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$_2$ global warming agents at the same time. Trees also absorb air pollutants, helping to filter them from the air.

Whereas NDAACS is recommended in a 100 percent WWS world, SDACCS is not. **SDACCS is basically a cost, or tax, added to the cost of fossil fuel generation, so it raises the cost of using fossil fuels while reducing no air pollution and providing no energy security.** To the contrary, it permits the fossil fuel industry to expand its devastation of the environment and human health by allowing mining and air pollution to continue at an even higher cost to consumers than with no carbon capture.

If the same funds were instead used to replace fossil fuels entirely with clean, renewable energy, air pollution and carbon emissions from fossil fuels would be eliminated, as would fossil fuel mining, all at a lower cost. Because the cost of renewables replacing fossils and eliminating their carbon emissions is lower than the cost of SDACCS taking carbon out of the air, using renewables reduces carbon more than does using SDACCS and eliminates air pollution, which SDACCS does not. As such, SDACCS represents an opportunity cost in multiple respects. 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,

\[
\text{MgCO}_3 + \text{heat} \rightarrow \text{CO}_2 + \text{MgO} \tag{3.11}
\]
\[
\text{CaCO}_3 + \text{heat} \rightarrow \text{CO}_2 + \text{CaO} \tag{3.12}
\]
released a gas (CO\(_2\)) that could not sustain life or fire. The remaining solids, magnesium uste (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

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

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

\[
\text{K}_2\text{CO}_3 + \text{MgO} \rightarrow \text{K}_2\text{O} + \text{MgCO}_3 \tag{3.14}
\]

resulted in MgCO\(_3\). The mass of MgCO\(_3\) exceeded that of MgO by the same mass that was lost when MgCO\(_3\) was heated by Reaction 3.11 to form MgO. The difference in mass in both cases was the mass of CO\(_2\). As such, Black quantified the mass of CO\(_2\) 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 CO\(_2\) from the air with (a) alkali and alkaline Earth metal oxides and hydroxides and (b) organic-inorganic sorbents consisting of amines. The CO\(_2\) 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 CO\(_2\) with air are discussed followed by an examination of the issues associated with SDACCS.

### 3.6.1. Reaction of CO\(_2\) With Alkali and Alkaline Earth Metal Oxides and Hydroxides

One way to remove CO\(_2\) from the air is to react it with alkali and alkaline Earth metal oxides and hydroxides (Duan and Sorescu, 2010).

**Alkali metal oxides** include Na\(_2\)O and K\(_2\)O.

**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 CO\(_2\) from the air while recycling the material that is removing it is by exposing CO\(_2\) to a large pool of limewater (an Alkaline Earth metal hydroxide) by Equation 3.13. The resulting solid CaCO\(_3\) is heated to 700 K, releasing a concentrated stream of CO\(_2\) through Equation 3.12 that can be captured and used. The CaO is then returned to limewater by

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

(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 CO\(_2\) processed. An alternative process, which has been used in the paper industry for a long time, is

\[
\text{CO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \tag{3.16}
\]

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

\[
\text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2 \tag{3.18}
\]
CaO + H₂O → Ca(OH)₂ (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 (CH₃, C₂H₅, C₃H₇, etc…) 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

CO₂ + 2RNH₂ → RNH₃⁺ + 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 the same as the impact of preventing one molecule from getting into the air in the first place.

The differences between WWS 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; and (f) reduce the large-scale blackout risk associated with centralized power plants by decentralizing/distributing power.

SDACCS does none of that. Its sole benefit is to remove CO₂ from the air. To do that, it costs more than renewable energy. In fact, SDACCS is basically just a cost added onto the cost of using fossil fuels. Since new wind and solar for electricity generation, in particular, are less expensive than the least expensive fossil fuels for electricity generation, replacing fossils with wind and solar reduces cost. On the other hand, spending the same money on SDACCS is a cost, or tax, effectively added to the cost of fossil fuel generation.

The differences between WWS and SDACCS technologies just outlined translate to a severe 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 CO\textsubscript{2} 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 CO\textsubscript{2} and air pollution emissions increasing relative to no SDACCS. Similarly, if a dedicated fossil power generator is purchased and the CO\textsubscript{2} 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\textsubscript{2} and air pollution more than if the same money were spent on WWS technologies.

Even if the cost per unit mass of CO\textsubscript{2} removed by SDACCS were the same as or lower than that of WWS, SDACCS would still increase CO\textsubscript{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\textsubscript{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\textsubscript{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 based on data from a real case study. In the plant examined, a natural gas combined cycle gas turbine is used to provide the electricity needed to remove CO\textsubscript{2} from the air. In one case, combustion emissions from the gas plant are not captured. In the other, they are. In both cases, upstream emissions from mining and transporting natural gas still occur.

**Example 3.12. Costs and Impacts On CO\textsubscript{2}e and Air Pollution Emissions of SDACCS.**

Compare the cost range of SDACCS, $94 to $232 per tonne-CO\textsubscript{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\textsubscript{2} emissions, but not upstream CO\textsubscript{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$e from the grid with SDACCS of $162 to $399 per MWh-electricity-produced. In comparison, a wind turbine direct cost is $29 to $56 per MWh. Thus, SDACCS costs 2.9 to 14 times the direct cost of onshore wind to avoid the same CO$_2$. However, subtracting the avoided air pollution social cost ($127/MWh) from the direct cost of wind gives the overall social 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$_2$e emissions from the gas plant are 404 + 199 = 603 kg-CO$_2$e/MWh. Multiplying by 1.21 MWh per tonne-CO$_2$-removed from Case (a) gives 730 kg-CO$_2$e-emitted from the gas turbine per tonne-CO$_2$ removed. The net CO$_2$e removal from the air for every tonne captured from the air is then 1 tonne minus 0.73 tonnes = 0.27 tonnes. In other words, of every tonne of CO$_2$ removed from the air by this process, 73 percent is re-emptied due to using the gas turbine and only 27 percent is actually sequestered.

Multiplying the $94 to $232 per tonne-CO$_2$ removed by 1 tonne-CO$_2$-removed / 0.27 net-tonnes-CO$_2$-removed = $348 to $859 per net-tonne-CO$_2$-removed. Multiplying by the U.S. grid emission rate (557.3 kg-CO$_2$e/MWh) gives an equivalent cost of reducing CO$_2$e from the grid in this case with SDACCS of $194 to $479 per MWh-electricity-produced, which is 3.5 to 17 times the direct cost of onshore wind to avoid the same CO$_2$. However, since the social cost of a wind turbine is -$98 to -$71 per MWh, the social cost of SDACCS is $265 to $577 per MWh higher than that of wind.

----------

In Case (c) the total CO$_2$e emissions from the gas plant are only the upstream emissions, 199 kg-CO$_2$e/MWh, because the plant captures the combustion emissions. However, the plant requires more energy per tonne-CO$_2$ captured from the air, because not only is the plant capturing CO$_2$ from the ambient air, but it is also capturing CO$_2$ from the gas plant. The additional CO$_2$ it is capturing from the gas plant is 404 kg-CO$_2$/kWh directly emitted by the plant multiplied by 1.21 MWh per tonne-CO$_2$ removed from the ambient air, which equals 489 kg-CO$_2$/tonne-CO$_2$-removed-from-the-air. Multiplying this again by 1.21 MWh per tonne-CO$_2$ removed gives the additional energy required to remove this CO$_2$, 0.59 MWh per tonne-CO$_2$-removed-from-the-ambient-air. Adding this to the original 1.21 MWh per tonne-CO$_2$-removed gives 1.80 MWh per tonne-CO$_2$-removed-from-the-air, now accounting for energy needed to capture the gas plant emissions. Of this total, 67.2 percent of the energy is used to remove CO$_2$ from the ambient air and the rest is used to remove CO2 from the gas direct emissions.

Multiplying 1.80 MWh per tonne-CO$_2$-removed by the upstream emissions from the gas plant, 199 kg-CO$_2$e/MWh, gives 358 kg-CO$_2$e emitted due to the gas turbine per tonne-CO$_2$-removed-from-the-ambient-air. This represents a net reduction of 0.642 tonnes-CO$_2$e per tonne-CO$_2$ removed from the air. In other words, of every tonne of CO$_2$ removed from the air in this case, 35.8 percent is re-emptied and 64.2 percent is sequestered.

Because the CO$_2$ removal cost, $94 to $232 per tonne-CO$_2$ removed, applies to all CO$_2$ removed, but we want to know the cost as applied to the CO$_2$ removed from the ambient air, we must multiply the removal cost by the ratio 1.49:1, which is the ratio of the tonnes-CO$_2$ captured from the gas plant plus from the ambient air divided by that from the ambient air alone. The result is $140 to $346 per tonne-CO$_2$-removed-from-the-ambient-air. Further multiplying this cost by 1 tonne-CO$_2$-removed / 0.642 net-tonnes-CO$_2$-removed to account for the fact that 35.8 percent of the CO$_2$ is effectively returned to the air gives $218 to $539 per net-tonne-CO$_2$-removed from the air.

Next, multiplying by the U.S. grid emission rate (557.3 kg-CO$_2$e/MWh) gives an equivalent cost of reducing CO$_2$ from the grid in this case with SDACCS of $121 to $300 per MWh-electricity-produced. This cost is 2.2 to 10 times the direct cost of
onshore wind. However, since the overall social cost of a wind turbine is -$98 to -$71 per MWh, the social cost of SDACCS is $192 to $398 per MWh higher than that of wind.

An alternative way to look at this result is as follows: If the same direct-cost capital spent on SDACCS were spent on wind, instead, the wind would result in 2.2 to 10 times [in Case (c)] or 3.5 to 17 times [in Case (b)] the CO\(_2\)e emission reduction. The wind also would have eliminated air pollution from grid electricity.

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\(_2\), SDACCS will either need to be stored at additional cost and energy or used for a purpose that will itself require energy thus results in more emissions. To date, most CO\(_2\) captured has been used for enhanced oil recovery.

In the case in Example 3.12 where the CO\(_2\) is not captured from the gas plant, 73 percent of all CO\(_2\) captured is effectively re-emitted to the air either as gas combustion emissions or upstream emissions of CO\(_2\). In that case, the direct cost of CO\(_2\) captured from the ambient air per unit grid energy used to produce the CO\(_2\) is 3.5 to 17 times the cost of preventing the emissions in the first place with a wind turbine replacing grid electricity. In addition, because the system does not eliminate any air pollution emissions from grid electricity, the air pollution plus energy social cost of this SDACCS system is $265 to $577/MWh higher than that of wind.

In the case where the CO\(_2\) is captured from the gas plant, 36 percent of all CO\(_2\) captured is effectively re-emitted to the air. The direct cost of CO\(_2\) captured from the ambient air per unit grid energy used to produce the CO\(_2\) is still 2.2 to 10 times the cost of preventing the emissions in the first place with a wind turbine. The air pollution plus energy social cost of this SCACCS system is $192 to $398/MWh higher than that of wind.

In sum, 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. Further, it always increases the mining, transport, and processing of fossil fuels compared with using WWS instead.

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\(_2\) 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\(_2\)e removed exceeds that of reducing non-energy CO\(_2\)e 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\(_2\) 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


