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

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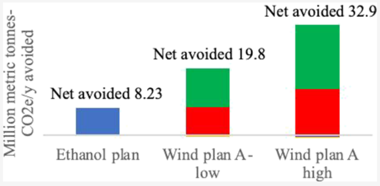

ABSTRACT: An important issue today is whether gasoline vehicles should be replaced by flex-fuel vehicles (FFVs) that use ethanol-gasoline blends (e.g., E85), where some carbon dioxide (CO_2) from ethanol's production is captured and piped, or battery-electric vehicles (BEVs) powered by wind or solar. 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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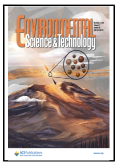

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compared the impacts on CO_2e, air pollution, land use, and water use of transitioning all U.S. vehicles to E85 or to BEVs running on electricity from either wind, solar photovoltaics (PV), concentrated solar, geothermal, hydro, tidal, wave, nuclear, 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

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 × vv[b]	\$54.3–90.1 billion
AA)	savings BEV v FFV \$21.7K higher BEV cost = yy − \$21.7K × 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 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).

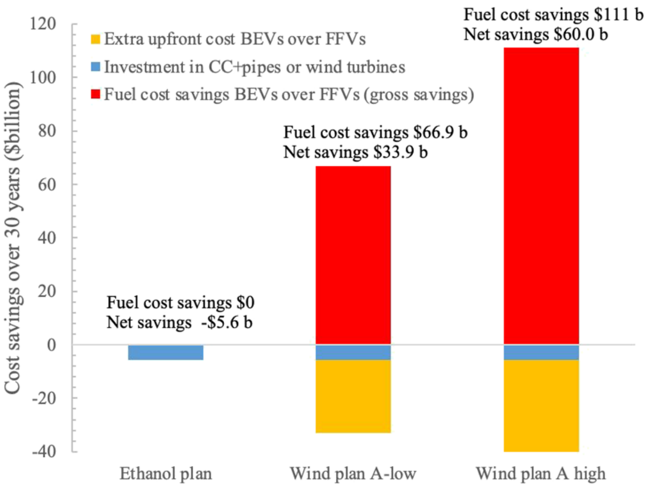

Figure 1. Investment cost, difference in vehicle cost, and difference in fuel cost over 30 years for the ethanol plan versus wind plan A. The gross savings is the savings before the investment cost is added in. The net savings is the savings after the investment cost is added in. Table 1 contains the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

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 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.

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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.

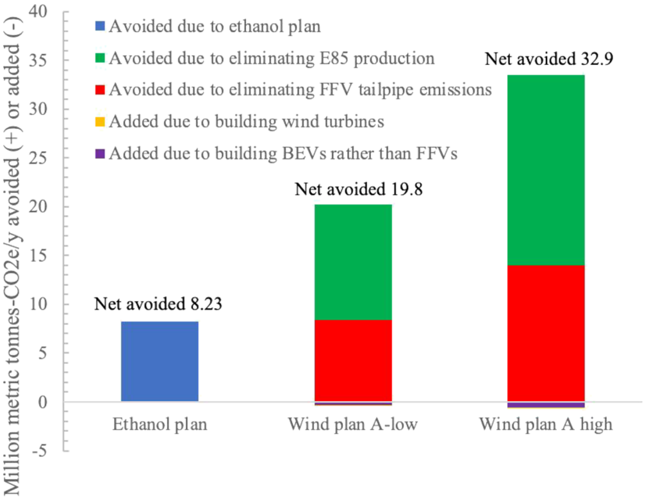

Figure 2. Million metric tonnes per year of avoided CO_2e due to the ethanol plan versus wind plan A. Data are from Table 2, last two columns. The net value in the ethanol plan includes the CO_2e removed by carbon capture plus the CO_2e added back to the air due to electricity needed for CO_2 compression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

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 nation-wide 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.

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= lifecycle 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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