STATE OF NORTH DAKOTA

PUBLIC SERVICE COMMISSION

IN THE MATTER OF THE APPLICATION OF SCS CARBON TRANSPORT LLC FOR A CERTIFICATE OF CORRIDOR COMPATIBILITY AND ROUTE PERMIT FOR THE MIDWEST CARBON EXPRESS PROJECT IN BURLEIGH, CASS, DICKEY, EMMONS, LOGAN, MCINTOSH, MORTON, OLIVER, RICHLAND AND SARGENT COUNTIES, NORTH DAKOTA	)))))))))	Case No. PU-22-391

DIRECT TESTIMONY OF

DR. MARK Z. JACOBSON

ON BEHALF OF LANDOWNER INTERVENORS

700 PU-22-391 Filed: 7/1/2024 Pages: 24
LO Exhibit LO-27 - Pre-Filed Testimony of Dr. Mark Jacobson With Attachments (Dkt. #575)

Knoll Leibel, LLP, on behalf of the Intervenors

LO #27 – 5/24/24
PU-22-391

Q: Please state your name and purpose for providing testimony in these proceedings.

A: My name is Mark Z. Jacobson. I am a professor of Civil and Environmental Engineering at Stanford University. The purpose of my testimony is to provide information on the technical and economic issues regarding carbon capture and storage generally, and more specifically, on the project proposed by Summit. I will discuss the efficacy of carbon capture and storage as a purported solution to climate change, both in terms of its effectiveness, its impacts on air pollution, and its economic competitiveness in relation to other alternatives for addressing climate change. I will also cover my research and writing on these subjects.

Q: What experience, education, training, or background qualify you to provide opinions and your concerns as you have herein?

A: Please see a summary of my education and experience in **Attachment No. 1**.

Q: What are your primary areas of research and writing?

A: Since 1989, I have been researching academically and professionally, the impacts of human emissions of gases (including carbon dioxide and other greenhouse gases) and particles (including black carbon) on air pollution, human health, weather, and climate. Starting in 1999, I began examining in detail clean, renewable energy solutions to these problems. With respect to ethanol, in 2007, I published a study examining the effects of E85 versus gasoline combustion exhaust on air pollution health in the United States . A Ph.D. student of mine and I co-published several additional studies on this topic. In 2009, I published a review paper that also examined the impacts of E85 vehicles on climate, air pollution, land use, and water supply relative to battery-electric vehicles (BEVs) and hydrogen-fuel-cell-electric vehicles powered by renewable electricity. With respect to carbon capture, I have performed comparative studies involving coal electricity generation with carbon capture, direct air capture, natural gas for hydrogen production with carbon capture, and ethanol production with carbon capture. In 2019, I published a paper entitled, "The health and climate impacts of carbon capture and direct air capture". In 2021, I co-authored a paper comparing hydrogen production from natural gas with and without carbon capture. In 2023, I published a paper that analyzed the costs and benefits of a transportation system that relies on vehicles fueled by ethanol from facilities operating carbon capture technology in comparison with one that relies on battery-electric vehicles powered by wind. I have also written two books that discuss carbon capture and ethanol extensively.

Q: **Can you explain what carbon capture and storage is?**

A: Carbon capture and storage (CCS) involves the separation of carbon dioxide from other exhaust gases following fossil fuel or biofuel combustion; following chemical reaction such as during cement or steel manufacturing; or during fermentation to produce ethanol. The purified carbon dioxide is usually compressed, often from 1 bar (atmospheric pressure) to 150 bars so that it can be transferred in a pipe. At a certain point during compression, carbon dioxide converts from a gas to a liquid. In the present proposal, however, the carbon dioxide would be compressed to above 74.5 bars and the temperature raised to above 31.1 degrees Celsius so that it would reside in a supercritical state, which is a very dense form of carbon dioxide that is neither liquid nor gas. The supercritical CO2 is then sent by pipe to an underground geological formation such as a saline aquifer, a depleted oil or gas field, or an un-minable coal seam. The remaining combustion gases are emitted to the air or filtered further.

Q: **What is your understanding of Summit's proposed carbon capture and storage project?**

A: Summit's proposal is first to capture carbon dioxide from the fermentation process at 57 ethanol-production facilities in five states: Iowa, Nebraska, South Dakota, Minnesota, and North Dakota. Because carbon dioxide off-gassed during fermentation is relatively pure, traditional carbon capture equipment needed to separate carbon dioxide from other impurities in natural gas or coal electricity generating plants is not needed. However, electricity is still needed to dehydrate, compress, and heat the carbon dioxide so that it can enter a supercritical state. The electricity needed is estimated to be similar to that needed simply to dehydrate the CO_2 and compress it to 150 bars, which is about 110 kWh/tonne of CO_2-compressed. This additional electricity requirement is estimated to result in carbon dioxide emissions that would offset about 15.2% of the captured and piped CO_2. The carbon dioxide, after it is compressed to a supercritical state, would be piped to an underground storage site near Bismarck, North Dakota. The transportation of the captured carbon would require approximately 2,500 miles of pipeline. It is not clear if the carbon dioxide would be permanently sequestered there or used later for some other purpose, such as enhanced oil recovery.

Q: Based on your experience and understanding of the project, what is your opinion regarding the role carbon capture and storage, and Summit's project in particular, would have in addressing climate change?

A: It is my opinion that the Summit project, which involves spending $8 billion on pipes and carbon capture from ethanol refineries to power flex-fuel vehicles, is a significant opportunity cost. It substantially increases consumer costs and carbon dioxide and air pollution emissions in the five states at issue relative to a viable alternative. Specifically, based on the attached published paper, which relied on an earlier version of the Summit proposal (involving 34 ethanol refineries, 2000 miles of pipelines, and a $5.6 billion up-front cost), if the same money is instead spent on onshore wind and/or solar photovoltaics (PVs) to power battery-electric vehicles (BEVs), drivers in the five states will likely save $40-$66 billion over 30 years and due to the price difference between E85 and electricity and due to the far greater mileage per unit energy of a BEV than an equivalent FFV, even when a BEV initially costs $21,700 more upfront than an FFV. What is more, using the same funds to instead produce wind electricity for BEVs will likely reduce 2.4-4.2 the carbon dioxide emissions as will capturing carbon from ethanol refineries that provide E85 for FFVs [19.8-32.9 million metric tonnes of CO_2 per annum

(MMTPA) avoided with BEVs versus 8.2 MMTPA avoided with FFVs]. Finally, Summit's plan will significantly increase air pollution and land use requirements while creating fewer jobs than using the same money to invest in legitimate, proven energy sources.

Q: Does <u>Attachment No. 2</u> expand on the economic costs associated with Summit's proposed project in comparison to alternative energy sources?

A: Yes, Attachment No. 2 is a research paper I published last year titled "Should Transportation Be Transitioned to Ethanol with Carbon Capture and Pipelines or Electricity? A Case Study". I stand by the positions discussed therein and am competent to testify about them as necessary.

Q: Does Attachment No. 3 to this testimony describe the social cost of carbon capture in comparison to wind energy?

A: Yes, Attachment No. 3 is a true and accurate copy of an article I authored on the subject. I stand by the content discussed therein and am competent to testify about them as necessary. I urge the PSC to carefully consider this testimony during the Hearing in this matter and in your deliberations. I further reserve the right to amend or modify these opinions upon presentation of any additional information that may justify such a change.

Q: Are all of your statements and opinions rendered here, including in your Attachments, given to a reasonable degree of professional certainty and based upon your education, experience, background, and training?

A: Yes.

<u>*/s/ Dr. Mark Z. Jacobson*</u>

Dr. Mark Z. Jacobson

State of California)

) ss.

County of Santa Clara)

I, Mark Jacobson, being first duly sworn on oath, depose and state that I am the person identified in the above Pre-Filed Direct Testimony that I have caused to be prepared and I am familiar with the contents therein and competent to testify on these matters. My Pre-Filed Direct Testimony found in the foregoing pages is true and correct to the best of my knowledge.

Mark Jacobson

Subscribed and sworn to before me, a Notary Public in and for said County and State this ________ day of May, 2024

____

Notary

Notary Public Commission expires: ______________________

PLEASE SEE ATTACHED ACKNOWLEDGMENT/JURAT FROM NOTARY PUBLIC

A notary public or other officer completing this certificate verifies only the identity of the individual who signed the document to which this certificate is attached, and not the truthfulness, accuracy, or validity of that document.

State of California
County of San Mateo

Subscribed and sworn to (or affirmed) before me on this 9th day of May, 2024, by mark Jacobson,
proved to me on the basis of satisfactory evidence to be the person(s) who appeared before me.

(Seal) Signature Helen Sutherland

HELEN SUTHERLAND
COMM. # 2363802
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SAN MATEO COUNTY
Comm. Exp. JULY 27, 2025
MGC1

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Top Skills

Science

Mathematical Modeling

Climate Change

Publications

Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight

The effects of aircraft on climate and pollution. Part II: 20-year impacts of exhaust from all commercial aircraft worldwide treated individually at the subgrid scale

[redacted]ing of impact from the mega-[redacted]banization of Beijing between 2000 and 2009

Saturation wind power potential and its implications for wind energy

100% clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States

Mark Jacobson

Professor-Civil & Environ Eng, Director-Atmos/Energy Program at Stanford U; Co-founder-Solutions Project & 100% Movement

Stanford, California, United States

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Stanford University

Professor of Civil & Environmental Engineering and Director Atmosphere/Energy Program

September 1994 - Present (29 years 9 months)

Education

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MS Atmospheric Sciences, PhD Atmospheric Sciences · (1989 - 1994)

Stanford University

BS Civil and Environmental Engineering, BA Economics, MS Environmental Engineering · (1983 - 1988)

Attachment 2

Environmental Science & Technology

pubs.acs.org/est

Article

Should Transportation Be Transitioned to Ethanol with Carbon Capture and Pipelines or Electricity? A Case Study

Mark Z. Jacobson*

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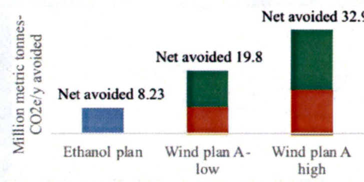
ABSTRACT: An important issue today is whether gasoline vehicles should be replaced by flex-fuel vehicles (FFVs) that use ethanol-gasoline blends (e.g., E85), where some carbon dioxide (CO_2) from ethanol's production is captured and piped, or battery-electric vehicles (BEVs) powered by wind or solar. This paper compares the options in a case study. It evaluates a proposal to capture fermentation CO_2 from 34 ethanol refineries in 5 U.S. states and build an elaborate pipeline to transport the CO_2 to an underground storage site. This "ethanol plan" is compared with building wind farms at the same cost to provide electricity for BEVs ("wind plan A"). Compared with the ethanol plan, wind plan A may reduce 2.4–4 times the CO_2, save drivers in the five states \$40–\$66 billion (USD 2023) over 30 years even when BEVs initially cost \$21,700 more than FFVs, require 1/400,000th the land footprint and 1/10th–1/20th the spacing area, and decrease air pollution. Even building wind to replace coal ("wind plan B") may avoid 1.5–2.5 times the CO_2 as the ethanol plan. Thus, ethanol with carbon capture appears to be an opportunity cost that may damage climate and air quality, occupy land, and saddle consumers with high fuel costs for decades.



KEYWORDS: *ethanol, carbon capture, pipelines, wind, flex-fuel vehicles, battery-electric vehicles*

■ INTRODUCTION

A major question today is whether gasoline-powered transportation should be transitioned to ethanol with carbon capture and pipelines or electricity powered by wind or solar. Those in favor of ethanol produced from corn argue that ethanol-gasoline blends, such as E85, produce lower lifecycle carbon dioxide-equivalent (CO_2e) emissions than gasoline for three reasons: (1) carbon dioxide removed from the air by photosynthesis during corn growth offsets CO_2 emissions from fermentation and combustion during ethanol production and combustion, respectively, (2) CO_2 emitted during ethanol production is modest, (3) and land-use change (LUC) emissions associated with corn production are small.[1] However, Lark et al.,[2] who analyzed the U.S. experience with corn ethanol, calculate that LUC emissions due to corn ethanol are much higher than those proposed by others[1] (see also a debate on this issue[3,4]), resulting in lifecycle CO_2e from corn ethanol up to 24% greater than that of gasoline, even after accounting for CO_2 uptake due to plant photosynthesis.[2]

To bolster the argument for the use of E85 as a climate solution, three companies (Navigator CO2 Ventures, Wolf Carbon Solutions US LLC, and Summit Carbon Solutions LLC, hereinafter "Summit") have proposed to add carbon capture equipment to the fermentation process during ethanol production and build pipelines under the properties of hundreds to thousands of landowners across multiple states to transfer the CO_2 to an underground storage facility.[6] Navigator is proposing an ~1300-mile pipeline; Wolf, an ~380-mile pipeline; and Summit, an ~2000-mile pipeline. This study evaluates the Summit proposal. Ethanol is already used primarily to produce blended fuels, such as E10, E15, and E85.

E10 contains ~10–10.49% ethanol and 89.51–90% gasoline; E15 contains 10.5–15% ethanol and 85–89.5% gasoline; and E85 contains 51–83% ethanol and 17–47% gasoline. Gasoline vehicles can use either gasoline (E0) or E10 fuel. Higher blends of ethanol (e.g., E15 and E85) must be used in a flex-fuel vehicle (FFV), which can also run on E0 or E10. By far, most ethanol today is blended as E10. However, due to the planned phase-out of gasoline in the United States and elsewhere based on climate concerns, the increased development of FFVs, and U.S. federal tax subsidies promoting ethanol, the use of E85 is increasing rapidly. As such, the focus of this study is on E85.

U.S. subsidies also encourage the addition of carbon capture equipment to ethanol refineries. In theory, capturing CO_2 from the fermentation process during ethanol production may reduce ethanol's overall lifecycle CO_2 emissions by ~30 g-CO_2e/MJ,[1] slightly below those of gasoline. However, comparing the lifecycle emissions of ethanol with gasoline vehicles alone ignores the fact that battery-electric vehicles (BEVs) emit far less than both and ignores the impacts of ethanol-fuel combustion on air pollution, land, and water. For example, one study[6]

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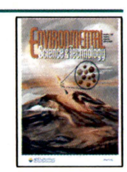

compared the impacts on CO_2e, air pollution, land use, and water use of transitioning all U.S. vehicles to E85 or to BEVs running on electricity from either wind, solar photovoltaics (PV), concentrated solar, geothermal, hydro, tidal, wave, nuclear, or coal with carbon capture sources. The study found that BEVs powered by all sources reduced CO_2e significantly more than using either corn or cellulosic ethanol for E85. The study also found that BEVs reduced air pollution mortality, land requirements, and water needs versus E85. Other studies, which also examine emissions from manufacturing vehicles, similarly find that BEVs reduce overall vehicle lifecycle CO_2e emissions compared with FFVs.[7,8]

With respect to air pollution, tailpipe emissions from E85 vehicles may increase the level of ozone throughout most of the United States in comparison with tailpipe emissions from gasoline vehicles.[9−13] Ozone increases mostly where the background ratio of nitrogen oxides (NO_x) to reactive organic gases is high; ozone decreases mostly where the ratio is low (e.g., in the southeast U.S.).[9] A study in Brazil similarly found that conversion from E100 vehicles to gasoline vehicles decreased ozone.[14] A study in Sweden, where little urban ozone forms, found a small difference in air pollution mortality between tailpipe emissions of gasoline versus E85 vehicles.[15] Increases in many pollutants, including ozone, due to tailpipe emissions of E85 versus gasoline vehicles widen with decreasing temperature.[10,16] Moreover, the production, transport, and refining of corn to produce ethanol creates air pollution that may exceed the upstream pollution from gasoline.[6,17,18]

Air pollution impacts of vehicles are relevant because, in the U.S., outdoor air pollution alone causes ∼94,000 premature deaths per year, and worldwide, indoor plus outdoor air pollution causes ∼7.4 million premature deaths per year.[19] BEVs eliminate 100% of tailpipe emissions of both greenhouse gases and air pollutants and, if powered by renewable electricity, 100% of upstream electricity-production emissions aside from emissions associated with manufacturing the electricity infrastructure.[6] BEVs still have emissions associated with their manufacture, maintenance, and decommissioning, as do FFVs.[7,8]

Thus, a relevant scientific and policy question is what is the opportunity cost of Summit's "ethanol plan" (capturing fermentation CO_2 from ethanol refineries, building a CO_2 pipeline to sequester the CO_2 underground, blending ethanol to produce E85, and using the E85 in FFVs) versus investing the same funds in, for example, wind turbines for powering BEVs ("wind plan A") or for replacing coal plants directly ("wind plan B"). Wind plan A will avoid the need to emit, let alone sequester, any CO_2, and it will eliminate air pollution from combustion vehicle exhaust and from ethanol fuel production. By avoiding emissions of CO_2, wind plan B should reduce more CO_2 than capturing CO_2 at ethanol refineries and should eliminate coal air pollution, which capturing CO_2 does not do.

The purpose of this paper is to carry out such an evaluation. Not only are differences in CO_2e emissions considered but so are differences in vehicle fuel costs, land use, and air pollution. The results here are obtained from a spreadsheet (see Acknowledgments) that considers annual rather than continuous emissions. Whereas a spreadsheet model is simple compared with an optimization model that treats continuous emissions, the annual differences in emissions and costs among the cases examined here are so large that a continuous calculation does not appear necessary. Sensitivity tests are performed to demonstrate this.

■ MATERIALS AND METHODS

A spreadsheet was developed to analyze emissions and cost differences among the three proposals. In this section, Summit's ethanol plan is examined briefly. The Results section compares the three plans.

Summit proposes to capture ∼30 g-CO_2/MJ as a coproduct of fermentation[20,1] at 34 ethanol-producing facilities in 5 midwestern U.S. states: Iowa, Nebraska, South Dakota, Minnesota, and North Dakota. The CO_2 will then be compressed to a supercritical state and piped underground through a pipeline, which Summit will also build, connecting the 34 refineries.[5] The original proposal called for a 1958-mile (3152-km) pipeline connecting 33 refineries. In June 2023, an additional 31-km pipeline connecting a 34th refinery was proposed,[21] bringing the total pipeline length to 1989 miles (3202 km). The pipeline will end at an underground storage site near Bismarck, North Dakota. Summit's pipeline permit requests state that the CO_2 they capture will be "permanently stored" in North Dakota, thus not used for any other purpose, including enhanced oil recovery.[5] If the CO_2 is ever used for enhanced oil recovery, that could result in 40% of the captured CO_2 being released back into the air.[22]

Summit states that the estimated capital cost of the project (to purchase and install the carbon capture equipment and to build the pipeline) is \$5.6 billion.[23] This is \$1.1 billion more than the \$4.5 billion estimated cost in 2022.[5] Summit also states that the pipeline will carry 9.5 million metric tonnes per annum (MMTPA) of CO_2 collected from the 34 ethanol facilities, based on their current ethanol output, although the pipeline has the potential to carry more.[22]

Because the CO_2 that is emitted during fermentation is relatively pure, traditional carbon capture equipment needed to separate carbon dioxide from other impurities emitted from natural gas or coal electricity generation stacks is not needed. However, equipment is still needed to trap the CO_2. Some of the CO_2 may escape, and the capture equipment will occasionally be down for planned and unplanned maintenance. As such, the overall annual-average capture efficiency, even from the fermentation process, may be 90%[24] or less. Ethanol has an energy content of 36.78 g-ethanol/MJ, and the fermentation of dextrose produces 1 mol of CO_2 per mol of ethanol. Thus, fermentation releases 35.14 g-CO_2/MJ. If ∼30 g-CO_2/MJ is captured,[1] the overall capture efficiency is ∼85.4%. This capture efficiency is higher than those from any coal, natural gas, or pure hydrogen facility to date, which ranges from ∼30−80%.[25]

Once CO_2 is captured, electricity is needed to dehydrate it and compress it for pipe transport. Usually, purified CO_2 is compressed, often from 1 bar (atmospheric pressure) to 150 bar, for pipe transport. This requires ∼110 kWh/tonne-CO_2-compressed.[26] In Summit's proposal, however, the CO_2 will be compressed to only above 74.5 bar, but the temperature will also be raised to above 31.1 °C to enter a supercritical state, which is a very dense form of CO_2 that is neither liquid nor gas. The supercritical CO_2 was then piped to an underground storage facility.

The electricity needed to dehydrate, compress (to 74.5 bar), and heat the CO_2 until it is in a supercritical state is estimated to be ∼90 kWh/tonne-CO_2-compressed.[27,28] This extra electricity is a new demand on the grid that is not needed for any purpose. If it is taken from the grid, then more coal will likely be used in each state to replace that grid electricity since increasing coal electricity output is the easiest way to supply a constant

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Table 1. Input Data and Calculated Parameters Relevant to the Results Shown in Table 2[a]

a)	ethanol plan project cost[23]	\$5.6 billion
b)	estimated project life	30 years
c)	ethanol plan projected CO_2 avoided per year[23]	9.5 MMTPA
d)	electricity to compress one tonne of CO_2[27,28]	90 kWh/tonne-CO_2
e)	fermentation carbon captured per MJ[1]	30 g-CO_2/MJ
f)	electricity to compress CO_2 per MJ-ETOH = $d \times e/10^6$	0.0027 kWh/MJ
g)	coal upstream plus stack emissions (20 years time frame)[31]	1381 g-CO_2/kWh
h)	energy penalty to compress CO_2 = $f \times g$	3.73 g-CO_2/MJ
i)	energy penalty to compress CO_2 during project = $c \times h/e$	1.18 MMTPA
j)	CO_2e to build CO_2 pipelines (see text)	0.087 MMPTPA
k)	net CO_2 avoided per year from ethanol plan = $c - i - j$	8.23 MMTPA
l)	2023 Ford F-150 4WD 8-cylinder FFV E85[36]	14 mi/gal-E85
m)	2023 Ford F-150 4WD Ext. Range BEV[36]	480 Wh/mi
n)	moles CO_2 per mole of ETOH combusted	2
o)	ethanol molecular weight	46.07 g/mol
p)	carbon dioxide molecular weight	44.01 g/mol
q)	ethanol density	789.3 g-ETOH/L
r)	liters per gallon	3.785 L/gal
s)	percent gasoline added to pure ETOH as denaturant	2%
t)	tailpipe CO_2 from ETOH = $n \times (p/o) \times q \times r/1000$	5.71 kg-CO_2/gal-ETOH
u)	tailpipe CO_2 from gasoline	8.79 kg-CO_2/gal-gasoline
v)	tailpipe CO_2 from E85 = $(t \times (1 - s) + u \times s) \times 0.85 + u \times 0.15$	6.22 kg-CO_2/gal-E85
w)	wind turbine capital cost[34]	\$1.025–\$1.7 million/MW-wind
x)	capital cost of additional transmission for wind (10% of w)	\$103,000–\$170,000/MW-wind
y)	wind turbine capacity factor[35]	38.5%
z)	wind electricity transmission/distribution/charging losses	10%
aa)	nameplate capacity of wind turbines = $a/(w + x)$	3.0–4.97 GW
bb)	wind electricity output before losses = $aa \times y \times 8760$ h/year/10^6	10.1–16.75 TWh/year
cc)	wind electricity output after losses = $bb(1 - z)$	9.09–15.1 TWh/year
dd)	miles F-150 BEV can travel with this output = $10^{12} \times cc/m$	18.9–31.4 billion miles/year
ee)	lifecycle CO_2e due to building wind turbines[38]	8.6–4.8 g-CO_2e/kWh
ff)	total CO_2e due to building wind turbines = $ee \times bb/1000$	0.087–0.08 MMTPA
gg)	lifecycle CO_2e due to building BEVs[7]	47 g-CO_2e/km
hh)	CO_2e building/maintaining BEVs = $ff \times dd \times 1.61$ km/mi/10^3	1.43–2.38 MMTPA
ii)	lifecycle CO_2e due to building/maintaining FFVs[7]	36 g-CO_2e/km
jj)	CO_2e building/maintaining FFVs = $ii \times dd \times 1.61$ km/mi/10^3	1.1–1.82 MMTPA
kk)	CO_2e added from building BEVs instead of FFVs = $hh - jj$	0.34–0.56 MMTPA
ll)	tailpipe CO_2 avoided due to wind-BEVs = $dd \times v/l$	8.42–13.96 MMTPA
mm)	CO_2e avoided due to wind replacing coal = $cc \times g/1000 - ff$	12.5–20.7 MMTPA
nn)	E85 fuel cost in Iowa, Jul 2022-Aug 2023 average[42]	\$2.53/gallon
oo)	residential electricity cost Iowa, Jan–Dec, 2022 average[43]	\$0.131/kWh
pp)	gallons/y E85 to drive the same distance as BEV = dd/l	1.35–2.24 billion gallons E85
qq)	energy in a gallon of E85	89.27 MJ/gal-E85
rr)	conversion of kWh to MJ	3.6 MJ/kWh
ss)	distance/energy 2023 Ford F-150 FFV-E85 = $l \times 1000/qq$	156.8 Mi/GJ
tt)	distance/energy 2023 Ford F-150 BEV = $10^6/(m \times rr)$	578.7 Mi/GJ
uu)	average yearly miles driven assumed	15,000 mi/year
vv)	number of BEVs that can be purchased = dd/uu	1.262–2.094 million
ww)	fuel cost driving F-150 FFV over project life= $pp \times nn \times b$[b]	\$102.7–170 billion
xx)	fuel cost driving F-150 BEV over project life = $cc \times oo \times b$[b]	\$35.8–59.4 billion
yy)	fuel cost savings due to BEV v FFV over project life = $ww - xx$[b]	\$66.9-\$111 billion
zz)	savings BEV v FFV \$10K higher BEV cost = $yy -$ \$10K $\times vv$[b]	\$54.3–90.1 billion
AA)	savings BEV v FFV \$21.7K higher BEV cost = $yy -$ \$21.7K $\times vv$[b]	\$39.5–65.6 billion
BB)	net savings BEVs after investment cost included = $AA - a$[b]	\$33.9–60.0 billion

[a]ETOH = ethanol. [b]In USD 2023. It is assumed that the 2022–23 E85 cost per gallon (nn) and residential electricity rate (oo) increase each year due to inflation, but future year costs of fuel and electricity are discounted back to USD 2023 at the same inflation rate. Thus, fuel costs and electricity rates for future years are brought back to the same values as those for 2022–23 to obtain overall results in USD 2023.

incremental electricity demand in each state. About 25.4, 48.8, 10, 26.4, and 57% of all electricity generated in Iowa, Nebraska, South Dakota, Minnesota, and North Dakota, respectively, is from coal.[29] Even if existing wind were used to provide incremental electricity for carbon capture, that wind could no longer displace coal electricity. Similarly, if new natural gas was used to power the carbon capture equipment, that natural gas would not be able to replace coal. Thus, in all cases, the incremental electricity demand increases coal electricity use or prevents coal electricity from being reduced.

Coal electricity generation results in ~1381 g-CO_2e/kWh electricity generated over a 20-year time frame (most relevant for climate tipping points[30]) and ~1168 g-CO_2e/kWh over a 100-year time frame.[31] These numbers include not only coal combustion emissions but also coal mining and transport emissions of both CO_2 and methane. Multiplying 1381 g-CO_2e/kWh by 90 kWh/tonne-of-CO_2-compressed gives 124 g-CO_2e-emitted per kg-CO_2-compressed (or 3.73 g-CO_2/MJ-electricity-for-compression - Table 1). This compares with 30 g-CO_2/MJ captured.[1] Thus, ~12.4% (1.18 MMTPA) of the 9.5 MMTPA of CO_2 that is captured will be returned to the air through electricity-related emissions from compressing and heating the CO_2 (Table 1).

When coal is eliminated from these five states, natural gas will remain. In that case, even if wind is used to provide compression electricity, the wind will be prevented from replacing natural gas on the grid, adding CO_2 back to the air, just as in the coal case. Natural gas combined cycle plants (the most efficient) emit, over their lifecycle (accounting for natural gas mining, transport, and combustion), ~900 g-CO_2e/kWh over a 20-year time

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frame.[32] Multiplying by 90 kWh/tonne-of-CO_2-compressed gives 81 g-CO_2e-emitted/kg-of-CO_2-compressed. Thus, even after coal is gone, 8.1% of the CO_2 captured at the ethanol refineries will be returned to the air through natural gas electricity use.

The ethanol plan also requires the construction, installation, and decommissioning of the CO_2 pipes. A pipeline built today is estimated to emit, averaged over its life, ~27.2 tonnes-CO_2/km/year.[33] This is found by summing the nonoperation emissions of the three projects in Table 5−1 of ref 33. (1.96 million metric tonnes-CO_2) by the 2401 km of pipelines for those projects and by an estimated 30-year project life. For the proposed 3202-km Summit pipeline, this translates into ~0.087 MMTPA, or 0.92% of the 9.5 MMTPA captured by the ethanol plan. Subtracting the compression and pipeline emissions from the CO_2 captured by the ethanol plan gives a net capture of 8.23 MMTPA, or 86.6% of the gross capture rate (Table 1).

■ RESULTS

Does Summit's ethanol plan help consumers and the climate, or is it an opportunity cost relative to wind plans A and B? To answer this question, the ethanol plan is first compared with wind plan A. Specifically, the production of E85 from ethanol with carbon capture, followed by E85's use in a 2023 Ford F-150 four-wheel drive (4WD), 8-cylinder FFV, is compared with the production of wind electricity, followed by its use in a 2023 Ford F-150 Lightning 4WD extended range BEV. The Lightning has a range of 320 mi (515 km). The 8-cylinder FFV is chosen because it gives the closest acceleration to the BEV version of the F-150. These two vehicles are selected not only because they are built by the same manufacturer and are roughly equivalent in capabilities but also because they are common vehicle types used in these states.

Results suggest that, if the same $5.6 billion allocated for the ethanol plan is instead spent on wind plan A, drivers in the five states may save $66.9−$111 billion (USD 2023) over 30 years in fuel costs alone due to the price difference between E85 ($2.53/gallon in Iowa in 2022−23) and residential electricity ($0.131/kWh in Iowa in 2022) and due to the far greater mileage per unit energy of the Ford F-150 BEV (578.7 mi/GJ) over the equivalent FFV (156.8 mi/GJ) (Table 1). Even if the BEV initially costs $10,000 more than the FFV and that cost difference disappears in 15 years, the net fuel minus upfront car cost savings over 30 years may still be $54.3−$90.1 billion (USD 2023) (Table 1). Even if the upfront BEV cost is $21,700 higher (the current price difference between the F-150 BEV and FFV), the fuel minus car cost savings is still $39.5−$65.6 billion (USD 2023) (Table 1, Figure 1).

What is more, spending on wind plan A may avoid 2.4−4.0 times the CO_2e emissions as spending the same funds on the ethanol plan [19.8−32.9 MMTPA avoided with wind plan A versus 8.23 MMTPA avoided with the ethanol plan (Table 2, Figure 2)]. In fact, even building wind electricity to replace coal plants (wind plan B) may avoid 1.5−2.5 times the CO_2e than will the ethanol plan (12.5−20.7 MMTPA avoided with wind plan B versus 8.23 MMTPA avoided with the ethanol plan) (Table 1). Finally, the ethanol plan may significantly increase air pollution and land use needs compared with the wind plans.

The cost savings due to wind plan A are derived as follows. Lazard[34] provides the 2022 unsubsidized capital cost of buying and installing a new wind turbine in the U.S. as $1.025−$1.7 million/MW. This accounts for the costs of the turbine, financing, a wind resource analysis, a site analysis, land leasing or

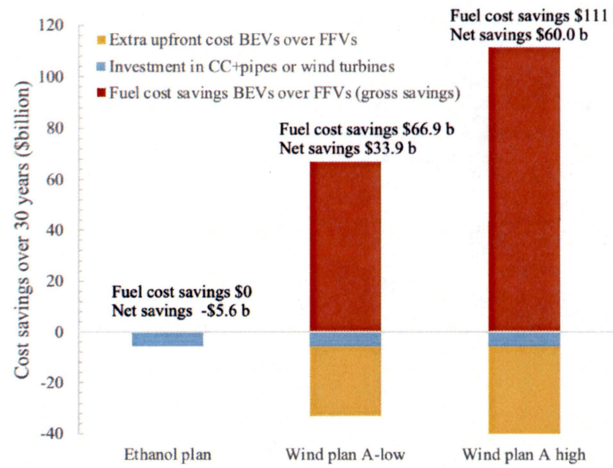

Figure 1. Investment cost, difference in vehicle cost, and difference in fuel cost over 30 years for the ethanol plan versus wind plan A. The gross savings is the savings before the investment cost is added in. The net savings is the savings after the investment cost is added in. Table 1 contains the data. Values are in USD 2023.

purchase, a permitting and interconnection study, utility system upgrades, construction, transformers, protection and metering equipment, insurance, and legal and consultation fees. Another 10% of the capital cost ($103,000−$170,000/MW) is included to upgrade the transmission capacity of the new turbines.

Dividing the $5.6 billion initial outlay for the ethanol plan by the new wind turbine and transmission capital costs gives 3.0−4.97 GW nameplate capacity of wind that can be purchased instead for wind plan A or B (Table 1). Assuming a 38.5% wind capacity factor, which is the mean capacity factor of all U.S. wind projects built from 2014 to 2021[35] plus transmission, distribution, and BEV charging losses amounting to 10% of the raw wind electricity output, the new electricity produced by these wind turbines that may be available to electric vehicles is 9.1−15.1 TWh/year (Table 1). Applying a U.S. EPA mileage rating[36] of 480 Wh/mi for the 2023 F-150 BEV gives 18.9−31.4 billion miles per year drivable by such BEVs (Table 1).

The U.S. Department of Energy[37] defines E85 as "containing 51 to 83% ethanol, depending on geography and season". E85 consists of E100 blended with gasoline. E100 contains at least 2% gasoline as a denaturant, so that people do not drink it. Thus, if 15% gasoline is blended with 85% E100, the resulting mixture (E85) contains 83.3% ethanol and 16.7% gasoline. This is the mixture assumed here. With such a mixture, an E85 vehicle emits 6.22 kg-CO_2/gallon-E85 at the tailpipe (Table 1).

Multiplying the miles per year drivable by BEVs replacing FFVs by the combustion CO_2 emissions of E85 fuel in FFVs, then dividing by the 14 mpg EPA mileage rating[36] of a 2023 Ford F-150 4WD, 8-cylinder FFV running on E85 gives the tailpipe emissions from FFVs avoided by BEVs as 8.4−14.0 MMTPA (Table 1). In other words, BEVs have zero tailpipe emissions, whereas FFVs have substantial tailpipe emissions that BEVs eliminate.

However, ~4% of this reduction may be lost due the ~30% higher (~47 vs ~36 g-CO_2e/km) lifecycle emissions due to building a BEV SUV versus a FFV SUV and due to building BEV batteries.[7] In this study, this translates into ~0.34−0.56 MMTPA additional emissions due to building and maintaining the Ford F-150 BEV instead of the Ford F-150 FFV.

Table 2. Row 1: LCA emissions, including LUC emissions, for corn-ethanol (ETOH) production and distribution without carbon capture, from four studies. Row 2: LCA values from the four studies minus their LUC emissions. Row 3: LUC emissions from the four studies. Row 4: LUC emissions from L23. Row 5: Non-LUC LCA emissions from the four studies plus the LUC emissions from L23. Row 6: LCA emissions of gasoline. Row 7: LCA emissions from Row 5 converted to emissions per gallon of pure ethanol (without a denaturant added). Row 8: LCA emissions of gasoline per gallon of gasoline. Row 9: Total LCA emissions (with LUC) per gallon of E85 after accounting for the addition of 2% gasoline as a denaturant to pure ethanol; E85 consists of 85% ethanol with denaturant and 15% gasoline. Row 10: Million metric tonnes per annum (MMTPA) of CO_2e emissions avoided due to ethanol plan (from Table 1). Row 11: MMTPA of CO_2e emissions avoided from E85 fuel production by using wind-BEVs (wind plan A) instead of E85 from corn ethanol with carbon capture and pipelines (ethanol plan), calculated as Row 9 multiplied by the miles/year driven from Table 1 and divided by the FFV miles per gallon from Table 1. Row 12: Tailpipe CO_2 emissions avoided with wind plan A, from Table 1. Row 13: Lifecycle CO_2e emissions added to air due to building wind turbines for wind plans, from Table 1. Row 14: Lifecycle CO_2e emissions added due to manufacturing and maintaining BEV, from Table 1. Row 15: Equals Rows 11 + 12 minus Rows 13 + 14. Row 16: Equals Row 15 divided by Row 10[a]

	EPA RIA[b]	CARB LCFS[b]	GREET[b]	Scully et al.[1]
1) Original LCA (g-CO_2e/MJ)	73.2	71	53.6	51.4
2) LCA without LUC (g-CO_2e/MJ)	77	66	51.6	47.5
3) LUC from given study (g-CO_2e/MJ)	−3.77	5.03	2.03	3.9
4) LUC from L23 (g-CO_2e/MJ)	38.7	38.7	38.7	38.7
5) LCA w/L23 LUC (g-CO_2e/MJ)	115.7	104.7	90.3	86.2
6) LCA gasoline (L23) (g-CO_2e/MJ)	93.1	93.1	93.1	93.1
7) LCA ETOH (kg-CO_2e/gal-ETOH)	9.4	8.5	7.3	7
8) LCA gas (kg-CO_2e/gal-gasoline)	12.1	12.1	12.1	12.1
9) LCA E85 (kg-CO_2e/gal-E85)	9.84	9.1	8.12	7.85

									average	
	Hi	Lo	Hi	Lo	Hi	Lo	Hi	Lo	Hi	Lo
10) MMTPA avoided due to ethanol plan	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	**8.23**	**8.23**
11) Fuel prod MMTPA avoided due to BEVs	22.08	13.31	20.41	12.30	18.22	10.99	17.60	10.61	**19.6**	**11.8**
12) Tailpipe MMTPA avoided due to BEVs	13.96	8.42	13.96	8.42	13.96	8.42	13.96	8.42	**14.0**	**8.42**
13) MMTPA added due to wind turbines	0.087	0.080	0.087	0.080	0.087	0.080	0.087	0.080	**0.09**	**0.08**
14) MMTPA added due to BEV veh. prod	0.56	0.34	0.56	0.34	0.56	0.34	0.56	0.34	**0.56**	**0.34**
15) Total MMTPA avoided due to BEVs	35.39	21.31	33.72	20.31	31.54	18.99	30.92	18.61	**32.9**	**19.8**
16) Ratio BEV:E85 MMTPA avoided	4.30	2.59	4.10	2.47	3.83	2.31	3.76	2.26	**4.00**	**2.41**

[a]L23 = Lark et al.[2] [b]From Table 2 of L23, where EPA RIA, U.S. Environmental Protection Agency Regulatory Impact Analysis model; CARB LCFS, California air resources board low-carbon fuel standard model; GREET, Greenhouse gases, regulated emissions, and energy uses in technologies model.

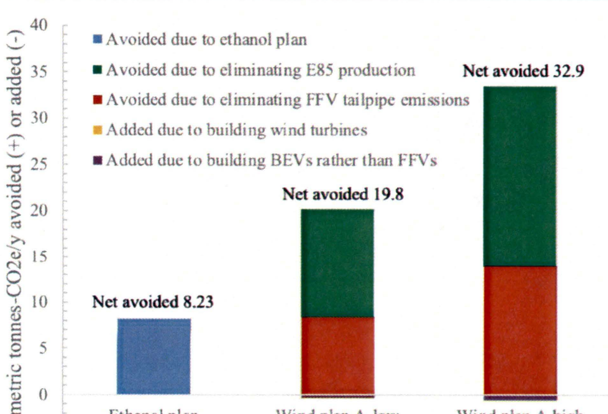

Figure 2. Million metric tonnes per year of avoided CO_2e due to the ethanol plan versus wind plan A. Data are from Table 2, last two columns. The net value in the ethanol plan includes the CO_2e removed by carbon capture plus the CO_2e added back to the air due to electricity needed for CO_2 compression and due to building the pipeline (Table 1).

In addition, the construction, installation, and decommissioning of onshore wind turbines today cause emissions of ~6.7 (4.8−8.6) g-CO_2e/kWh.[38] This range accounts for some reduction in CO_2e due to wind turbines reducing water vapor, a greenhouse gas.[38] For the 13.5 (10.1−16.8) TWh/year of wind electricity produced (before transmission and distribution losses) by the wind turbines built to replace the ethanol plan here, that translates into ~0.08−0.087 MMTPA of CO_2e due to the wind turbines (Table 1). Subtracting the CO_2e added to the air due to building both the wind turbines and BEVs from the CO_2e avoided by eliminating FFV tailpipe emissions gives a net savings so far due to wind plan A of 7.98−13.35 MMTPA.

However, the overall avoided CO_2e due to wind plan A is far greater. By eliminating the use of FFVs, wind plans A and B also eliminate CO_2e due to producing E85 for FFVs. The ethanol at issue here is produced from corn, which grows via photosynthesis by pulling CO_2 and water vapor from the air and soil. However, even with BEVs, CO_2 is still pulled from the air to grow corn or another crop or vegetation on the same land; therefore, transitioning to BEVs eliminates entirely tailpipe emission from FFVs without reducing the carbon uptake by vegetation. In fact, reducing or eliminating the use of corn for fuel may increase the uptake of CO_2 in vegetation if some of the freed-up land is instead used to grow more carbon-intensive vegetation than corn. However, this study assumes no increase in the level of CO_2 uptake upon replacing corn with another crop or vegetation.

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The lifecycle emissions, excluding LUC, of producing and distributing corn ethanol are estimated from multiple studies to be 47.5−77 g-CO_2e/MJ (Table 2).[1,2] Lark et al.[2] performed a detailed analysis of LUC emissions associated with the U.S. renewable fuels standard (RFS) from 2008 to 2016 and concluded as follows:

"We find that the RFS increased corn prices by 30% and the prices of other crops by 20%, which, in turn, expanded US corn cultivation by 2.8 Mha (8.7%) and total cropland by 2.1 Mha (2.4%) in the years following policy enactment (2008 to 2016). These changes increased annual nationwide fertilizer use by 3 to 8%, increased water quality degradants by 3 to 5%, and caused enough domestic LUC emissions such that the carbon intensity of corn ethanol produced under the RFS is no less than gasoline and likely at least 24% higher".

Lark et al. addressed some issues in previous studies that treated LUC, as also discussed in Spawn-Lee et al.,[3] which was responded to.[4] Lark et al.'s estimate of LUC emissions associated with ethanol production for 2008−2016 was a mean of 38.7 g-CO_2e/MJ (Table 2). This estimate is added to the non-LUC LCA emission range here for all years past 2016 since it is the latest and most detailed value available. The resulting total LCA-with-LUC emissions due to ethanol are 86.2−115.7 g-CO_2e/MJ (Table 2). This compares with 93.1 g-CO_2e/MJ for gasoline.[2] Thus, corn-ethanol CO_2e emissions appear to be near or above those of gasoline. The ethanol LCA emission range just cited corresponds to 7.0−9.4 kg-CO_2e/gallon-ethanol, or 7.9−9.8 kg-CO_2e/gallon-E85 (Table 2).

Replacing FFVs with BEVs eliminates the emissions associated with the upstream production of E85 (7.9−9.8 kg-CO_2e/gallon-E85) (Table 2). This is equivalent to 11.8−19.6 MMTPA of CO_2 avoided over all miles driven by BEVs replacing FFVs (Table 2). Combining this upstream-avoided emission with tailpipe-avoided emissions and emissions added due to producing, maintaining, and decommissioning BEVs versus FFVs and to producing wind turbines gives an overall reduction of 19.8−32.9 MMTPA of CO_2e due to BEVs replacing FFVs (Table 2). This compares with 8.23 MMTPA avoided by capturing CO_2 from ethanol refineries per the ethanol plan (Table 2). In sum, investing in wind plan A results in 2.4−4.0 times the CO_2 avoided as investing in the ethanol plan (Table 2, Figure 2).

What is more, burning E85 in FFVs emits health-affecting pollutants[9,11,14] as does running tractors that cultivate corn, trucks, trains, and barges that transport corn and E85, and ethanol refineries.[6,17,18] BEVs eliminate 100% of air pollution emissions from the farming, transporting, and refining of corn to produce E85 and from FFV exhaust. The overall tailpipe and nontailpipe non-CO_2 air pollution impacts from producing plus using E85 are estimated to exceed those of gasoline.[6,17,18]

Further, ethanol with carbon capture for E85 vehicles uses far more land than does wind or solar producing electricity for BEVs.[6] First, photosynthesis is only 1% efficient. Solar PV panels, for example, are 20−23% efficient. As such, a solar PV farm needs only 1/20th−1/23rd of the land to produce the same energy as does a biofuel crop. Further, BEVs convert 80−90% of the electricity within a battery to motion. The rest is waste heat. FFVs running on E85 convert roughly ∼17−24% of energy in the E85 to motion. As such, driving a BEV requires 1/4th the energy of driving a FFV running on E85. For instance, the 2023 Ford F-150 BEV obtains 579 mi/GJ, whereas the 2023 Ford F-150 FFV obtains 156.8 mi/GJ (Table 1), a factor of 3.7 difference. Combining the difference in PV versus photosynthesis efficiency with the difference in BEV versus FFV efficiency indicates that driving a BEV powered by solar PV requires ∼1/80th the land area on the ground as driving an FFV powered by E85 from corn ethanol.[6] A wind turbine requires less than 1/5000th the footprint on the ground (accounting for only pole in the ground plus a cement base) as does a solar PV farm to provide the same electricity.[6] As such, BEVs may take up less than 1/400,000th the footprint as do corn-E85 vehicles.[6] Wind turbines do require space between them to prevent interference of the wakes of one turbine with that of another turbine. However, even the spacing area for wind turbines powering BEVs may be ∼1/10th to 1/20th the land needed to grow corn for E85 powering FFVs.[6] Because most of the wind's spacing area is open space between turbines, crops can grow or solar PV can be placed within the spacing area.

On top of the land needed to grow corn, the ethanol plan requires 1989 miles (3202 km) of new pipelines. The pipelines will be underground, but constructing them will require vegetation removal and other land disturbance over a 110-foot (33.5-m) footprint that will evolve into a 50-foot permanent easement.[39] The construction footprint across the five states is thus ∼41.4 sq mi (107.3 sq km) or about 0.07% the size of Iowa. Many permanent valves and interconnect sites and temporary access roads will also be built along the pipeline routes.[39]

■ DISCUSSION

This study concludes that investing in wind turbines to provide electricity for BEVs is far more beneficial in terms of consumer cost savings, CO_2e emissions, land use, and air pollution than making the same investment in a plan to capture CO_2 from ethanol refineries, pipe the CO_2 to an underground storage facility, and use the ethanol to produce E85 for FFVs. The fuel cost savings alone ($66.9−$111 billion over 30 years, USD 2023) of wind plan A is 12−20 times the $5.6 billion investment in Summit project.

As of August 2023, the base manufacturer's suggested retail price of the Ford F-150 4WD extended range BEV was $69,995,[40] and that of the F-150 4WD, 8-cylinder FFV was $48,290.[40] Thus, the cost difference was $21,705. Even with this upfront cost difference and assuming the difference for new electric vehicles disappears after 15 years, the net fuel cost minus upfront vehicle cost savings to drivers over 30 years is still $39.5−$65.6 billion (USD 2023), still 7−12 times Summit's investment (Table 1). The reason for the large benefit of wind plan A is that combustion fuels are extremely inefficient. A BEV travels about 3.7 times the distance as an equivalent FFV running on E85 for the same energy (Table 1). This difference, combined with the relative prices of electricity versus E85, gives enormous fuel cost savings due to BEVs. Summit's investment in an ethanol pipeline will lock in five states to promote a very inefficient fuel for decades to come.

Similarly, the CO_2e emissions avoided from the ethanol plan are only 25−41.6% and 39.7−66% of those obtainable by investing instead in wind plans A and B, respectively. With respect to wind plan A, this is because wind-BEVs eliminate 100% of both tailpipe and upstream ethanol production emissions, whereas the ethanol plan eliminates only a portion of the upstream CO_2e emissions and no tailpipe emissions. With respect to wind plan B, this is because eliminating CO_2e from coal mining and combustion reduces much more CO_2e than simply capturing some CO_2 from ethanol refineries.

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Air pollution levels from producing and burning ethanol in an FFV are similar to or greater than those from burning gasoline. BEVs powered by wind or solar eliminate 100% of tailpipe emissions and ambient pollution and 100% of ethanol production emissions, so they improve health compared with both. Land footprint areas on the ground are reduced by factors of 80 and 400,000 per kilometer driven by solar PV and wind, respectively, powering BEVs compared with FFVs running on corn-E85.

Although the results here contain significant uncertainties, the cost, CO_2e, and land benefits of the wind plans over the ethanol plan are so enormous that substantially different input assumptions do not change the conclusions. For example, if the additional transmission capital cost for wind is 100% instead of 10% of the wind turbine capital costs, the overall cost benefit to consumers, even with a ~$21,700 higher BEV than FFV vehicle cost, is still $21.7−$36.1 billion (USD 2023), rather than $39.5−$65.6 billion (USD 2023), over 30 years. In another example, even if the Summit pipeline carried 18 rather than 9.5 MMTPA of CO_2, wind plan A would still avoid 1.3−2.1 rather than 2.4−4.0 times the CO_2e avoided as the ethanol plan while still saving consumers $39.5−$65.6 billion over 30 years. Thus, uncertainties in inputs are unlikely to affect any conclusion here. Rather, the main uncertainty is whether political willpower can be obtained to implement a large-scale transition to BEVs powered by wind or solar electricity in states in which corn is abundant.

Finally, is there enough renewable electricity (primarily wind and solar) to cover not only normal electricity needs in the five states at issue but also the electricity needed for electrified transportation, buildings, and industry in those states? The answer is yes. In every state, electrification of all energy is estimated to reduce end-use energy demand by 50−60%.[41] Almost all remaining energy will be electricity; thus the ratio of electricity needed upon electrification to that before electrification ranges from 1.42 (North Dakota) to 3.43 (Iowa).[41] The new footprint plus spacing areas required for wind and solar to meet the all-purpose end-use demand range from 0.25% (South Dakota) to 2.2% (Iowa) of each state's land area.[41] As such, there is plenty of available space for wind and solar electricity to power these states for all purposes.

In sum, redirecting investments from carbon capture equipment and pipelines for ethanol refineries to wind and solar farms for powering BEVs will benefit the climate, health, and land use tremendously while saving consumers enormous sums of money.

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Notes

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ABBREVIATIONS

4WD= four-wheel drive
BEV= battery-electric vehicle
CARB= California Air Resources Board
CO2e= carbon dioxide-equivalent emissions
EPA= U.S. Environmental Protection Agency
ETOH= ethanol
FFV= flex-fuel vehicle
GREET= greenhouse gases, regulated emissions, and energy uses in technologies
LCA= lifecyle assessment
LCFS= low-carbon fuel standard
LUC= land-use change
MMPTA= million metric tonnes per annum
PV= photovoltaic
RFS= renewable fuels standard
RIA= regulatory impact analysis
ROG= reactive organic gas
USD= United States Dollars

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

Mark Z. Jacobson

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

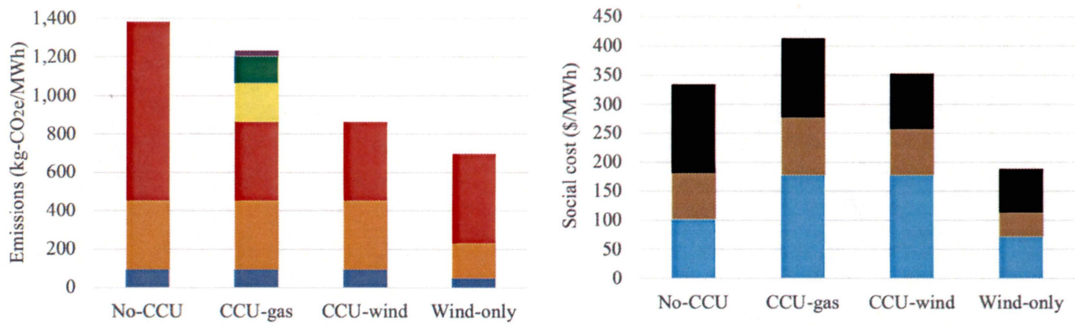

Fig. 1 Left: CO_2e emissions, averaged over 20 years, from the Petra-Nova coal plant before (No-CCU) and after (CCU-gas) the addition of CCU equipment powered by natural gas. Also shown are emissions when the CCU equipment is powered by wind energy (CCU-wind) and when the portion of wind energy used 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.

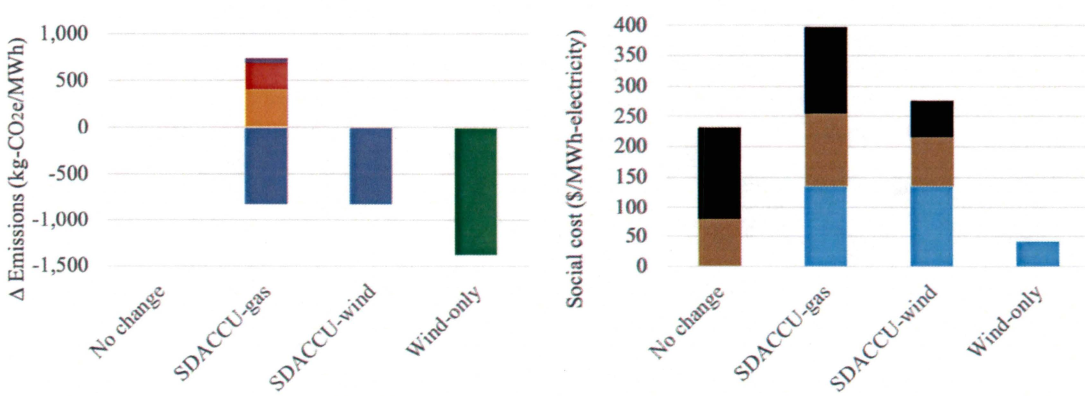

Fig. 2 Left: Change in CO_2e emissions, averaged over 20 years, per unit electricity needed to run SCACCU equipment resulting from either no action (no-change), using an SDACCU plant with equipment powered by natural gas (SDACCU-gas), using an SDACCU plant with equipment powered by wind (SDACCU-wind), 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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