3.6. Why Not Synthetic Direct Air Carbon Capture and Storage?

Synthetic direct air carbon capture and storage (SDACCS) is the direct removal of CO$_2$ from the air by its chemical reaction with other chemicals. Upon removal, the CO$_2$ is sequestered either underground or in a material, just as CO$_2$ from fossil fuels with carbon capture and storage (CCS) is. Alternatively, the CO$_2$ is sold for use in industry, just as CO$_2$ from fossil fuels with carbon capture and use (CCU) is.

SDACCS should not be confused with natural direct air carbon capture and storage (NDACCS), which is the natural removal of carbon from the air by either planting trees or reducing permanent deforestation (by reducing open biomass burning -- Section 2.9.1). Growing a tree removes CO$_2$ naturally by photosynthesis and sequesters the carbon within organic material in the tree for decades to centuries. Reducing open biomass burning similarly sequesters carbon in trees and eliminates emissions of health-affecting air pollutants and climate-affecting non-CO$_2$ chemicals contributing to global warming. Trees also absorb air pollutants, helping to filter air pollution from the air. Whereas NDAACS is recommended in a 100 percent WWS world, SDACCS is not. In this section, methods of SDACCS and their consequences are discussed.

In 1754, Joseph Black (1728 to 1799), a Scottish physician and chemist, isolated CO$_2$, which he named fixed air. He found that heating the odorless white powder magnesium alba (magnesium carbonate, MgCO$_3$) or limestone (calcium carbonate, CaCO$_3$) by the respective reactions,

\[
\text{MgCO}_3 + \text{heat} \rightarrow \text{CO}_2 + \text{MgO} \quad (3.11)
\]

\[
\text{CaCO}_3 + \text{heat} \rightarrow \text{CO}_2 + \text{CaO} \quad (3.12)
\]

released a gas (CO$_2$) that could not sustain life or fire. The remaining solids, magnesium usta (magnesium oxide, MgO) and quicklime (calcium oxide, CaO), respectively, weighed less than the original solids. He found further that by dissolving the gas in a solution of limewater [calcium hydroxide, Ca(OH)$_2$], the gas “fixed” to the CaO, reforming the calcium carbonate by

\[
\text{CO}_2 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \quad (3.13)
\]

The calcium carbonate precipitated as a white solid from the solution. He similarly found that adding potash (potassium carbonate, K$_2$CO$_3$) to magnesium oxide by
K₂CO₃ + MgO → K₂O + MgCO₃  \hspace{1cm} (3.14)

resulted in MgCO₃. The mass of MgCO₃ exceeded that of MgO by the same mass that was lost when MgCO₃ was heated by Reaction 3.11 to form MgO. The difference in mass in both cases was the mass of CO₂. As such, Black quantified the mass of CO₂ for the first time.

Black soon recognized that the fixed air he had isolated was the same gas that the Belgian John Baptist Van Helmont (1577 to 1644) found by fermenting alcoholic liquor, burning charcoal, and acidifying marble and chalk. Van Helmont had called this vapor gas silvestre (“gas that is wild and dwells in out-of-the-way places”).

Today, SDACCS techniques include reacting CO₂ from the air with (a) alkali and alkaline Earth metal oxides and hydroxides and (b) organic-inorganic sorbents consisting of amines. The CO₂ sequestered by these methods can either be stored underground, sequestered in concrete (Section 2.4.8), or sold for use in industry. Below, methods of reacting CO₂ with air are discussed followed by an examination of the issues associated with SDACCS.

3.6.1. Reaction of CO₂ With Alkali and Alkaline Earth Metal Oxides and Hydroxides

One way to remove CO₂ from the air is to react it with alkali and alkaline Earth metal oxides and hydroxides (Duan and Sorescu, 2010).

**Alkali metal oxides** include Na₂O and K₂O.

**Alkali metal hydroxides** include NaOH and KOH.

**Alkaline Earth metal oxides** include BeO, MgO, CaO, SrO, and BaO.

**Alkaline Earth metal hydroxides** include Be(OH)₂, Mg(OH)₂, Ca(OH)₂, Sr(OH)₂, and Ba(OH)₂.

A classic method of removing CO₂ from the air while recycling the material that is removing it is by exposing CO₂ to a large pool of limewater (an Alkaline Earth metal hydroxide) by Equation 3.13. The resulting solid CaCO₃ is heated to 700 K, releasing a concentrated stream of CO₂ through Equation 3.12 that can be captured and used. The CaO is then returned to limewater by

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2
\]  \hspace{1cm} (3.15)

(Lackner et al., 1999). The problem with this process is that it needs a continuous net input of energy, which can become enormous with a large amount of CO₂ processed. An alternative process, which has been used in the paper industry for a long time, is

\[
\text{CO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O}
\]  \hspace{1cm} (3.16)

\[
\text{Na}_2\text{CO}_3 + \text{Ca(OH)}_2 \rightarrow 2\text{NaOH} + \text{CaCO}_3
\]  \hspace{1cm} (3.17)

\[
\text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2
\]  \hspace{1cm} (3.18)

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2
\]  \hspace{1cm} (3.19)

(Sanz-Perez et al., 2016). However, this reaction sequence also requires a net input of energy that accumulates with an increasing amount of CO₂ processed. In general, removing CO₂ from the air with some hydroxides and oxides [e.g., Na₂O, K₂O, MgO, NaOH, KOH, and Mg(OH)₂] is more efficient than with others (Duan and Sorescu, 2010). However, all reaction sequences result in net additions of energy that accumulate with increasing amounts of CO₂ processed.

3.6.2. Reaction of CO₂ With Organic-Inorganic Sorbents Consisting of Amines

Another approach to removing CO₂ from the air is by reacting it with an organic-inorganic sorbent containing amines. **Amines** are derived from **ammonia (NH₃)** by replacing one or more hydrogen atom with an **alkyl group**
or aryl group (a functional group containing an aromatic ring). In such cases, the alkyl or aryl group can be denoted simply with an R, so an organic-inorganic sorbent containing amines can take the form of RNH₂. Reaction of CO₂ with RNH₂ results in

\[ \text{CO}_2 + 2\text{RNH}_2 \rightarrow \text{RNH}_2^+ + \text{RNHCOO}^- \] (3.20)

The advantage of this reaction is that CO₂ forms strong bonds with the amine group, so CO₂ can be absorbed effectively at low partial pressures. This method of CO₂ removal is used in submarines to purify air, but its application to removing CO₂ from the ambient atmosphere then returning the RNH₂ still requires a net energy input and high cost.

### 3.6.3. Opportunity Cost of SDACCS

By removing CO₂ from the air, SDACCS does exactly what WWS generators, such as wind turbines and solar panels, do. This is because WWS generators replace fossil generators, preventing CO₂ from getting into the air in the first place. The impact on climate of removing one molecule of CO₂ from the air is effectively the same as the impact of preventing one molecule from getting into the air in the first place.

The differences between WWS generators and SDACCS equipment, though, are that the WWS generators also (a) eliminate non-CO₂ air pollutants from fossil fuel combustion; (b) eliminate the upstream mining, transport, and refining of fossil fuels and the corresponding emissions; (c) largely reduce the pipeline, refinery, gas station, tanker truck, oil tanker, and coal train infrastructure of fossil fuels; (d) largely eliminate oil spills, oil fires, gas leaks, and gas explosions; (e) substantially reduce international conflicts over energy; (f) reduce the large-scale blackout risk due to the distributed nature of many WWS technologies; and so on.

SDACCS does none of that. Its sole benefit is to remove CO₂ from the air. To do that, it costs more than renewable energy. The Intergovernmental Panel on Climate Change review of SDACCS technologies concludes,

> “The energy requirements and economic costs of Direct Air Carbon Capture and Storage (DACCS) and enhanced weathering remain high.” (De Coninck et al., 2018, p. 4-7).

The differences between WWS and SDACCS technologies just outlined translate to an opportunity cost of using SDACCS. For example, because SDACCS removes no health-affecting air pollutants from the air; money spent on it takes funding away from the purchase of clean, renewable WWS technologies that do replace fossil fuel power plants or vehicles and eliminate their health-affecting emissions and associated health costs.

Second, SDACCS requires substantial electricity and heat to work, and this must come from the grid, a dedicated fossil fuel source, or a dedicated WWS source. If grid electricity is used, air pollution emissions directly increase compared with no SDACCS. In addition, some of the CO₂ emissions reduced by SDACCS are offset by increases in CO₂ from the grid electricity. If instead, capital is used to purchase WWS electricity to power the SDACCS plant, less capital is available to purchase WWS electricity to displace grid electricity. This also results in CO₂ and air pollution emissions increasing relative to no SDACCS. Similarly, if a dedicated fossil power generator is purchased and the CO₂ emissions are captured by the SDACCS facility, less capital is available to purchase WWS electricity to offset grid emissions.

Third, because SDACCS increases or prevents the reduction of grid electricity use, it extends the life of fossil fuel and nuclear power plants and the upstream mining, transport, and processing of fossil fuels and the resulting emissions associated with them. It similarly increases the energy insecurity and environmental and health consequences of the fossil fuel and nuclear infrastructures, including the yearly increase in land degradation due to these industries.
Fourth, the higher cost of SDACCS relative to WWS electric power technologies ensures that a fixed amount of capital spent on SDACCS increases CO$_2$ and air pollution more than if the same money were spent on WWS technologies.

Even if the cost per unit mass of CO$_2$ removed by SDACCS were the same as or lower than that of WWS, SDACCS would still increase CO$_2$ and air pollution relative to WWS because of (a) the need for SDACCS to use electricity and (b) the fact that SDACCS does not reduce any air pollutants, whereas all WWS technologies do. Because SDACCS needs electricity, it either increases CO$_2$ from the background grid directly or increases it indirectly by requiring a dedicated WWS or fossil fuel source to provide that electricity. The capital spent on either prevents WWS from otherwise being purchased and used to displace fossil fuel grid electricity or transportation. Either way, SDACCS results in more CO$_2$ than WWS.

In terms of cost, one final factor is social cost, discussed in more detail in Chapter 7. The **social cost of air pollution** is the health-related cost of air pollution to society. For example, air pollution increases death and illness, both of which increase hospitalization stays, emergency room visits, lost work days, lost school days, insurance rates, taxes, workman’s compensation rates, and loss of companionship, among other costs. A derived worldwide mean health cost of fossil-fuel energy among all energy sectors is about $127 per MWh of electricity or other energy produced (Table 7.11). The cost of a new wind turbine is about $43 (29 to 56) per MWh of electricity produced (Lazard, 2018). Thus, a new wind turbine displacing a fossil fuel power plant immediately reduces society’s direct energy cost plus health cost by about $43 minus $127 = -$84/MWh. In other words, every wind turbine installed avoids a high cost to society. On the other hand, SDACCS does not reduce any air pollution, so **even if SDACCS were free, purchasing a wind turbine would cost society less than would SDACCS**.

Example 3.12 illustrates the direct and social cost of SDACCS. The example illustrates that, so long as grid emissions occur, SDACCS will always increase air pollution no matter how low its cost, and SDACCS will always increase CO$_2$e emissions until its direct cost is much lower than that of WWS technologies.

Example 3.12: Costs and Impacts On CO$_2$e and Air Pollution Emissions of SDACCS.

Compare the cost range of SDACCS, $94 to $232 per tonne-CO$_2$-removed (Keith et al., 2018), with the 2017 cost of onshore wind in the United States, $43 (29 to 56) per MWh of electricity produced (Lazard, 2018) under three scenarios: (a) all energy for the SDACCS plant is provided by the electric power grid, (b) all energy for the plant is provided by a dedicated natural gas powered combined cycle gas turbine (CCGT) whose emissions are allowed to escape, and (c) all energy for the plant is provided by the same CCGT turbine, but whose combustion CO$_2$ emissions, but not upstream CO$_2$e emissions, are also captured by the plant. In each case, account for the social cost of air pollution ($127/MWh) avoided by wind but not by SDACCS and estimate the resulting difference in overall cost per MWh between the technologies.

Assume the SDACCS equipment removes 825 kg-CO$_2$ from the air per MWh of energy required to run the plant. This number is derived from Keith et al. (2018) by noting that the gas turbine used in that study emits 0.48 megatonnes-CO$_2$/y, while the plant captures 0.98 megatonnes-CO$_2$/y and that the CO$_2$ combustion emissions from a CCGT are 404 kg-CO$_2$/MWh (Table 3.1). Also assume that the average CO$_2$e emissions (assuming a 100-year time frame) on the U.S. grid in 2017 are about 557.3 kg-CO$_2$e per MWh of electricity produced and that the upstream CO$_2$e emissions (with a 100-year time frame) from the CCGT are 199.1 kg-CO$_2$e/MWh (Table 3.1).

Solution:

In Case (a), 1 tonne-CO$_2$ removed from the air requires 1 tonne / (0.825 tonne-CO$_2$-removed / MWh) = 1.21 MWh of electricity. Multiplying 1.21 MWh per tonne-CO$_2$-removed by 557.3 kg-CO$_2$e/MWh of emissions from the background grid gives 676 kg-CO$_2$e-emitted from the grid per tonne-CO$_2$ removed. Thus, the net removal of CO$_2$e from the air for every tonne captured from the air is 1 tonne minus 0.676 tonnes = 0.324 tonnes. Multiplying the $94 to $232 per tonne-CO$_2$ removed by 1 tonne-removed / 0.324 net-tonnes-removed = $290 to $716 per net-tonne-CO$_2$-removed. Multiplying the average U.S. grid emission rate of 557.3 kg-CO$_2$e/MWh by the cost of SDACCS per net-tonne-CO$_2$-removed gives an equivalent cost of reducing CO$_2$ from the grid with SDACCS of $162 to $399 per MWh-electricity-produced. In comparison, a wind turbine
The direct cost is $29 to $56 per MWh. Thus, SDACCS costs 2.9 to 14 times the direct cost of onshore wind to avoid the same CO\textsubscript{2}. However, subtracting the avoided air pollution social cost from the direct cost of wind gives the overall cost of a wind turbine as -$98 to -$71 per MWh, so the social cost of SDACCS is $233 to $497 per MWH higher than that of wind.

In Case (b) the total CO\textsubscript{2} emissions from the gas plant are 404 + 199 = 603 kg-CO\textsubscript{2}/MWh. Multiplying by 1.21 MWh per tonne-CO\textsubscript{2} removed from Case (a) gives 730 kg-CO\textsubscript{2} emitted from the gas turbine per tonne-CO\textsubscript{2} removed. The net CO\textsubscript{2} removal from the air for every tonne captured from the air is then 1 tonne minus 0.73 tonnes = 0.27 tonnes. Multiplying the $94 to $232 per tonne-CO\textsubscript{2} removed by 1 tonne-removed / 0.27 net-tonnes-removed = $348 to $859 per net-tonne-CO\textsubscript{2}-removed. Multiplying by the U.S. grid emission rate gives an equivalent cost of reducing CO\textsubscript{2} from the grid in this case with SDACCS of $194 to $479 per MWh-electricity-produced, which is 3.5 to 17 times the direct cost of onshore wind to avoid the same CO\textsubscript{2}. However, the social cost of SDACCS is $265 to $577 per MWH higher than that of wind.

In Case (c) the total CO\textsubscript{2} emissions from the gas plant are the upstream emissions, 199 kg-CO\textsubscript{2}/MWh. Performing the same calculation as in Case (b) gives 241 kg-CO\textsubscript{2} emitted from the gas turbine per tonne-CO\textsubscript{2} removed, a net reduction of 0.759 tonnes-CO\textsubscript{2} per tonne-CO\textsubscript{2} removed from the air, a cost of $124 to $306 per net-tonne-CO\textsubscript{2}-removed from the air, and an equivalent cost of reducing grid electricity CO\textsubscript{2} of $69-$171 per MWH-electricity produced, 1.2 to 6 times the direct cost of onshore wind. The social cost of SDACCS is $140 to $269 per MWH higher than that of wind.

The implication of these results are that, in terms of direct cost, 1.2 to 17 times more CO\textsubscript{2} is avoided per MWh produced with a new wind turbine than can be removed from the air by SDACCS per MWH of background power produced. In terms of direct plus air pollution health cost, SDACCS is $140 to $577 per MWH more expensive than wind.

An alternative way to look at this result is as follows: The same direct-cost capital used on SDACCS could have been spent on 1.2 to 17 times the CO\textsubscript{2} emission reduction with new wind displacing grid electricity, which also would have reduced air pollution.

In addition, because SDACCS allows fossil fuels and nuclear power to continue, it exacerbates the problems and emissions associated with mining, transporting, and processing fossil fuels and uranium. Finally, the cost discussed in this example ignores the cost of storage. Upon removal of large amounts of CO\textsubscript{2}, SDACCS will either need to be stored at additional cost and energy or used for a purpose that will itself requires energy thus results in more emissions. To date, most CO\textsubscript{2} captured has been used for enhanced oil recovery.

The only condition under which SDACCS can provide a benefit for both air pollution and climate is when the background grid is 100 percent WWS. In that case, SDACCS can reduce CO\textsubscript{2} without increasing air pollution. Also at that point, there is no more health cost benefit of implementing more WWS. Even then though, the question is whether the cost of SDACCS per unit mass of CO\textsubscript{2} removed exceeds that of reducing non-energy CO\textsubscript{2} from open biomass burning, agriculture and waste, halogen emissions, and nitrous oxide emissions (Section 2.9).

Whether SDACCS should be applied to filtering the CO\textsubscript{2} emissions from a steel or concrete manufacturing plant is an interesting question. In theory, this is a good idea for tackling a point source of air pollution. However, until all energy has been converted to 100 percent WWS, using limited capital for an SDACCS facility rather than using it to purchase WWS electricity or heat to replace fossil fuel electricity, heat, and transportation fuel may be a significant climate plus air pollution opportunity cost, particularly given the energy input needed for the SDACCS facility. Any proposal for such a SDACCS at a steel or concrete plant would need to be evaluated critically.

References


