

Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol

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The quantity of land available to grow biofuel crops without impacting food prices or greenhouse gas emissions from land conversion is limited. Therefore, bioenergy should maximize land use efficiency when addressing transportation and climate change goals. Biomass could power either internal combustion or electric vehicles, but the relative land use efficiency of these two energy pathways is not well quantified. Here we show that bioelectricity outperforms ethanol across a range of feedstocks, conversion technologies, and vehicle classes. Bioelectricity produces an average 81% more transportation kilometers and 108% more emissions offsets per unit area cropland than cellulosic ethanol. These results suggest that alternative bioenergy pathways have large differences in how efficiently they use the available land to achieve transportation and climate goals.

Concerns over petroleum prices and greenhouse gas (GHG) emissions are driving research investments into alternative transportation technologies, but the preferred technology is debated (1–5). There is surging interest in using agriculture lands to grow energy feedstocks for these alternative transportation technologies. Two leading technology developments, cellulosic ethanol and electric vehicle batteries, provide alternative pathways for bioenergy-based transportation. Biomass can be converted into ethanol to power internal combustion vehicles (ICVs) or converted into electricity to power battery electric vehicles (BEVs). It is uncertain which pathway could reach technical and economic maturity first. The cellulosic ethanol pathway benefits from commercially available flex-fuel vehicles but requires significant investments in infrastructure as well as technology advancements to reduce costs for energy conversion (6). The bioelectricity pathway shows promise in existing distribution infrastructure and emerging commercial offerings of battery electric vehicles that meet technology challenges of range, cost, and charging time. Electricity produced from biomass is a near-term renewable energy source that can be implemented with biomass boilers, Integrated Gasification Combined

Cycle (IGCC) power plants, or co-combustion with coal (7, 8).

While both of these bioenergy pathways have real potential to meet transportation goals, their relative performance with respect to land use efficiency is not well quantified. Given the limited area of land that is available to grow biofuels crops without causing direct or indirect land use impacts (9–12), bioenergy applications should maximize the efficiency with which a given land area is used to meet transportation and climate change goals. In one study the use of willow biomass for electricity was shown to have greater transportation fuel displacement and GHG offsets than corn ethanol (13). A quantification of the transportation output and GHG offset per unit area of cropland, across a range of feedstocks, energy conversion technologies, and vehicle types is needed to assess the land use efficiency of these alternative energy pathways.

Here we present a life cycle assessment comparing the performance of bioelectricity and ethanol with respect to transportation kilometers and GHG offsets achieved per unit area of biofuels cropland. The Energy and Resources Group Biofuel Analysis Meta-Model (EBAMM) is used to consider scenarios that cover a range of feedstocks and energy conversion technologies including corn and cellulosic ethanol (14). A range of vehicle classes is evaluated with published EPA efficiencies for highway and city driving of ICVs and BEVs (15). The life cycle assessment includes accounting of the fuel cycle energy (energy input needed to grow the feedstock and convert it to either electricity or ethanol) (14) and vehicle cycle energy (energy input needed to manufacture and dispose of vehicles) (16–18). Co-product credits in EBAMM favor the ethanol pathway by accounting for ethanol co-products but not potential bioelectricity co-products including steam for heat and fly-ash for cement. While new corn ethanol refineries may have higher efficiencies than those used in EBAMM (19, 20), the cellulosic case provides a much higher ethanol efficiency case for comparing ethanol to bioelectricity (biomass is used to power the cellulosic ethanol conversion process). Since crop yields (21, 22) and land use impacts (12) vary beyond those

applied in the EBAMM model, our analysis is best suited for a comparison of these two pathways rather than quantification of the total land area needed for an individual pathway. While burning kernels for electricity is an unlikely pathway, the kernels of the corn plant are harvested for energy use in the corn scenarios for comparison of the ethanol and bioelectricity pathways (23). Detailed methods and results are provided in the supporting online material (SOM).

The net transportation output per hectare is larger for the bioelectricity case. With BEVs and ICVs of similar size, one can travel farther on biomass grown on a hectare of land when it is converted to electricity than when it is converted to ethanol. To illustrate the transportation results we show the various inputs and outputs in Fig. 1 for the case of the switchgrass feedstock with small SUV driving on the highway. For this case, the gross transportation output per hectare is 85% greater for bioelectricity than cellulosic ethanol. This is largely due to fact that the small SUV BEV has an electric motor that is 3.1 times as efficient as the internal combustion engine of the small SUV ICV for highway driving (24). The fuel cycle and vehicle cycle account for the energy inputs and co-products during the production of the biomass, fuel, and vehicles. Gross transportation output is converted to net transportation output by subtracting the fuel cycle and vehicle cycle costs. Input costs were converted from energy units ($\text{MJ ha}^{-1} \text{y}^{-1}$) to transportation distance units ($\text{km ha}^{-1} \text{y}^{-1}$) using the ICV efficiency for petroleum inputs, and using the BEV efficiency for coal, natural gas, and electricity inputs. The vehicle cycle inputs per hectare of cropland (costs to manufacture, maintain and dispose of the vehicle over its lifetime) are large for the bioelectricity case for two reasons (24). First, the vehicle cycle costs per hectare are calculated by scaling the lifetime vehicle costs by the gross distance traveled per hectare and the gross distance is larger for bioelectricity than ethanol. Second the lifetime vehicle costs are larger for the BEV than the ICV due to the cost of the batteries. The net transportation output per hectare is 56% greater for the bioelectricity pathway than the ethanol pathway for this case of a switchgrass feedstock with small SUV driving on the highway.

The gross and net transportation outputs for a range of feedstocks and vehicle classes are shown in Fig. 2. For the gross transportation distance, the bioelectricity output is on average 112% greater than the ethanol output for the full range of feedstocks, energy conversions, and vehicle efficiencies. For the net transportation distance, several of the corn ethanol cases result in negative distances because the distance that could be traveled with the net fuel cycle inputs (petroleum via ICV and electricity, coal and natural gas via BEV) is greater than the distance that could be traveled with the gross ethanol output. The average net transportation

distance for the switchgrass feedstock was 81% larger ($\text{SE} = 21\%$) for bioelectricity than ethanol. While bioelectricity generally performed better than ethanol, the bioelectricity and ethanol pathways had similar results for highway driving with the small car and full-size SUV. The two BEVs tested by the EPA for these vehicle classes had particularly low highway efficiencies and low ranges ($<166 \text{ km}$). This suggests that these specific BEVs were not designed for highway driving, as opposed to the midsize car BEV and small SUV BEV which perform well for city and highway driving. A high efficiency case (hybrid ICVs, IGCC power plant, exclude low range BEV) results in 95% greater net transportation output for bioelectricity than ethanol (24). The relative efficiency of these pathways may be altered in the future with new powertrain technologies (5), heating co-products, and electricity storage approaches (25). However, based on the efficiencies of deployed bioelectricity technologies and emerging cellulosic ethanol technologies, the bioelectricity pathway consistently produces more transportation kilometers than the ethanol pathway.

The gross and net GHG offsets for a range of feedstocks and vehicle classes are shown in Fig. 2. For the switchgrass feedstock, the average net offset for bioelectricity is 108% greater ($\text{SE} = 28\%$) than the offset for ethanol. For both pathways, these GHG offsets could only be achieved if land use impacts are avoided (9–12). For the bioelectricity pathway, the GHG offsets could be greatly increased by accounting for the steam co-products during electricity generation. Furthermore, the application of carbon capture and sequestration (CCS) technologies with bioelectricity could result in a carbon-negative energy source. By sequestering the flue gas CO_2 at the power plant, the bioelectricity pathway could result in a net removal of CO_2 from the air.

The life cycle assessment considered here suggests that a limited area of cropland would deliver more transportation and GHG offsets with a bioelectricity pathway than an ethanol pathway. These results provide further support for general bioelectricity applications which are already thought to have greater climate mitigation benefits than ethanol (26–28). Electric transportation may also provide a bridge that connects transportation to future renewable energy sources such as solar and wind power. Combining CCS with the bioelectricity pathway could result in a carbon-negative energy source that removes CO_2 from the atmosphere. On the other hand, electric transportation also provides a bridge to the use of conventional coal energy for transportation. These results do not indicate that bioelectricity is the preferred pathway over ethanol as there are numerous other criteria that need to be evaluated such as impacts on regional water resources (29), battery toxicity and recycling (30), air pollution (7), and economic constraints (18). The optimal

pathway for biomass will also depend on how efficiently other feedstocks can be converted to both liquid fuels and electricity. Specifically, the competitiveness of biomass ethanol depends on the cost of petroleum, whereas the competitiveness of biomass electricity depends on the cost of coal, wind, hydro, solar, and nuclear. These results do suggest, however, that alternative bioenergy pathways have large differences in how efficiently they use the limited available land to maximize transportation and climate benefits.

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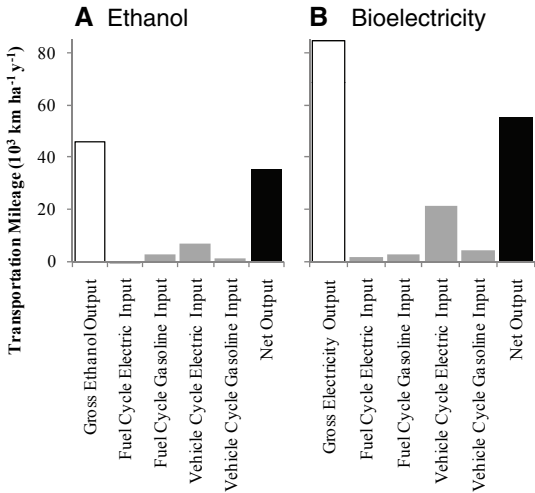
Supporting Online Material

www.sciencemag.org/cgi/content/full/1168885/DC1
Tables S1 to S13
References

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Fig. 1. Transportation for the switchgrass feedstock with highway driving in a small SUV. Electric inputs account for natural gas, coal, and electricity used in the fuel cycle and vehicle cycle. The liquid fuel inputs are accounted for as transportation input using the ICV efficiency and the electric inputs are accounted for using the BEV efficiency. Co-products in the ethanol pathway are subtracted from the ethanol inputs in EBAMM. Vehicle cycle inputs are scaled by the total vehicle lifetime distance relative to the distance traveled with the gross fuel minus the fuel cycle inputs (24).

Fig. 2. Transportation and GHG offsets from bioelectricity and ethanol based on a range of vehicle classes, agriculture systems, and energy conversion technologies. Net output accounts for co-products as well as input in the fuel cycle and vehicle cycle. Results are not plotted for cases when more kilometers could be traveled with input energy than with gross output energy (24).



Corn

Switchgrass

