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The Climate Impacts of Bioenergy Systems Depend on Market and Regulatory Policy Contexts

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Biomass can help reduce greenhouse gas (GHG) emissions by displacing petroleum in the transportation sector, by displacing fossil-based electricity, and by sequestering atmospheric carbon. Which use mitigates the most emissions depends on market and regulatory contexts outside the scope of attributional life cycle assessments. We show that bioelectricity's advantage over liquid biofuels depends on the GHG intensity of the electricity displaced. Bioelectricity that displaces coal-fired electricity could reduce GHG emissions, but bioelectricity that displaces wind electricity could increase GHG emissions. The electricity displaced depends upon existing infrastructure and policies affecting the electric grid. These findings demonstrate how model assumptions about whether the vehicle fleet and bioenergy use are fixed or free parameters constrain the policy questions an analysis can inform. Our bioenergy life cycle assessment can inform questions about a bioenergy mandate's optimal allocation between liquid fuels and electricity generation, but questions about the optimal level of bioenergy use require analyses with different assumptions about fixed and free parameters.

Introduction

A biomass resource can contribute to greenhouse gas (GHG) emission goals through several pathways. First, converting the biomass to liquid fuels can displace fossil fuels in transportation. Second, biomass can be combusted to generate heat and electricity that can displace fossil fuel sources of heat and electricity. Third, the biomass can be left in place, thereby sequestering carbon that could otherwise be released to the atmosphere. Models' predicted optimal use of biomass resources for climate mitigation depend on assumptions about relative production costs, the cost of GHG emissions, the direct and indirect effects of alternative biomass uses, and the values affected by biomass utilization.

Several studies have suggested that using biomass for heat and electricity may be more cost-effective at mitigating CO_2 emissions than is using biomass for biofuels (*1*−*4*). Nonetheless, bioenergy policies recently enacted in the U.S. and Europe aim to reduce GHG emissions from the transportation sector through markets and performance standards based on the life cycle GHG emissions from fuels (*5*−*7*). Life cycle assessment (LCA) characterizes the environmental effects of a product by aggregating flows of energy and materials across all phases of production, use, and disposal of the product (*8*). Two styles of LCA have emerged in the literature: attributional LCA is a static analysis based on a product's supply chain, whereas consequential LCA considers the net environmental effects induced by a change in production (*9*). Both styles of LCA have been used in recent regulations aiming to reduce GHG emissions from the transportation sector. Through its static nature and its focus on a product's supply chain, attributional LCA tempts analysts to draw conclusions that ignore the market conditions that affect ultimate environmental outcomes. Consequential LCA, in contrast, recognizes that environmental effects are not limited to a single supply chain's impacts and generally depend on policy and market contexts, though the results of consequential LCAs can also mislead analysts if presented without useful framing and sensitivity assessments.

We use the case of bioelectricity and biofuels to demonstrate how the results of comparative LCA are sensitive to model assumptions about factors outside the scope of attributional LCA. While a change in production may affect that product's supply chain in ways that do not depend strongly on the larger market and policy context, its effect on GHG emissions may depend strongly on how that change in production impacts the production of other goods and services. In particular, we show that the GHG intensity of the electricity displaced by bioelectricity determines whether bioelectricity is less carbon-intensive than biofuels. The model assumptions used by LCA-based policies can therefore affect long-lasting investment in energy infrastructure and feedstock development. More broadly, we argue that whether modelers treat the vehicle fleet and bioenergy use as fixed or free parameters strongly influences model results and the questions they can address. When developing a portfolio of climate policies that might affect both electrified vehicle adoption and biomass resource allocation, policymakers should consult models that assume that both the vehicle fleet and bioenergy use are free parameters that can respond to policy decisions.

Bioelectricity versus Biofuels: The Importance of Assumptions about Displacement

A recent life cycle assessment suggested that converting biomass into electricity for electrified vehicles abates more GHG emissions than does converting biomass into liquid fuels for use in today's conventional vehicles (*10*). This analysis has been used to argue for a redirection of biofuel subsidies toward electric vehicle adoption (*11*). Crucially, these results assume that bioelectricity generation displaces gasoline. However, under existing institutional and technical arrangements, bioelectricity production does not cause a reduction in gasoline use. Electricity from all sources flows into the grid and is used to meet instantaneous system-wide demand. Bioelectricity could only displace gasoline if its generation were to increase charging by electrified vehicles

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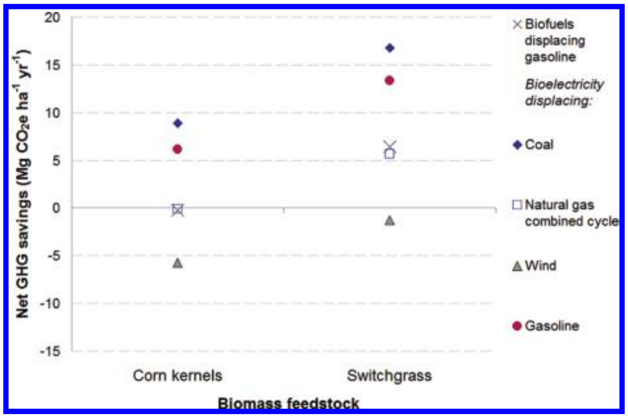


FIGURE 1. Net GHG savings per area of cropland are sensitive to displacement assumptions. The X marker shows ethanol displacing gasoline. The red circle follows ref *10* in assuming that bioelectricity is used to power electrified vehicles and displaces gasoline. The diamond, square, and triangle (coal, natural gas combined cycle, and wind electricity) show the GHG benefit (or cost) when bioelectricity displaces each of these types of power. See Supporting Information for details.

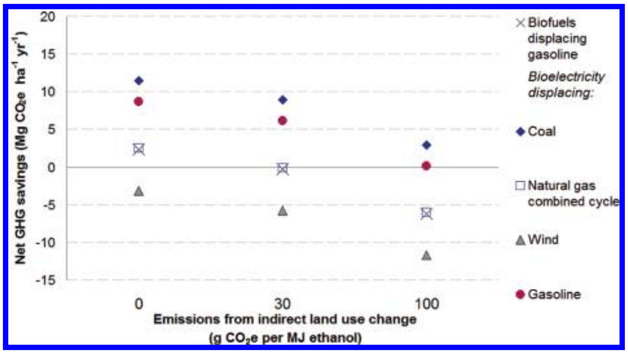


FIGURE 2. Net GHG savings per area of cropland under varying assumptions about emissions from indirect land use change due to cultivation of corn for biofuels or bioelectricity. The X marker shows ethanol displacing gasoline. The red circle follows ref *10* in assuming that bioelectricity is used to power electrified vehicles and displaces gasoline. The diamond, square, and triangle (coal, natural gas combined cycle, and wind electricity) show the GHG benefit (or cost) when bioelectricity displaces each of these types of power. See Supporting Information for details.

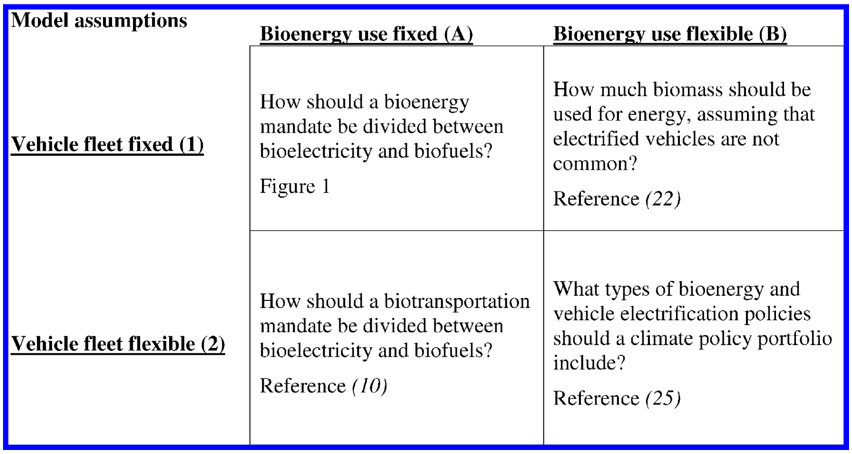
already in the fleet or if its generation caused vehicle purchases to shift from gasoline-fueled vehicles to electrified vehicles. Yet owners of existing electrified vehicles are unlikely to vary their charging habits according to the quantity of bioelectricity on the grid (*12*). Further, decisions to purchase electrified vehicles and decisions to use biomass as a primary fuel for electricity are made by different people, at different times, in different places, and without knowledge or concern for the others' decisions. Unless vehicle purchasers expect additional bioelectricity generation to substantially reduce electricity prices (*13*), it is difficult to imagine plausible technological or policy mechanisms that would link these decisions such that each increase in biomass electricity production is met with an equal expansion of electrified vehicle charging as well as a decline in gasoline vehicle fueling. A more realistic assessment of GHG mitigation benefits would recognize that an increase in bioelectricity generation in fact displaces other sources of electricity. The specific benefits depend on the type of electricity replaced, which in turn depends on the structure of the regional electricity market.

We estimate the GHG abatement due to bioelectricity and biofuels produced from corn grain and from switchgrass (see Supporting Information). These results depend not only on the direct emissions from producing biofuels and bioelectricity but also on the emissions avoided by displacing some other energy carrier (Figure 1). In line with the aforementioned study's results, we find that bioelectricity can abate approximately 6 Mg CO_2e ha^{-1} yr^{-1} more GHGs than do biofuels when using the unrealistic assumption that bioelectricity displaces gasoline; however, more realistic displacement scenarios produce different results (*14*). First, we find that converting a given feedstock to bioelectricity or to biofuels produces similar levels of abatement if bioelectricity displaces electricity generated from natural gas, but bioelectricity from switchgrass abates more GHGs in this displacement scenario than does ethanol produced from corn. Second, we find that the bioelectricity pathway abates approximately 9 Mg CO_2e ha^{-1} yr^{-1} more GHGs than does the biofuels pathway when bioelectricity displaces coal-fired electricity, and the GHG savings are greater when comparing switchgrass bioelectricity to corn ethanol. Because biomass can be cofired with coal, this may be the most likely short-term displacement scenario in the absence of policies constraining renewable energy or greenhouse gas emissions. Third, if bioelectricity displaces low-carbon power sources such as wind, bioelectricity generation may actually increase net GHG emissions by approximately 6 Mg CO_2e ha^{-1} yr^{-1}. Bioelectricity generation may displace low-carbon sources if, as in many U.S. states, the electricity sector must satisfy a Renewable Portfolio Standard that specifies a minimum share of generation to come from designated renewable sources. In this case, additional bioelectricity generation may decrease other renewable energy installations. Fourth, if electricity sector emissions are subject to a binding GHG cap that is not adjusted to reflect anticipated vehicle electrification, then using biomass for electricity production should not cause any net change in GHG emissions. Thus, under this type of GHG cap, which conversion pathway abates more GHGs depends solely on whether biofuels are more or less GHG-intensive than gasoline.

Recent analyses suggested that production of biofuels can affect commodity prices and thus induce conversion of land to replace displaced food crops. The size and existence of this effect is highly uncertain, but the resulting GHG emissions could dominate the other life cycle emissions for these products (*15*−*18*). Assumptions about indirect land use change (ILUC) emissions can affect absolute emissions from biofuels and bioelectricity, reducing their benefits (or increasing their penalties) relative to the business-as-usual scenario (Figure 2). For instance, under the assumption of no ILUC emissions, corn ethanol provides GHG savings relative to gasoline, and bioelectricity from corn provides GHG savings relative to other forms of electricity unless it displaces wind power. Under ILUC emission assumptions greater than or equal to the one adopted for the California Low-Carbon Fuel Standard (30 g CO_2e (MJ ethanol)$^{-1}$) (*5*), ethanol no longer provides GHG savings relative to gasoline, and electricity from corn grain achieves a net GHG reduction only if the displaced electricity comes from coal-fired plants.

Policy Questions Should Guide Assumptions about Decision-Making Contexts

While assumptions about product markets and regulatory systems can affect the conclusions of a study, higher-level assumptions constrain the policy questions to which a study's conclusions may apply. We develop a typology of modeled assumptions in bioenergy analyses that includes two dimensions of variability: whether the vehicle fleet is fixed or free, and whether the magnitude of overall bioenergy use is fixed or free (Figure 3). Different combinations of these assumptions affect the form of an analysis as well as the questions it can answer.



Model assumptions	Bioenergy use fixed (A)	Bioenergy use flexible (B)
Vehicle fleet fixed (1)	How should a bioenergy mandate be divided between bioelectricity and biofuels? Figure 1	How much biomass should be used for energy, assuming that electrified vehicles are not common? Reference *(22)*
Vehicle fleet flexible (2)	How should a biotransportation mandate be divided between bioelectricity and biofuels? Reference *(10)*	What types of bioenergy and vehicle electrification policies should a climate policy portfolio include? Reference *(25)*

FIGURE 3. Assumptions in a bioenergy- and transportation-focused analysis about whether bioenergy use and the vehicle fleet are fixed (taken as given) or free (allowed to vary) strongly influence the questions modelers can address and the results they obtain. For each pair of assumptions, the cells contain examples of the types of questions that analyses can answer and examples of the types of analyses that can contribute to answering the questions.

An analysis that compares the GHG benefits of bioelectricity and biofuel conversion pathways assumes that bioenergy use is fixed (column A in Figure 3). Analyses like the one in the previous section do not ask how much biomass energy should be used but instead ask whether a unit of biomass delivers more GHG abatement if converted to electricity or to a liquid fuel. To assume that bioelectricity displaces gasoline as in ref *10*, one must not only assume that gasoline fueling and bioelectricity generation are linked but also that the vehicle fleet can adjust to include vehicles that use electricity (cell A2 in Figure 3). If the vehicle fleet is instead fixed because the chosen time horizon is too short or vehicle electrification policies are not under the decision-maker's control, then the fleet will lack electrified vehicles (cell A1 in Figure 3). In this case, as we have seen in Figure 1, the relative GHG abatement from using bioelectricity and biofuels depends on the electricity source displaced.

If we treat the quantity of bioenergy produced as a free parameter (column B in Figure 3), the analysis can extend beyond simply allocating bioenergy resources between bioelectricity and biofuels. Determining the socially optimal level of bioenergy utilization is important and has long-term consequences because the potential costs of bioenergy and associated global land-use changes are multidimensional and include effects on biodiversity, water use, food prices, carbon sequestration rates, and regional climate stability (*15, 19–21*). If the vehicle fleet is fixed (cell B1 in Figure 3), then assessing the level of bioenergy use requires an assessment of other fuel options for abating transportation sector GHGs. A study produced for the California Low-Carbon Fuel Standard considered the GHG emissions from several conventional and unconventional feedstocks for liquid fuels compatible with the current vehicle fleet (*22*). Absent policies that reduce the demand for vehicle kilometers traveled, biofuels are one of the few fuel alternatives with the potential to reduce the current vehicle fleet's GHG emissions to levels targeted by recent policies. Thus, biomass holds promise for decarbonizing transportation in the near-term vehicle fleet, but these benefits depend on complementary land use policies and must be considered in light of the many other values affected by bioenergy feedstock production (*23*).

Finally, we may assume that both the vehicle fleet and bioenergy use are free parameters (cell B2 in Figure 3). The resulting analysis would jointly consider the form of transportation and both the form and amount of bioenergy use (*24*). Policymakers developing a portfolio of climate policies could rely on such an analysis for insight into whether the government should promote electrified vehicles and for insight into how to design a bioenergy policy in light of changing vehicle technologies. The conclusions would depend on the cost of GHG abatement across both the transportation and electricity sectors (*25*), on how the time scales of investment and technological change compare to the time scales of GHG emission targets, and on the depth of reduction sought (*26*). Previous analyses have indicated that advanced biofuels might provide interim GHG abatement (*27*), that vehicle electrification promises medium-term abatement (*28, 29*), and that bioelectricity could accrue long-term importance from its ability to provide net negative GHG emissions when combined with carbon capture and sequestration (*30, 31*).

The choice of fixed and free parameters determines whether a model can inform policy decisions about the design, the magnitude, or the appropriateness of a bioenergy mandate. How such a bioenergy mandate should weight bioelectricity versus biofuels depends on the GHG intensity of the electricity that would be displaced. How much biomass should be used for energy depends on the other options for decarbonizing liquid fuels and electricity supply and on the broader social costs of producing energy crops and altering land use patterns. Finally, whether a climate policy portfolio should include policies specifically aimed at promoting bioenergy and/or electrified vehicles depends on the costs, benefits, and feasibility of such policies relative to other abatement options. The chosen combination of fixed and free parameters not only affects the model's results but also constrains the set of policy questions to which the results apply.

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Supporting Information Available

Complete description of the Energy Displacement Model. This material is available free of charge via the Internet at http://pubs.acs.org.

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