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The health and climate impacts of carbon capture and direct air capture

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Data from a coal with carbon capture and use (CCU) plant and a synthetic direct air carbon capture and use (SDACCU) plant are analyzed for the equipment's ability, alone, to reduce CO_2. In both plants, natural gas turbines power the equipment. A net of only 10.8% of the CCU plant's CO_2-equivalent (CO_2e) emissions and 10.5% of the CO_2 removed from the air by the SDACCU plant are captured over 20 years, and only 20–31%, are captured over 100 years. The low net capture rates are due to uncaptured combustion emissions from natural gas used to power the equipment, uncaptured upstream emissions, and, in the case of CCU, uncaptured coal combustion emissions. Moreover, the CCU and SDACCU plants both increase air pollution and total social costs relative to no capture. Using wind to power the equipment reduces CO_2e relative to using natural gas but still allows air pollution emissions to continue and increases the total social cost relative to no carbon capture. Conversely, using wind to displace coal without capturing carbon reduces CO_2e, air pollution, and total social cost substantially. In sum, CCU and SDACCU increase or hold constant air pollution health damage and reduce little carbon before even considering sequestration or use leakages of carbon back to the air. Spending on capture rather than wind replacing either fossil fuels or bioenergy always increases total social cost substantially. No improvement in CCU or SDACCU equipment can change this conclusion while fossil fuel emissions exist, since carbon capture always incurs an equipment cost never incurred by wind, and carbon capture never reduces, instead mostly increases, air pollution and fuel mining, which wind eliminates. Once fossil fuel emissions end, CCU (for industry) and SDACCU social costs need to be evaluated against the social costs of natural reforestation and reducing nonenergy halogen, nitrous oxide, methane, and biomass burning emissions.

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Broader context

The Intergovernmental Panel on Climate Change concludes that carbon capture and storage/use (CCS/U) and synthetic direct air carbon capture and storage/use (SDACCS/U) are helpful technologies for avoiding 1.5 °C global warming. However, no study has evaluated their performance or social cost compared with merely replacing fossil with renewable electricity. Here, data from CCU and SDACCU equipment powered by natural gas are evaluated. Only 10.8% of the CCU plant's CO_2-equivalent (CO_2e) emissions and 10.5% of the CO_2 removed from the air by SDACCU are captured over 20 years; only 20–31% are captured over 100 years. Moreover, both plants increase air pollution and social cost *versus* no capture. Powering the equipment with wind instead of gas reduces CO_2e but allows the same pollution as and increases the social cost *versus* no capture. Replacing coal with wind (without capture) reduces CO_2e, pollution, and social cost substantially. In sum, spending on capture rather than wind replacing fossil or bioenergy always increases social cost. No improvement in CCU or SDACCU equipment can change this conclusion while fossil emissions exist. Once fossil emissions end, CCU (for industry) and SDACCU social costs must be evaluated against those of reforestation and reducing nonenergy halogen, nitrous oxide, methane, and biomass burning emissions.

Introduction

Carbon capture and storage (CCS) and use (CCU) involve the installation of equipment in a coal, natural gas, oil, or biomass electric power or heat generating facility to remove carbon dioxide (CO_2) from the exhaust and either sequester it underground or in a material (CCS) or sell it for industrial use (CCU).

Synthetic direct air carbon capture and storage (SDACCS) or use (SDACCU) is the removal of CO_2 from the air by chemical reaction. Upon removal, the CO_2 is either sequestered (SDACCS) or sold (SDACCU). SDACCS differs from natural direct air carbon capture and storage (NDACCS), which is the natural removal of carbon from the air by either planting trees or reducing biomass burning.

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Both CCS/U and SDACCS/U have been proposed as technologies to reduce atmospheric CO_2 and global warming. For example, IPCC[1] states that "capture, utilization, and storage" (CCS/U) can help reduce 75–90% of global CO_2 emissions and that it is "technically proven at various scales." They also identify SDACCS as a method to limit warming to 1.5 °C.

Historically, researchers have assumed CCS/U removes 85–90% of CO_2 exhaust with an energy penalty of ~25%.[2–4] An energy penalty is the additional electricity required to run the carbon capture equipment per unit electricity produced by the power plant for normal electricity consumption. However, until recently,[5] no public data from a commercial power plant with CCU were available to test these numbers. Similarly, until recently,[6] no data were available to evaluate an operating SDACCU plant. Models have also not evaluated the social cost of air pollution that CCS/U and SDACCS/U increase due to their energy use. Air pollution already kills 4–9 million people worldwide annually.[7] Evaluating the emissions and social (energy plus health, plus climate) cost of any proposed technology is critical given the enormous cost of eliminating world emissions (~$100 trillion – Table S9 of ref. 8).

Prior studies have also not evaluated the opportunity cost of using renewable electricity to power CCS/U or SDACCS/U equipment instead of using the renewable electricity to displace fossil fuel power plants. Given limited national budgets, the enormous cost of reducing global air pollution and carbon emissions, and limitations in land areas available in each country to install renewables to replace fossil energy, it is essential to compare the air pollution and carbon emissions of using renewables to power carbon capture equipment with, instead, displacing fossil fuel electricity directly with renewables, thus avoiding emissions in the first place.

Coal-CCU plant

This study first quantifies the carbon dioxide equivalent (CO_2e) emissions from a retrofitted pulverized coal boiler connected to a steam turbine at the W. A. Parish coal power plant near Thompsons, Texas. The plant was retrofitted with carbon capture (CC) equipment as part of the Petra Nova project and began using the equipment during January 2017. The CC equipment (240 MW) receives 36.7 percent of the emissions from the 654 MW boiler. The equipment requires about 0.497 kWh of electricity to run per kWh produced by the coal plant (Table 2, footnote g). A natural gas turbine with a heat recovery boiler was installed to provide this electricity. A cooling tower and water treatment facility were also added. The retrofit cost $1 billion ($4200 per kW) beyond the coal plant cost.[9]

CO_2 from the gas turbine is not captured. Natural gas production also has upstream CO_2e emissions, including CH_4 leaks, which are not captured. Upstream CO_2 and CH_4 emissions from the coal plant are also uncaptured. Table 1 shows the January through June CO_2 coal combustion emission data[5] from the plant before (in 2016) and after (in 2017) the addition of the CC equipment. The table also shows the gas combustion emissions from powering the CC equipment. The table then

Table 1 Columns a–d: raw emissions for January through June 2016 and 2017 from the 654 MW (-all-coal) Petra Nova coal-CCU unit.[5] The 2016 data are before carbon capture was added. The 2017 data include combustion CO_2 from the coal plant and, separately, from the natural gas combined cycle turbine installed to run the CC equipment. Columns e–h: emissions (in units of kg-CO_2 per MWh) for the 240 MW (coal-CC) portion of the 654 MW coal unit subject to carbon capture in 2016 and 2017. Column e equals column (a) multiplied by K = 0.4536 kg lb^{-1}. Column f equals $[b - a(1 - F)]K/F$, where b and a are the CO_2 stack emission rates for each month in 2017 (column b) and 2016 (column a), respectively, and F = 0.367 = 240 MW/654 MW is the fraction of the coal unit subject to carbon capture. Column g equals column c multiplied by K/F

	(a) 2016 coal CO_2 no CC lb-CO_2 per MWh-all-coal[5]	(b) 2017 coal CO_2 with CC lb-CO_2 per MWh-all-coal[5]	(c) 2017 gas CO_2 with CC lb-CO_2 per MWh-all-coal[5]	(d) 2017 total CO_2 with CC lb-CO_2 per MWh-all-coal = $b + c$	(e) 2016 coal CO_2 no CC kg-CO_2 per MWh-coal-CC = aK	(f) 2017 coal CO_2 with CC kg-CO_2 per MWh-coal-CC = $[b - a(1 - F)]K/F$	(g) 2017 gas CO_2 with CC kg-CO_2 per MWh-coal-CC = cK/F	(h) 2017 total CO_2 with CC kg-CO_2 per MWh-coal-CC = f + g
Jan	2060	1500	220	1720	934.4	242.2	271.9	514.1
Feb	2110	1615	225	1840	957.1	345.2	278.1	623.3
Mar	2130	1950	60	2010	966.2	743.7	74.2	817.8
Apr	2050	1550	155	1705	929.9	311.8	191.6	503.4
May	2010	1640	160	1800	911.7	454.4	197.8	652.2
Jun	1950	1550	155	1705	884.5	390.1	191.6	581.7
Average	**2052**	**1634**	**163**	**1797**	**930.6**	**414.6**	**200.9**	**615.4**

translates the emissions from the full 654 MW coal unit to the 240 MW portion of the unit subject to CC. When upstream emissions are excluded, the CC equipment captures an average of only 55.4% (Table 2) of coal combustion CO_2 (rather than 90%) and only 33.9% of coal plus gas combustion CO_2.

Table 2 and Fig. 1 expand results from Table 1 to account for upstream emissions from the mining and processing of coal and natural gas. The CC equipment reduces coal and gas combustion plus upstream CO_2 a net of only 10.8% over 20 years (Fig. 1) and 20% over 100 years. 20 years is a relevant time frame to avoid 1.5° global warming and resulting climate feedbacks.[1]

When wind, instead of gas, is used to power the CC equipment, CO_2e decreases by 37.4% over 20 years and 44.2% over 100 years compared with no CC (Table 2 and Fig. 1). The CO_2e decrease exceeds that in the CCU-gas case because wind powering CC equipment case does not result in any combustion or upstream emissions from wind, as seen in Fig. 1.

However, using the wind electricity that powers the CC equipment instead to replace coal electricity directly at the same plant reduces CO_2e by 49.7% compared with no CC (Table 2 and Fig. 1). It is not 100% because only the wind used to run the capture equipment replaces coal. More wind would be needed to replace the whole coal plant. This third strategy is the best for reducing CO_2e among the three cases. Using solar PV to replace coal directly results in a similar benefit as using wind.

But, CO_2e is only part of the story. Because CCU equipment does not capture health-affecting air pollutants, air pollution emissions continue from coal and rise by about 25% compared with no capture from the use of natural gas to run the Petra Nova equipment (Table 2). Even when wind powers the CC equipment, air pollution from the coal plant continues as before (but not from using the new wind turbine). Only when wind partially replaces the use of coal itself does air pollution decrease by ~50% (Table 2).

The equipment cost of new coal and wind electricity in the U.S. are a mean of \$102 per MWh and \$42.5 per MWh, respectively.[10] The capital cost of CC equipment, \$4200 per kW,[9] is about 74% the capital cost of a new coal plant (\$5700 per kW),[10] suggesting that new coal plus CCU is 1.74 × \$102 per MWh/\$42.5 per MWh = 4.2 times the equipment cost of new wind. Since CC equipment reduces only 10.8% of coal CO_2e over 20 year and 20% over 100 year, the equipment for coal-CCU powered by natural gas alone costs 39 and 21 times that of wind-replacing coal per mass-CO_2 removed over 20 and 100 years, respectively.

Major additional social costs associated with coal electricity generation are air pollution and climate costs. The health cost of coal emissions in the U.S. is calculated as a mean of \$80 per MWh, which is much lower than the world average (\$169 per MWh, Table 2, footnote m). Since the use of CC equipment requires 50% more electricity than the coal plant produces but the health cost of natural gas emissions are about half those of coal, the use of gas to run the CC equipment increases health costs by ~25% compared with no capture (Table 2, row o). Mean climate costs of U.S. emissions are estimated as \$152 per MWh, close to the world mean of \$160 per MWh (Table 2, footnote m). CC equipment with natural gas is estimated to reduce this cost by only 10.8% and 20% over 20 and 100 years, respectively (Table 2, row n).

In sum, the total social cost (equipment plus health plus climate cost) of coal-CCU powered by natural gas is over twice that of wind replacing coal directly (Table 2 and Fig. 1). Moreover, the social cost of coal with CC powered by natural gas is 24% higher over 20 years and 19% higher over 100 years than coal without CC. Thus, no net social benefit exists of using CC equipment. In other words, from a social cost perspective, using CC equipment powered by natural gas causes more damage than does doing nothing at all.

When wind powers CC equipment, the social costs are still 6% and 2% higher over 20 and 100 years, respectively, than not using CC (Table 2 and Fig. 1). Although wind-powering-CC decreases CO_2e, thus climate cost, compared with coal without CC, wind-CC allows the same air pollution emissions from coal as no CC, and the cost of the wind plus CC equipment outweighs the CO_2e cost reduction (Fig. 1).

Only when wind replaces coal electricity production directly does the total social cost drop 43% compared with no CC (Table 2). This is the best scenario. A similar benefit occurs if wind replaces natural gas and no CC is used.

Some may argue that (a) the six months of data with *versus* without the CC equipment are insufficient for drawing conclusions about this plant and (b) future plants may improve upon the Petra Nova plant. Whereas both points are valid, in order for the social cost of using the CC equipment powered by natural gas to be less than that of doing nothing, the CO_2e reemitted by the Petra Nova plant would need to be 37% or less instead of 89.8% over 20 years. However, this is all but impossible, because 59.2% of the re-emissions is due to upstream coal and gas emissions and natural gas combustion emissions, so little to do with how effective the CC equipment is at capturing carbon. In other words, even if the CC equipment captured 100% of the stack CO_2, which no-one is proposing is feasible, the reemissions would still be 59.2%. This is because controlling 100% of the coal stack emissions can reduce only 40.8% of the total upstream plus stack coal emissions due to the additional upstream and combustion emissions of the gas plant over a 20 year time frame. As such, the data indicate that no technological improvement will result in the social cost of using CC equipment powered by natural gas being less than that of not using the equipment.

When CC is powered by wind, it is theoretically possible, albeit challenging, to reduce the total social cost below that of no CC. However, it is impossible to reduce the total social cost below that of wind replacing coal electricity directly because wind-powering-CC also incurs a CC equipment cost and never reduces air pollution or mining from coal, whereas wind replacing coal incurs no CC equipment cost and eliminates coal air pollution and mining.

SDACCU plant

This section evaluates the efficiency of CO_2 removal from the air by an SDACCU facility,[6] where electricity for the air capture

Table 2 Comparison of relative CO_2e emissions, electricity use, and electricity social costs among three scenarios related to the Petra Nova coal-CCU facility, each over a 20 year and 100 year time frame. The first scenario is using natural gas to power the carbon capture (CC) equipment. This is based on data from the Petra Nova facility (Table 1). The second scenario is running the CC equipment with onshore wind instead of natural gas. The third is using the same quantity of wind electricity required to run the CC equipment to instead replace coal electricity from the coal plant. In all cases, the additional energy required to run the CC equipment is equivalent to 49.7% of the energy output of the coal plant (footnote g). The coal plant has a nameplate capacity of 654 MW, but only 240 MW (36.7%) is subject to CC. The numbers in the table are all based on the portion subject to CC. All emission units (including of natural gas emissions) are g-CO_2e per kWh-coal-electricity-generation

	Coal with gas-powered CC 20 year	Coal with gas-powered CC 100 year	Coal with wind-powered CC 20 year	Coal with wind-powered CC 100 year	Wind used for CC replacing coal + remaining coal 20 year	Wind used for CC replacing coal + remaining coal 100 year
(a) Upstream CO_2 from coal[a]	97.2	97.2	97.2	97.2	48.9	48.9
(b) Upstream CO_2e of leaked CH_4 from coal[b]	353	140	353	140	177.6	70.4
(c) Coal stack CO_2 before capture[c]	930.6	930.6	930.6	930.6	468.1	468.1
(d) Total coal CO_2e before capture (a + b + c)	1381	1168	1381	1168	695	587
(e) Remaining stack CO_2 after capture[d]	414.6	414.6	414.6	414.6	—	—
(f) CO_2 captured from stack (*c*–*e*)	516.0	516	516	516	—	—
(g) Percent stack CO_2 captured (f/c)	55.4	55.4	55.4	55.4	—	—
(h) CO_2 emissions gas combustion[e]	200.9	200.9	0	0	0	0
(i) Upstream CO_2e of CH_4 from gas leaks[f]	139.2	55.03	0	0	0	0
(j) Upstream CO_2 from gas mining, transport[g]	26.85	26.85	0	0	0	0
(k) Total CO_2e emissions (a + b + e + h + i + j)	1,232	934.5	865	652	695	587
(l) Percent of coal CO_2e re-emitted (k/d)[h]	**89.2**	**80.0**	**62.6**	**55.8**	**50.3**	**50.3**
(m) Percent of coal CO_2e captured (100-l)	**10.8**	**20**	**37.4**	**44.2**	**49.7**	**49.7**
(n) Relative CO_2e to original (l/100)[i]	0.892	0.80	0.626	0.558	0.503	0.503
(o) Relative air pollution to original[j]	1.25	1.25	1.0	1.0	0.503	0.503
(p) Energy required relative to original[k]	1.497	1.497	1.497	1.497	1	1
(q) Private energy cost per kWh relative to original[l]	1.74	1.74	1.74	1.74	0.71	0.71
(r) Social cost before changes ($ per MWh)[m]	334	334	334	334	334	334
(s) Social cost after changes ($ per MWh)[n]	413	399	353	342	189	189
(t) Social cost ratio (s/r)	1.24	1.19	1.06	1.02	0.57	0.57

[a] Coal upstream emissions are estimated as 27 g-CO_2 per MJ = 97.2 g-CO_2 per kWh.[11] Upstream emissions include emissions from fuel extraction, fuel processing, and fuel transport. Upstream CO_2 emissions (from the portion of the coal plant not replaced) for the wind-replacing some coal cases (last two columns) are the same as in the other cases, but multiplied by 0.503, which equals 1 minus the fraction of coal electricity used to run the carbon capture equipment, which is derived in footnote g. Since the electricity used to run the CC equipment is used to replace coal in this case, upstream coal emissions are reduced accordingly. [b] For coal, the 100 year CO_2e from CH_4 leaks is estimated from (ref. 12, slide 17). The emission factor is derived from that number and the 100 year GWP of CH_4, 34 from ref. 13. The 20 year CO_2e is then derived from the resulting emission factor (4.1 g-CH_4 per kWh) and the 20 year GWP of CH_4, 86. Emissions in the wind cases are reduced as described under footnote a. [c] The average coal stack emission rate for the Petra Nova facility in 2016, prior to the addition of CC equipment, is from Table 1, column e. In the wind-replacing-coal cases (last two columns), the emission rate is reduced as described under footnote a. [d] The coal-stack CO_2 remaining after capture is from Table 1, column f. [e] The natural gas combustion emissions resulting from powering the CC equipment is from Table 1, column g. [f] Natural gas upstream leaks are obtained by dividing the raw emission rate of CO_2 from natural gas for each month January through June 2017 from Table 1 (in kg-CO_2 per MWh-coal-electricity) by the molecular weight of CO_2 (44.0098 g-CO_2 per mol) to give the moles of natural gas burned per MWh-coal-electricity. Multiplying the moles burned per MWh by the fractional number of moles burned that are methane (0.939)[14] and the molecular weight of methane (16.04276 g-CH_4 per mol) gives the mass intensity of methane in the natural gas burned each month (kg-CH_4-burned per MWh-coal-electricity). The upstream leakage rate of methane is then the kg-CH_4-burned per MWh-coal-electricity multiplied by $L/(1 - L)$, where $L = 0.023$ is the fraction of all methane produced (from conventional and shale rock sources) that leaks,[15] giving the methane leakage rate in kg-CH_4 per MWh-coal-electricity. This leakage rate is conservative based on a more recent full-lifecycle leakage rate estimate of methane from shale rock alone of $L = 0.035$.[16] Using the latter estimate would result in CCS/U with natural gas re-emitting even more CO_2e than calculated here. Multiplying the kg-CH_4 per MWh-coal-electricity by the 20- and 100 year GWPs of CH_4 (86 and 34, respectively)[13] gives the CO_2e emission rate of methane leaks each month. The monthly values are linearly averaged over January through June 2017. [g] The non-CH_4 upstream CO_2e emissions rate is estimated as 15 g-CO_2 per MJ-gas-electricity = 54 g-CO_2 per kWh-gas-electricity.[11] Multiplying that by 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced gives 26.8 kg-CH_4 per MWh-coal-electricity. 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced, or 49.7%, is calculated by dividing the average gas combustion emission from Petra Nova (200.9 g-CO_2 per kWh-coal from the present table) by the combustion emissions per unit electricity from a combined cycle gas plant (404 g-CO_2 per kWh-natural-gas). [h] The percent CO_2 reemitted for the wind cases (last two columns) equals row k for the wind cases divided by row d for either of the non-wind cases. [i] CO_2e emissions relative to coal with no CC equipment. [j] Air pollution emissions relative to coal with no CC equipment. In the natural gas cases, all air pollution from coal emissions still occurs. Although gas is required to produce 0.497 MWh of electricity for the CC equipment per MWh of coal electricity, gas is assumed to be 50% cleaner than coal, so the overall air pollution in this case increases only 25% relative to the no CC case. In the wind-CC cases, all upstream and combustion emissions from coal still occur. [k] The electricity required (for end-use consumption plus to run the CC equipment) in all CC cases is 49.7% higher than with no CC. In the wind-replacing coal case, no electricity is needed to run the CC equipment, but electricity is still needed for end use. [l] The private energy cost in all CC cases is assumed to be 74% higher than coal with no CC because the CC equipment (including the gas plant) costs $4200 per kW, which represents about 74% of the mean capital cost of a new coal plant ($5700 per kW) from.[10] For simplicity, it was assumed that the cost of a wind turbine running the CC equipment was the same as of a gas turbine running the equipment. In the wind-replacing-coal cases, the cost of coal was assumed to be a mean of c = $102 per MWh and of wind, w = $42.5 per MWh.[10] The final ratio was calculated as $(0.503c + 0.497w)/c$. [m] The social cost before changes is the private energy cost of new coal without CCU [$102 per MWh from ref. 10] plus air pollution mortality, morbidity, and non-health environmental costs of coal power plant emissions in the U.S. plus the global climate costs of U.S. emissions ($152 per MWh).[18] U.S. coal power plant emissions health costs are estimated as $80 per MWh, which is twice the background grid health cost of $40 per MWh.[17] In the worldwide average, from the same source, the health cost of background grid emissions is estimated as $169 per MWh, so use of the U.S. number here is likely to underestimate the health costs of using carbon capture outside the U.S. [n] The social cost after changes is the sum of the private energy cost multiplied by row q, the air pollution health cost multiplied by row o, and the climate cost multiplied by row n.

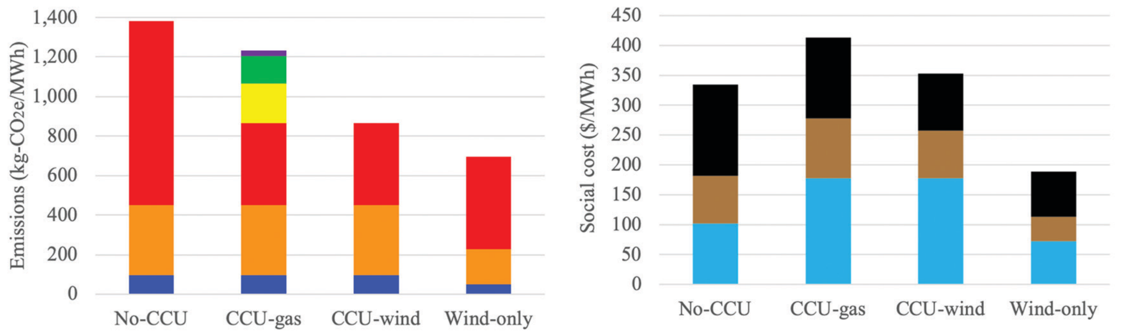

Fig. 1 Left: CO_2e emissions, averaged over 20 years, from the Petra-Nova coal plant before (No-CCU) and after (CCU-gas) the addition of CCU equipment powered by natural gas. Also shown are emissions when the CCU equipment is powered by wind energy (CCU-wind) and when the portion of wind energy used to power the CCU equipment is instead used only to replace a portion of the coal power (thus some power is generated by coal and some by wind). Blue is upstream CO_2e from coal mining and transport aside from CH_4 leaks; orange is upstream CO_2e from coal mining CH_4 leaks; red is coal combustion CO_2; yellow is natural gas combustion CO_2; green is CO_2e from natural gas mining and transport CH_4 leaks; and purple is natural gas mining and transport CO_2e aside from CH_4 leaks. Right: Mean estimate of social costs per unit electricity over 20 years generated by the coal plant (in the first three cases) or the residual coal plant plus replacement wind plant (fourth case) for each of the four cases shown on the left. Light blue is the cost of electricity generation plus CCU equipment; brown is air pollution health cost; and black is 20 year climate cost. All data are from Table 2.

(AC) equipment is provided by a natural gas combined cycle turbine.

Table 3 indicates that, averaged over 20 and 100 years, 89.5% and 69%, 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, the equipment cost and air pollution cost far outweigh that decrease, resulting in a near doubling of the total social cost per MWh of electricity use relative to the health and climate cost per MWh of coal power plant emissions (Fig. 2).

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 (Fig. 2). 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 and Fig. 2). 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. 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.

Discussion

Tables 1–3 suggest virtually no carbon benefit of and greater air pollution damage from CCS/U and SDACCS/U before considering the disposition of the captured CO_2.

Three reasons this result has not been identified previously, aside from the lack of data, are that previous studies and models did not consider upstream fossil emissions, the air pollution social cost resulting from the additional energy needs, or the higher fossil emissions due to using renewable electricity for CC or AC equipment instead of to displace fossil electricity. Air pollutants not captured by CC or AC equipment from fossil or bioenergy plants include CO, NO_x, SO_2, organic gases, mercury, toxins, black and brown carbon, fly ash, and other aerosol components.

Ref. 4 found that even after assuming 90% capture by equipment (and ignoring upstream and combustion emissions to run the capture equipment), renewables return better on investment than CC. The results here suggest that a specific coal-CCU plant reduces only 10.5% and 20% of the plant's overall CO_2e over 20 and 100 years, respectively, while increasing air pollution and land degradation (from additional mining). More than half the re-emissions are due to upstream coal and gas emissions and natural gas combustion emissions to run the CC equipment. In addition, CC always incurs an equipment cost and never reduces air pollution, whereas renewables have no such equipment costs and always reduce air pollution. For all these reasons, renewables replacing fossil fuels or bioenergy are a lower social-cost investment to address climate than even[4] found.

SDACCS/U powered by natural gas similarly increases air pollution by increasing fossil energy consumption and upstream mining. Clean electricity used to run SDACCS/U equipment does not increase air pollution but keeps it the same. However, the social cost of using that clean electricity to replace fossil fuels or bioenergy is always lower than the social cost of using the electricity to run SDACCS/U equipment. The reasons are that SDACCU equipment always incurs a cost that renewables never incur and SDACCU always allows air pollution and fuel mining to continue, whereas renewables eliminate air pollution and fuel mining.

The results here are independent of the fate of the CO_2 after it leaves the CC equipment, thus apply to CC with bioenergy (*e.g.*, BECCS/U) or cement manufacturing. The CC equipment

Table 3 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 year and 100 year time frame. The first scenario is using an on-site natural gas (NG) combined cycle turbine to power the direct air capture (DAC) equipment. The DAC 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 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 per MWh

	DAC with NG elec. 20 year	DAC with NG elec. 100 year	DAC with wind elec 20 year	DAC with wind elec. 100 year	Wind replacing coal 20 year	Wind replacing coal 100 year
(a) SDACCU removal from air[a]	825	825	825	825	—	—
(b) CO_2 emissions combined cycle gas turbine[b]	404	404	—	—	—	—
(c) Upstream CO_2e of CH_4 from gas leaks[c]	280	111	—	—	—	—
(d) Upstream CO_2 from gas mining, transport[d]	54	54	—	—	—	—
(e) Emission reduction due to replacing coal with wind[e]	0	0	0	0	−1381	−1168
(f) All emissions (b + c + d + e)	738	569	0	0	−1381	−1168
(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	1381	1168
(j) Low SDACCU (\$ per tonne-CO_2-removed)[a]	94	94	94	94	—	—
(k) High SDACCU (\$ per tonne-CO_2-removed)[a]	232	232	232	232	—	—
(l) Low private electricity cost (aj/1000) (\$ per MWh)[f]	78	78	78	78	29	29
(m) High private electricity cost (ak/1000) (\$ per MWh)[f]	191	191	191	191	56	56
(n) Health cost of background grid (\$ per MWh)[g]	40	40	40	40	40	40
(o) Ratio health cost of scenario to of background grid[h]	3	3	2	2	0	0
(p) Health cost of scenario (no) (\$ per MWh)	120	120	80	80	0	0
(q) Climate cost of background grid (\$ per MWh)[i]	152	152	152	152	152	152
(r) Ratio climate cost of scenario to of background grid[j]	0.937	0.781	0.403	0.294	0	0
(s) Climate cost of scenario (qr) (\$ per MWh)	142	119	61.2	44.6	0	0
(t) Low social cost (\$ per MWh) (l + p + s)	340	316	219	202	29	29
(u) High social cost (\$ per 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	—	—

[a] Ref. 6. Assumes values for DAC with wind electricity are the same as DAC with natural gas electricity. [b] Ref. 19. [c] Same methodology as in Table 2, footnote f, but using the CO_2 combustion emissions from row (b) here. [d] Ref. 11. [e] 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 2, row d. [f] Low and high wind electricity costs for wind-replacing coal are from.[10] Others are from the formula provided. [g] The U.S. health cost of \$40 per MWh for the background grid per MWh is from ref. 17. [h] 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 per unit energy, 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. [i] The U.S. climate cost of \$152 per MWh for the background grid is from ref. 17 and 18. [j] 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.

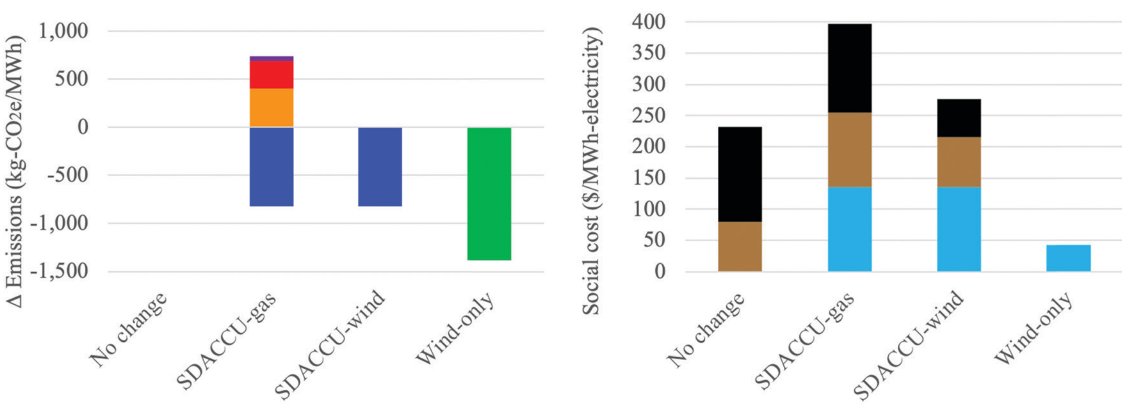

Fig. 2 Left: Change in CO_2e emissions, averaged over 20 years, per unit electricity needed to run SCACCU equipment resulting from either no action (no-change), using an SDACCU plant with equipment powered by natural gas (SDACCU-gas), using an SDACCU plant with equipment powered by wind (SDACCU-wind), 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, except that the costs in the no-change case are the health and climate costs of coal power plant emissions (\$80 per MWh health cost and \$152 per MWh climate cost – Table 2, footnote m). Such emissions costs are used as the background because the wind-only case removes such emissions.

always requires energy. If the energy comes from a fossil fuel, mining and combustion emissions from the fuel cancel most CO_2 captured. If it comes from a renewable, total social costs are still always greater than using the renewable to replace fossil fuels or bioenergy directly.

When the fate of captured CO_2 is considered, the problem may deepen. If CO_2 is sealed underground without leaks, little added emissions occur. If the captured CO_2 is used to enhance oil recovery, its current major application, more oil is extracted and burned, increasing combustion CO_2, some leaked CO_2, and air pollution. If the captured CO_2 is used to create carbon-based fuel to replace gasoline and diesel, energy is still required to produce the fuel, the fuel is still burned in vehicles (creating pollution), and little CO_2 is captured to produce the fuel with. A third proposal is to use the CO_2 to produce carbonated drinks. However, along with the issues previously listed, most CO_2 in carbonated drinks is released to the air during consumption. In addition, the quantity of CO_2 needed for carbonated drinks is small compared with the CO_2 released by fossil fuels globally.

Another argument for using SDACCS/U is that it will be needed for removing CO_2 from the air once all fossil fuels are replaced with renewables. If renewables are then used to power SDACCS/U they can reduce CO_2 without incurring an air pollution cost. However, the question at that point is whether growing more trees, reducing biomass burning, or reducing halogen, nitrous oxide, and non-energy methane emissions is a more cost-effective method of limiting global warming.

In sum, SDACCS/U and CCS/U are opportunity costs, not close to zero-carbon technologies. For the same energy cost, wind turbines and solar panels reduce much more CO_2 while also reducing fossil air pollution and mining, pipelines, refineries, gas stations, tanker trucks, oil tankers, coal trains, oil spills, oil fires, gas leaks, gas explosions, and international conflicts over energy. CCS/U and SDACCS increase these by increasing energy use and always increase total social costs relative to using renewables to eliminate fossil fuel and bioenergy power generation directly.

Author contributions

M. Z. J. performed the research and wrote the paper.

Data and materials availability

Virtually all data are provided within the paper and references therein but any data not provided may be obtained from the author.

Conflicts of interest

Author declares no competing interests.

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