches are currently less optimal than liquid absorption (*1*) for a variety of reasons. In addition to the costs associated with capturing CO_2, equipment must also be in place to transport the captured stream. The most popular method for transporting CO_2 is via pipeline in a liquid or supercritical state, a technique requiring significant compression and pumping energy, further increasing the cost (*2*).

Following capture and transport, storage must be performed. Multiple storage options exist, including mid- and deep-ocean injection (*4, 5*), mineralization, coal seam injection, enhanced oil recovery, and aquifer injection (*6*). Of these traditional options, aquifer injection is the most cost-effective and technologically feasible (*2*). A suitable site for aquifer injection must meet stringent criteria regarding seal integrity to prevent leakage, geological stability to minimize seismic activity risks, and groundwater/hydrological dynamics to ensure millennia-scale storage time, as well as sociopolitical and jurisdictional issues (*7*). Currently, cost and environmental risks are the main obstacles to performing deep aquifer injection. This scenario leads to the question: "Why is CCS such a popular component of the CO_2 mitigation strategy?" Perhaps because it would allow us to maintain our dependence on a source of energy with which we have considerable experience.

Virtual CCS. Objections to alternative energy generally focus on the high cost of these technologies, relative to coal and natural gas, for baseload and peaking capacities, re-

[1] Editor's Note: This manuscript was submitted prior to ES&T changing its manuscript parameters for Viewpoints. For the new format, please read the details at http://pubs.acs.org/doi/abs/10.1021/es903081n.

10.1021/es903626u
Published on Web 05/12/2010

spectively. Other obstacles including intermittency, an unprepared grid, and site specificity impede the implementation of alternative forms of energy. Nuclear energy must also deal with waste and security issues. Because fossil technologies are well-known and established, it is reasonable that efforts are being made to allow further use of these energy strategies while cautiously developing alternatives. Thus, CCS can be considered an effort to shield us from taking a large step away from fossil fuels for electricity production. The concept of virtual CCS is to take the resources that are being or expected to be directed to CCS efforts and, instead, direct them to alternative energy technologies. This activity would achieve the same goal as CCS, but by a different method. While transitioning to these alternatives seems a daunting task, the costs associated with CCS are so great that enormous progress can be made if we simply redirect our efforts and resources.

The mass basis for our calculations was the "stabilization wedges" concept of Pacala and Socolow (*8*): atmospheric CO_2 emissions can be stabilized by splitting carbon emissions mitigation among various technologies, including CCS, nuclear power, and wind power. A "wedge" is defined as the avoidance of 1/8 of increased CO_2 emissions over 50 years (y). Even though there is a high probability that economic realities will change substantially over a period of 50 years, this time scale was adopted in our analysis because it is of the same order as the lifetime of alternative energy installations that are proposed as an alternative to CCS. The CO_2 emission rate in 2010 is estimated at 30 $GtCO_2$/year (~8 GtC/year) and was projected to approximately double over the next 50 y. This projection represents an increase in emissions of 0.64 $GtCO_2$ each year, or 0.08 $GtCO_2$/y for a single wedge. Thus, a "wedge" of emissions totals 100 $GtCO_2$ over 50 y. We assumed that approximately 0.95 $kgCO_2$/kWh is emitted during electricity production from fossil fuels (*9*). The cost of capturing, transporting, and storing CO_2 was assumed to be \$51/tCO_2 (*2*) with an optimal combination of capture and storage technologies for a new pulverized-coal power plant. We note that the cost for retrofitting capture technology to an existing plant is higher than the new-plant cost—\$59/tCO_2 rather than \$41/tCO_2 (a 44% increase), resulting in a total CCS cost of approximately \$69/tCO_2 (a 17% increase) (*2*). A CCS cost of \$51/tCO_2 is considered current best-case, as higher costs can be found in the current literature. For example, Hamilton et al. (*10*) estimate the cost of CCS to be \$62/tCO_2 for a supercritical CO_2 pulverized coal plant; such increase in cost is partially attributed to recent increases in materials and fuel costs. Bukhteeva et al (*11*) estimate the total cost of CCS to be \$75.1/tCO_2 (\$56.2/$tCO_2$of which is due to separation and extra power required for separation). It should be noted that these costs are presented in constant 2010 (U.S.) dollars. Since the time scale of this project spans generations, constant dollar values accurately convey the cost of CCS (and revenues of alternative energy) to future generations. Discounting of these costs would eventually cause the cost of CCS to be negligible while compounding for inflation would introduce further uncertainty to these estimates. Thus, the constant dollar value offers a consistent, common comparison between CCS and alternative energy technologies.

The average installation cost for wind power is \$1700/kW with an average capacity factor of 30%, leading to an overall installation cost of \$5667/kW (*12*). Net revenue over the lifetime of a windmill (25 y) was estimated at \$394/y/kW (busbar price) after adjustment for operation and maintenance, land use, and other operating costs (*12*). The installed cost for a nuclear plant was initially estimated at \$4000/kW (*13, 14*), but adjustment for interest during construction was made, assuming a 5 y construction period. Assuming quarterly compounding of a 5% interest rate, a total interest adjustment of 13.52% was made, increasing the installed cost to \$4541/kW. Finally, considering the 90% capacity factor resulted in a "true" installed cost of \$5046/kW. Adjustment for CO_2 emissions associated with steel and concrete production for both wind and nuclear power was made (though these CO_2 emissions are negligible compared to the CO_2 avoided by using nonfossil energy). The recurring costs used in this study have been levelized over the lifetimes of the alternative energy installations. It is recognized here that all of the costs utilized in this study are volatile and subject to change. However, these calculations are designed to provide perspective on the economic efficiency with which CCS and alternative energy avoid CO_2 emissions.

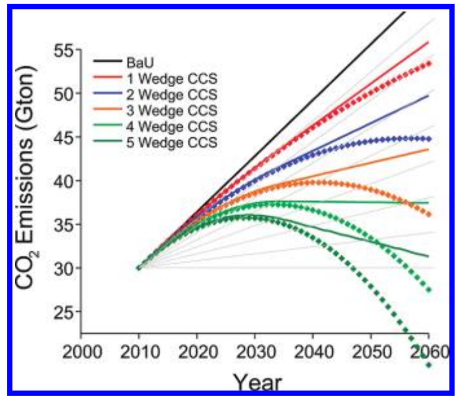


FIGURE 1. CO_2 emissions without virtual CCS (Business as Usual—BaU) and with investment in wind power (solid lines) or nuclear power (diamonds) in place of one to five wedges' worth of CCS. The light-gray lines correspond to the eight Pacala and Socolow wedges. It is demonstrated that CCS is not a cost-effective approach in reducing CO_2 emissions and that redirecting the CCS effort into alternative energy technologies would be more beneficial.

Virtual CCS for Wind and Nuclear Power. With these assumptions, as well as the assumption that alternative energy technologies can be readily deployed on a large scale, the total cost to perform CCS on a single wedge of CO_2 emissions was estimated to be \$5.10 trillion over 50 y. However, if \$5.10 trillion was spent to build windmills on an annual basis over the same period, 1.91 wedges' worth of CO_2 would be avoided over the lifetime of the windmills. Thus, wind power is roughly twice as effective at avoiding atmospheric CO_2 emissions as CCS on a per-dollar basis. In addition, a net pre-state incentive income of \$9.05 trillion in electricity sales would be earned over the lifetime of the windmills. Part of this income can then be spent on further developing wind power and supporting systems, a topic not considered here. The total useful wind power capacity for the world has been estimated at 72 TW (*15*); in our simulation, the maximum amount of one wedge of wind power employed at any time was 738 GW, 2 orders of magnitude below the total estimated capacity.

The results for nuclear power, instead of wind power or CCS, were even more impressive. For the same \$5.10 trillion investment over 50 y, a sufficient number of nuclear power plants could be installed to avoid 4.31 wedges' worth of CO_2 over the lifetime of the project. In addition to this CO_2 avoidance, approximately \$22.3 trillion would be generated via electricity sales during the lifetime of the nuclear plants. The attractive cost efficiency of nuclear plants stems from the competitive capital cost of \$5046/kW, high capacity factor (90%), and long lifetime (50 y). A maximum nuclear capacity of 1033 GW would be developed over the course of 50 y of virtual CCS.

Figure 1 illustrates carbon emissions after one to five wedges' worth of CCS have been used to develop wind (solid lines) and nuclear (diamonds) power. It is interesting to note that Figure 1 shows an initial increase in fossil energy for both cases because the alternative energy generated when CCS resources were first redirected was inadequate to offset

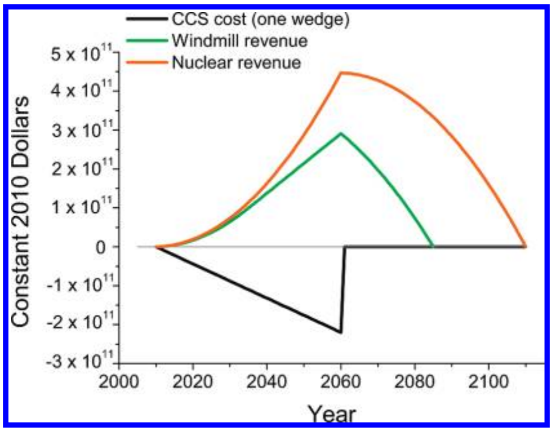


FIGURE 2. Comparison of wind power revenue (green line), nuclear revenue (orange line), and cost of CCS (black line) for one Pacala–Socolow wedge for a 50 y investment. Wind and nuclear power provide income beyond the 50 y investment because windmills have a lifetime of 25 y and nuclear plants have a lifetime of 50 y. Overall, $9.05 trillion for wind and $22.3 trillion for nuclear in revenue is realized from an investment of $5.1 trillion for one wedge.

TABLE 1. Dependence of Carbon Avoidance Ratio (Wind Power/CCS) on Wind Capacity Factor

wind capacity factor	30%	25%	20%	15%
WP/CCS (1 wedge)	1.95	1.59	1.27	0.95

energy demands. The fact that fossil energy will keep increasing for several years is expected to give adequate time for the development of alternative uses of coal. Fossil energy decreases (indicated by reduced CO_2 emissions) after sufficient alternative energy has been established, as a result of the cumulative effect of the alternative energy capacity. The light gray lines in Figure 1 correspond to the eight Pacala–Socolow wedges.

Figure 2 shows the constant value cost of CCS and revenue of wind and nuclear power from a $5.1 trillion investment (i.e., 1 wedge) over the period of 50 y. While CCS provides practically no revenue, wind and nuclear power will lead to revenues of $9.05 trillion and $22.3 trillion, respectively. The CCS cost is projected to increase over the 50 y period because of the expected increase in CO_2 emissions (Figure 1). This simulation does not reflect concurrent use of CCS and renewable energy. Rather, we propose to completely replace CCS efforts with the use of alternative energy. The alternative power revenue was found to initially increase exponentially and then follow a linear trend. This behavior is a result of the cumulative effect of alternative power establishment until the initial lifetime (25 y for wind, 50 y for nuclear) of the installations is exhausted. At this point, increases in alternative energy are tempered by loss of installations that have reached end of life. If virtual CCS were abandoned in 2060, wind power would continue to provide a revenue stream until all of the windmills reached 25 y of operation, while nuclear power would do the same until all nuclear plants reached 50 y of operation.

It is recognized here that the most productive wind sites will be developed first, as they should exhibit the highest capacity factors. As wind power is developed, it is possible that a capacity factor lower than 30% can be observed in some areas. Table 1 illustrates the dependence of carbon avoidance ratio on wind power capacity factor. Specifically, it shows how much CO_2 could be avoided by wind in place of CCS. It is apparent that, even as low as 15% capacity factor, wind is still competitive with CCS at avoiding CO_2 emissions.

TABLE 2. Dependence of Carbon Avoidance Ratio on Cost of CCS

Cost of CCS ($/ton)	27.0[a]	51.0 (*2*)	62.0 (*10*)	75.1 (*11*)
WP/CCS (1 wedge)	1.01	1.95	2.32	2.80
NP/CCS (1 wedge)	2.28	4.31	5.24	6.35

[a] The cost of $27.0/t$CO_2$ is included here to show the cost at which wind and CCS are equivalent for carbon avoidance.

However, the wind power development in this model does not exceed 2% of the expected world capacity for one Pacala-Socolow wedge. A similar effect is not considered for nuclear power since nuclear installations are typically operated at a 90% capacity factor for their lifetimes. It can be seen in Table 2 that both wind and nuclear power become increasingly more attractive than CCS as higher estimates of CCS cost are utilized. A CCS cost of $27/t$CO_2$ was estimated as the cost at which the wind power carbon avoidance ratio is equal to 1, which means that wind and CCS are equally cost efficient at avoiding CO_2 emissions. It should be noted that wind and nuclear power are expected to be components of a diverse energy portfolio. Also, since discounting would affect the cost of CCS and alternative energy technologies equally, the carbon avoidance ratio would be unchanged if discounting were applied.

Potential Implications of "Externalities" on CCS Cost. The cost of CCS is largely based on modeling since few large-scale CCS projects are operational worldwide to provide observational data. As such, small, "negligible" costs associated with CCS have not been included in the total CCS cost. For example, treatment of produced water from CCS applications in aquifers is considered an appreciable cost, which has been estimated at $1.50/t$CO_2$. For reference, monitoring and verification of an underground CO_2 plume has been estimated at approximately $0.3/t$CO_2$ and is often included in CCS cost estimates (*2*). The cost of produced-water treatment has not been included in the total cost of CCS of $51/t$CO_2$ (*2*). Although this cost is somewhat small compared with the overall CCS cost, it would result in an additional $0.14 trillion over 50 y for one wedge of CCS. Small, negligible costs such as this can add up to further increase the real cost of CCS. It is acknowledged that such externalities can also apply to alternative energy, but the wind and nuclear data used here are based on real-world observations of operational installations.

The calculations presented in this article should instill some caution in a decision to place emphasis on CCS. CCS consumes resources and provides no benefits other than CO_2 avoidance—a finding that should cause us to consider redirecting our efforts. Alternative energy technologies can avoid carbon emissions more efficiently than CCS and also produce profits. As we move forward in developing low-carbon energy production strategies, those strategies that have single benefits, with nothing else to offer, must be considered critically before substantial investments are made. The main difference between CCS and alternative energy technologies is that CCS is not an investment with expected revenue. If, instead of CCS, we focus on problems associated with sustainable solutions, we can go directly to solutions that simultaneously address both our current and future energy needs and the problem of atmospheric carbon emissions.

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Acknowledgments

This work was partially supported by the American Chemical Society Green Chemistry Institute (ACS-GCI) through a grant to Georgia Institute of Technology and conducted in collaboration with Oak Ridge National Laboratory (ORNL). ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy, under contract no. DE-AC05-00OR22725. The authors thank Drs. David DePaoli and Joanna McFarlane for reviewing the manuscript and Dr. Marsha Savage for editing the manuscript.

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ES903626U