Why Not Synthetic Direct Air Carbon Capture and Storage (SDACCS) as Part of a 100% Wind-Water-Solar (WWS) and Storage Solution to Global Warming, Air Pollution, and Energy Security

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Contact: Jacobson@stanford.edu; Twitter @mzjacobson

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 (SDACCU), just as CO_2 from fossil fuels with carbon capture and use (CCU) is.

SDACCS/U 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/U is basically a cost, or tax, added to the cost of fossil fuel generation**, so it raises the cost of using fossil fuels while increasing air pollution due to its energy requirements 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.

Based on data from an existing facility powered by natural gas (Table 3.7), a **SDACCS/U plant results in 90 percent (averaged over 20 years) to 69 percent (averaged over 100 years) of the CO_2e that it captures from the air being returned to the air due to the generation of energy required to run the equipment**. Even if SDACCS/U is powered by renewable electricity, it captures less CO_2e than the same renewable electricity replacing a coal or natural gas plant.

Because SDACCS/U reduces little carbon, allows air pollution to continue, and incurs an equipment cost, spending on it rather than on renewables replacing fossil fuels or bioenergy always increases total social cost (equipment plus health plus climate cost). No improvement in SDACCS/U equipment can change this conclusion, since SDACCS/U always incurs an equipment cost never incurred by renewables, and SDACCS/U never reduces, instead mostly increases, air pollution and mining.

In this section, methods of SDACCS/U and their consequences are discussed.

3.6.1. Discovery of Chemical Removal of CO_2 from the Air

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,

$$MgCO_3 + \text{heat} \rightarrow CO_2 + MgO \quad (3.12)$$
$$CaCO_3 + \text{heat} \rightarrow CO_2 + CaO \quad (3.13)$$

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

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \quad (3.14)$$

The calcium carbonate precipitated as a white solid from the solution. He similarly found that adding potash (**potassium carbonate**, **K_2CO_3**) to magnesium oxide by

$$K_2CO_3 + MgO \rightarrow K_2O + MgCO_3 \quad (3.15)$$

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 3.12 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/U 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/U.

3.6.2. 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_2O and K_2O.
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 the CO_2 to a large pool of limewater (an Alkaline Earth metal hydroxide) by Equation 3.14. The resulting solid

$CaCO_3$ is heated to 700 K, releasing a concentrated stream of CO_2 through Equation 3.13 that can be captured and used. The CaO is then returned to limewater by

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (3.16)$$

(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

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O \quad (3.17)$$
$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3 \quad (3.18)$$
$$CaCO_3 + heat \rightarrow CaO + CO_2 \quad (3.19)$$
$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (3.20)$$

(Sanz-Perez et al., 2016). However, this reaction sequence also requires a net input of energy that accumulates with an increasing amount of CO_2 processed. In general, removing CO_2 from the air with some hydroxides and oxides [e.g., Na_2O, K_2O, 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 CO_2 processed.

3.6.3. Reaction of CO_2 with Organic-Inorganic Sorbents Consisting of Amines

Another approach to removing CO_2 from the air is by reacting it with an organic-inorganic sorbent containing amines. **Amines** are derived from **ammonia** (**NH_3**) by replacing one or more hydrogen atom with an **alkyl group** (CH_3, C_2H_5, C_3H_7, 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 RNH_2. Reaction of CO_2 with RNH_2 results in

$$CO_2 + 2RNH_2 \rightarrow RNH_3^+ + RNHCOO^- \quad (3.21)$$

The advantage of this reaction is that CO_2 forms strong bonds with the amine group, so CO_2 can be absorbed effectively at low partial pressures. This method of CO_2 removal is used in submarines to purify air, but its application to removing CO_2 from the ambient atmosphere then returning the RNH_2 still requires a net energy input and high cost.

3.6.4. Opportunity Cost of SDACCS/U

By removing CO_2 from the air, SDACCS/U does exactly what WWS generators, such as wind turbines and solar panels, do. This is because WWS generators replace fossil generators, preventing CO_2 from getting into the air in the first place. The impact on climate of removing one molecule of CO_2 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 generators and SDACCS/U equipment, though, are that the WWS generators also (a) eliminate non-CO_2 air pollutants from fossil fuel combustion; (b) eliminate the upstream mining, transport, and refining of fossil fuels and the corresponding emissions; (c) reduce the pipeline, refinery, gas station, tanker truck, oil tanker, and coal train infrastructure of fossil fuels; (d) reduce 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/U does none of that. Its sole benefit is to remove CO_2 from the air, but at a higher cost than using renewable energy to do the same thing. In fact, SDACCS/U is basically a cost added onto the cost of using fossil fuels.

Moreover, SDACCS/U is an opportunity cost. Because SDACCS/U removes no health-affecting air pollutants from the air; money spent on it takes funds away from the purchase of clean, renewable WWS technologies that replace fossil fuel power plants and vehicles while eliminating their health effects and costs and more CO_2e than the SDACCS/U removes.

Second, SDACCS/U 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/U and a portion of the CO_2 emissions reduced by SDACCS/U is reemitted to the air due to the use of grid electricity.

Third, because SDACCS/U increases or prevents the reduction of grid electricity use, it extends the life of fossil fuel and nuclear power plants, the upstream mining, transport, and processing of fossil fuels and uranium for those plants, and the emissions associated with the upstream mining. SDACCS/U similarly increases the energy insecurity and environmental and health consequences of the fossil fuel and nuclear infrastructures.

Fourth, the higher cost of SDACCS/U relative to WWS electric power technologies ensures that a fixed amount of capital spent on SDACCS/U 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/U were the same as or lower than that of WWS, SDACCS/U would still increases air pollution relative to WWS because SDACCS/U does not reduce any air pollutants, whereas all WWS technologies do. In addition, when fossil fuels are used to power SDACCS/U equipment, such fossils increases CO_2.

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 workdays, lost school days, insurance rates, taxes, workman's compensation rates, and loss of companionship, among other costs. A worldwide mean health cost of fossil-fuel energy among all energy sectors is about $169 per MWh of energy produced but varying by country (Table 7.11). The cost of a new wind turbine is about $43 (29 to 56) per MWh of electricity produced (Lazard, 2018). This is less than the health cost that the wind turbine eliminates (a mean of $169 per MWh worldwide). Thus, a new wind turbine displacing a fossil fuel power plant immediately reduces society's direct energy cost plus health cost. In other words, every wind turbine installed avoids a high cost to society. On the other hand, SDACCS/U does not reduce any air pollution. SDACCS/U allows air pollution and its costs to persist. So, *a wind turbine replacing a fossil plant will always provide much more benefit than the same money spent on SDACCS/U equipment.*

Table 3.7 summarizes the inefficiency of CO_2 removal from the air by an existing SDACCU facility. Electricity for the air capture (AC) equipment is provided by a natural gas combined cycle turbine. The table indicates that, averaged over 20 and 100 years, 89.5 percent and 69 percent, respectively, of all CO_2 captured by the AC equipment is returned to the air as CO_2e. The emissions come from mining, transporting, processing, and burning the natural gas used to power the equipment.

In comparison with taking no action, using SDACCU equipment powered by natural gas also increases air pollution due to the combustion and upstream emissions associated with natural gas. With no action, SDACCU further incurs an equipment cost. Thus, although SDACCU powered by natural gas reduces some CO_2e, its equipment cost and air pollution cost far outweigh that decrease, resulting in a near doubling of its total social cost per MWh of electricity use relative to that of coal power plant emissions (Figure 3.4).

Table 3.7. Comparison of relative CO_2e emissions, electricity private costs, and electricity social costs among three scenarios related to the Carbon Engineering SDACCU plant, each over a 20-yr and 100-yr time frame. The first scenario is using an on-site natural gas combined cycle turbine to power the air capture (AC) equipment. The AC equipment does not capture the gas emissions; if it did, the results would be the same, since if the equipment captured turbine CO_2 emissions, it would not capture the equivalent CO_2 from the air. The second scenario involves using a wind turbine to power the AC equipment. The third scenario involves using the same wind turbine electricity to instead replace coal power generation without using AC equipment. All emission units (rows a-f, i) are kg-CO_2e/MWh. (From Jacobson, 2019).

	DAC with NG elec. 20 yr	DAC with NG elec. 100 yr	DAC with wind elec. 20 yr	DAC with wind elec. 100 yr	Wind replac-ing coal 20 yr	Wind replac-ing coal 100 yr
a) SDACCU removal from air[1]	825	825	825	825	--	--
b) CO_2 emissions combined cycle gas turbine[2]	404	404	--	--	--	--
c) Upstream CO_2e of CH_4 from gas leaks[3]	280	111	--	--	--	--
d) Upstream CO_2 from gas mining, transport[4]	54	54	--	--	--	--
e) Emission reduction due to replacing coal with wind[5]	0	0	0	0	-1,381	-1,168
f) All emissions (b+c+d+e)	738	569	0	0	-1,381	-1,168
g) Percent CO_2 returned (f/a)	**89.5%**	**68.9%**	**0%**	**0%**	**--**	**--**
h) Percent CO_2 captured (100-g)	**10.5%**	**31.1%**	**100%**	**100%**	**--**	**--**
i) Absolute emission reduction (a-f)	87	256	825	825	1,381	1,168
j) Low SDACCU (\$/tonne-CO_2-removed)[1]	94	94	94	94	--	--
k) High SDACCU (\$/tonne-CO_2-removed)[1]	232	232	232	232	--	--
l) Low private electricity cost (aj/1000) (\$/MWh)[6]	78	78	78	78	29	29
m) High private electricity cost (ak/1000) (\$/MWh)[6]	191	191	191	191	56	56
n) Health cost of background grid (\$/MWh)[7]	40	40	40	40	40	40
o) Ratio health cost of scenario to of background grid[8]	3	3	2	2	0	0
p) Health cost of scenario (no) (\$/MWh)	120	120	80	80	0	0
q) Climate cost of background grid (\$/MWh)[9]	152	152	152	152	152	152
r) Ratio climate cost of scenario to of background grid[10]	0.937	0.781	0.403	0.294	0	0
s) Climate cost of scenario (qr) (\$/MWh)	142	119	61.2	44.6	0	0
t) Low social cost (\$/MWh) (l+p+s)	340	316	219	202	29	29
u) High social cost (\$/MWh) (m+p+s)	454	430	333	316	56	56
v) Low social cost ratio (row t-SDACCU/u-wind)	6.1	5.6	3.9	3.6	--	--
w) High social cost ratio (row u-SDACCU/t-wind)	15.6	14.8	11.5	10.9	--	--

[1]Keith et al. (2018). Assumes values for DAC with wind electricity are the same as DAC with natural gas electricity.
[2]De Gouw et al. (2014).
[3]Same methodology as in Table 3.6, Footnote 6, but using the CO_2 combustion emissions from Row (b) here.
[4]Howarth (2014).
[5]Assumes wind that would otherwise be used to run the SDACCU equipment instead directly replaces coal electricity, its upstream CO_2 combustion, its upstream CH_4 leaks, and its stack combustion CO_2 emissions. The overall emission rates from coal are obtained from Table 3.6, Row d.
[6]Low and high wind electricity costs for wind-replacing coal are from Lazard (2018). Others are from the formula provided.
[7]The U.S. health cost of \$40/MWh for the background grid per MWh is from (Jacobson et al., 2019).
[8]The ratio of the health cost in the scenario to that of the background grid is defined as zero for the wind-replacing coal case, since wind produces zero emissions during its operation. In comparison, wind running SDACCU equipment allows those coal emissions, which are about twice background grid emissions, to continue, so the factor in that scenario is 2. Natural gas running SDACCU equipment not only allows those coal emissions to continue, but it also produces 50% more emissions, assumed equal to background grid emissions per MWh, so the factor in that scenario is 3.
[9]The U.S. climate cost of \$152/MWh for the background grid is from Jacobson et al. (2017, 2019).

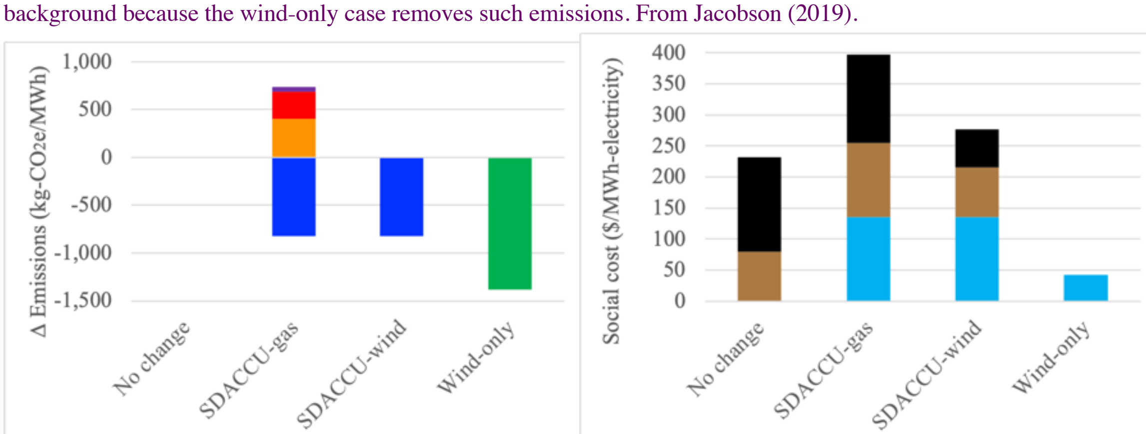
[10]The ratio of the climate cost of the scenario to that of the background grid is defined as zero for the wind-replacing coal case, since wind produces zero emissions during its operation. For the other cases, it is simply the absolute CO_2e emission reduction in the case minus that in the wind case all divided by that in the wind case, where all values are from Row i.

Even when zero re-emissions occur, such as when wind powers the SDACCU equipment, the mean social cost of using SDACCU still exceeds that of doing nothing (Figure 3.4). On the other hand, using wind to replace coal electricity instead of to run the AC equipment eliminates CO_2e and air pollution emissions and their associated costs from the coal. The resulting social cost is ~15% of that from wind powering SDACCU equipment (Table 3.7, Figure 3.4). A similar result is found when wind replaces a natural gas plant instead of a coal plant.

In fact, there is no case where wind powering an SDACCU plant has a social cost below that of wind replacing any fossil fuel or bioenergy power plant directly (Jacobson, 2019). The reasons are that wind-powering-SDACCU always incurs an SDACCU equipment cost that wind alone never incurs and SDACCU always allows air pollution and mining to continue, whereas wind always eliminates air pollution and mining.

Finally, Figure 3.4 illustrates that SDACCS/U powered by wind captures less CO_2e than the same wind replacing a coal plant.

Figure 3.4. Left: Change in CO_2e emissions, averaged over 20 years, per unit electricity needed to run SCACCU equipment resulting from either no action (no-change), using an SDACCU plant with equipment powered by natural gas (SDACCU-gas), using an SDACCU plant with equipment powered by wind (SDACCU-wind), and using the same quantity of wind required to run the SDACCU equipment but to replace coal power directly (wind-only). Blue is the removal of CO_2 from the air by the SDACCU equipment; orange is the natural gas turbine emissions; red is the CO_2e from natural gas mining and transport CH_4 leaks; purple is natural gas mining and transport CO_2e aside from CH_4 leaks; and green is the CO_2e emission reduction due to replacing coal power with wind power. Right: Mean estimate of social costs per unit electricity over 20 years for each of the four cases shown on the left. Light blue is the cost of equipment (either air capture equipment plus gas turbine, air capture equipment plus wind turbine, or wind turbine alone); brown is air pollution health cost; and black is 20-year climate cost. All data are from Table 3.7, except that the costs in the no-change case are the health and climate costs of coal power plant emissions ($80/MWh health cost and $152/MWh climate cost – Table 3.6, Footnote 13). Such emissions costs are used as the background because the wind-only case removes such emissions. From Jacobson (2019).



Example 3.12 illustrates the direct and social cost of SDACCS/U based on data from the same plant examined in Table 3.7. In the plant, a natural gas combined cycle gas turbine is used to provide the electricity needed to remove CO_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_2e and Air Pollution Emissions of SDACCU.

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_2e emissions, are also captured by the plant. In each case, account for the social cost of air pollution (~$40/MWh in the U.S. from Table 7.11) 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 lifecycle CO_2e emissions (assume a 100-year time frame) on the U.S. grid in 2017 are about 557.3 kg-CO_2e per MWh of electricity produced and that the upstream CO_2e emissions (with a 100-year time frame) from the CCGT are 165 kg-CO_2e/MWh (Table 3.7).

<u>Solution:</u>
In Case (a), the SDACCS equipment removes 825 kg-CO_2 from the air per MWh of electricity used to run the plant but re-emits 557.3 kg-CO_2e/MWh, or 67.6 percent of the CO_2e back to the air. Thus, it captures only 32.4 percent of what it intended to capture.

Multiplying $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_2e/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 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. Adding the air pollution social cost ($40/MWh), which SDACCS continues to allow but wind does not, to the SDACCS energy cost gives the energy plus air pollution cost of a SDACCS as $202 to $439 per MWh, or 3.6 to 15.1 the cost per MWh of wind.

In Case (b) the total CO_2e emissions from the gas plant are 404 + 165 = 569 kg-CO_2e/MWh. Multiplying by 1.21 MWh per tonne-CO_2-removed from Case (a) gives 689 kg-CO_2e-emitted from the gas turbine per tonne-CO_2 removed. The net CO_2e removal from the air for every tonne captured from the air is then 1 tonne minus 0.69 tonnes = 0.31 tonnes. In other words, of every tonne of CO_2 removed from the air by this process, 69 percent is re-emitted due to using the gas turbine and only 31 percent is actually sequestered.

Multiplying the $94 to $232 per tonne-$CO_2$ removed by 1 tonne-CO_2-removed / 0.31 net-tonnes-CO_2-removed = $303 to $748 per net-tonne-$CO_2$-removed. Multiplying by the U.S. grid emission rate (557.3 kg-CO_2e/MWh) gives an equivalent cost of reducing CO_2 from the grid in this case with SDACCS of $169 to $419 per MWh-electricity-produced, which is 3 to 14.4 times the direct cost of onshore wind to avoid the same CO_2. Adding the air pollution social cost ($40/MWh), which SDACCS continues to allow but wind does not, to the SDACCS energy cost gives the energy plus air pollution cost of a SDACCS as $209 to $459 per MWh, or 3.7 to 15.8 the cost per MWh of wind.

The result in Case (c) is the same as in Case (b). The plant emits 69 percent of what it is supposed to capture back to the air and retains only 31 percent. The reason is that the plant can remove only 825 kg-CO_2 from the air per MWh of electricity generated by the gas turbine. If the CO_2 is removed from the air (instead of from the turbine exhaust), the equivalent CO_2 from the turbine (404 kg-CO_2/MWh) will be released to the air and vice versa. In both cases, the upstream emissions from the natural gas mining and transport (165 kg-CO_2e/MWh) will also be released to the air. As such, while removing 825 kg-CO_2 from the air per MWh, the plant releases 569 kg-CO_2e/MWh (69 percent) back to the air. The resulting cost of SDACCS versus wind is the same as in Case (b).

Example 3.12 illustrates that using average grid electricity or a dedicated natural gas turbine to run a SDACCS/U plant results in 68 or 69 percent, respectively, of the CO_2 captured from the air being reemitted back to the air due to the energy required to run the equipment, over a 100-year time frame. Table 3.7 indicates that up to 89.5 percent of the CO_2 captured is returned to the air over a 20-year time frame.

An argument for using SDACCS/U is that it will be needed to remove CO_2 from the air once all fossil fuels are replaced with 100 percent WWS. If all energy is provided by renewables at that point, SDACCS/U should reduce CO_2 without increasing air pollution. However, the question at that point is whether growing more trees, reducing open biomass burning, reducing agriculture and waste burning, or reducing halogen, nitrous oxide, and nonenergy methane emissions (Section 2.9) is a more cost-effective method of limiting global warming. Until that time, when such an evaluation can be made, SDACCS/U will always be an opportunity cost.

In sum, like with CCS/U, SDACCS/U is not close to a zero-carbon technology. For the same energy cost, wind turbines and solar panels reduce much more CO_2 while also eliminating fossil air pollution, mining, and infrastructure, which SDACCS/U increases.

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