

Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol J. E. Campbell, et al. Science **324**, 1055 (2009):

Science **324**, 1055 (2009); DOI: 10.1126/science.1168885

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ity at a low discharge rate of C/10 increased from 143 mAh/g (E4) to 160 mAh/g with EC#1 and to 170 mA·hour/g with EC#2. The performance improvement is more pronounced at higher rates. Discharge profiles of the two-gene system show much lower polarization and maintain much higher capacity than those of the one-gene system at high rates. When compared with the best reported capacity for a-FePO₄ at a high rate of 3C (80 mAh/g) (21), EC#2 showed a capacity of 134 mAh/g, confirming substantially improved high-power performance. Moreover, when we cycled EC#2 between 1.5 and 4.3 V, the first discharge capacity at 10C reached 130 mAh/g. No published data for a-FePO₄ are available for comparison at rates higher than 3C, but this capacity value obtained for the twogene system is comparable to the capacity from state-of-the-art c-LiFePO₄. The power performance of the multifunctional virus-based cathode was further compared with a Ragone plot. Figure 4B shows that two-gene system-based materials delivered much higher energy than the one-gene system at high power. At a specific power of 4000 W/kg (corresponding to a rate of \sim 10C), the energy density of EC#1 and EC#2 was two times and three times as high, respectively, as that of E4. Again, the high-power performance scales with binding affinity. In Fig. 4B (inset), the rate performance of E4 virus-based cathodes with either Super P carbon or SWNTs was tested. Well-dispersed SWNTs by themselves make better electrical wiring to active materials due to better percolation networks than carbon black powders (23), confirming the importance of nanoscale electrical wiring. Figure 4C shows the stable capacity retention of a-FePO₄/SWNT hybrid electrodes upon cycling at 1C. Up to 50 cycles, virtually no capacity fade was observed. A slight capacity loss after the first cycle is a characteristic of a-FePO₄ materials (17, 21). When cycled at C/10 rate again after the sample was tested for several cycles at rates from C/10 to 10C, the original capacity was recovered, confirming structural stability (fig. S8B). Structural stability of viral a-FePO₄/SWNT hybrid nanostructures was induced by materials-specific binding and stiff, robust carbon nanotubes, leading to excellent retention at a low SWNT content of 5 wt %. Because the density of SWNTs is 1.33 g/cm³ (23), it would decrease the volumetric energy density of the hybrid electrodes. However, although we adopted SWNTs to show that we can achieve nanoscale wiring by genetic engineering, we expect that we could optimize the fraction of the conducting additives by using even betterconducting nanowires with high aspect ratio and higher density.

There have been efforts to electrically address electrode materials with poor electronic conductivity through nanoscale wiring of active materials (8, 29, 30). However, the wiring tools used so far were functionalized for a single component, either active materials (8, 30) or conducting materials (29). The wiring did not completely ex-

ploit specificity but depended on the random occurrence of contacts between conducting networks and active materials. By developing a twogene system with a universal handle to pick up electrically conducting carbon nanotubes, we devised a method to realize nanoscale electrical wiring for high-power lithium-ion batteries using basic biological principles. This biological scaffold could further extend possible sets of electrode materials by activating classes of materials that have been excluded because of their extremely low electronic conductivity.

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charging or discharging to the theoretical capacity of the materials in n hours. Here, 1C corresponds to 178 mA/q.

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- Abbreviations for the amino acid residues are as follows:
 D, Asp; G, Gly; H, His; L, Leu; M, Met; P, Pro; Q, Gln; R, Arg; S, Ser; T, Thr; V, Val; and Y, Tyr.
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Supporting Online Material

www.sciencemag.org/cgi/content/full/1171541/DC1 Materials and Methods Figs. S1 to S8 References

28 January 2009; accepted 25 March 2009 Published online 2 April 2009; 10.1126/science.1171541 Include this information when citing this paper.

Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol

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The quantity of land available to grow biofuel crops without affecting food prices or greenhouse gas (GHG) 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 of 81% more transportation kilometers and 108% more emissions offsets per unit area of cropland than does 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.

Oncerns over petroleum prices and greenhouse gas (GHG) emissions are driving research investments into alternative transportation technologies, but the preferred technology is still being debated (1-5). There is surging

interest in the use of 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-

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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 substantial 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 BEVs 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).

Although both of these bioenergy pathways have real potential to meet transportation goals, their relative performance with respect to landuse 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 U.S. Environmental Protection Agency (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. Whereas 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). Because 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. Although 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.

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 a small sport utility vehicle (SUV) driving on the highway. For this case, the gross transportation output per hectare is 85% greater for bioelectricity than for cellulosic ethanol. This is largely due to the 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 (megajoules per hectare per year) to transportation distance units (kilometers per hectare per year) using the ICV efficiency for petroleum inputs and the BEV efficiency for coal, natural gas, and electricity inputs.

Fig. 1. Transportation for ethanol (A) and bioelectricity (B) using 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 the 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).

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 is larger for bioelectricity than for ethanol. Second, the lifetime vehicle costs are larger for the BEV than the ICV because of 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 a 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 (SE = 21%) for bioelectricity than for ethanol. Whereas 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 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 highefficiency case (hybrid ICVs, IGCC power plant, excluding low-range BEV) results in 95% greater net transportation output for bioelectricity than for ethanol (24). The relative efficiency of these pathways may be altered in the future with new powertrain technologies (5), heating co-products,



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and electricity storage approaches (25). However, on the basis of 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 (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 coproducts 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 CO₂ 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 with 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 because 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 power. 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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- 31. This work was supported by University of California, Merced start-up funds, the Stanford University Global Climate and Energy Project, the Carnegie Institution, and NASA New Investigator grant no. NNX08AV25G to D.B.L. We thank K. Gillingham and C. Weber for critical comments on the manuscript.

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24 November 2008; accepted 15 April 2009 Published online 7 May 2009; 10.1126/science.1168885 Include this information when citing this paper.