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Authors
Yeh, Sonia
Lutsey, Nicholas P.
Parker, Nathan C.

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Complete List of Authors:	Yeh, Sonia; University of California, Davis, Institute of Transportation Studies Lutsey, Nicolas; University of California, Institute of Transportation Studies Parker, Nathan; University of California, Institute of Transportation Studies

Assessment of Technologies for Compliance with the Low Carbon Fuel Standard

Sonia Yeh, Nicholas P. Lutsey, and Nathan C. Parker*

Institute of Transportation Studies, University of California, Davis, One Shield Ave.,
Davis, CA 95616

Abstract

California's low carbon fuel standard (LCFS) was designed to incentivize a diverse array of available strategies for reducing transportation greenhouse gas (GHG) emissions. It provides strong incentives for fuels with lower GHG emissions, while explicitly requiring a 10% reduction in California's transportation fuel GHG intensity by 2020. This paper investigates the potential for cost-effective GHG reductions from electrification and expanded use of biofuels. This analysis indicates that fuel providers could meet the standard using a portfolio approach that employs both biofuels and electricity, which would reduce the risks and uncertainties associated with the progress of cellulosic and battery technologies, feedstock prices, land availability, and the sustainability of the various compliance approaches. This research is based on the details of California's development of an LCFS; however, this research approach could be generalizable to a national U.S. standard and to similar programs in Europe and Canada.

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* Corresponding author: slyeh@ucdavis.edu, Tel: (530) 754 9000, Fax: (530) 752-6572.

Keyword: Performance-based standard, carbon intensity, cost-effectiveness.

Briefs: A low carbon fuel standard can stimulate innovation in alternative low-carbon fuel technologies that contribute toward climate mitigation and energy security goals in California by 2020.

1. Introduction

The transportation sector is responsible for about 30% of U.S. and 40% of California's greenhouse gas (GHG) emissions and is growing faster than any other major economic sector. Transportation GHG emissions are primarily determined by vehicle efficiency, fuel GHG intensity, and vehicle travel demand. Whereas vehicle efficiency standards and vehicle travel demand reductions have often been addressed by government, the concept of a low carbon fuel standard (LCFS), which specifically aims to reduce transportation fuels' overall GHG emissions, is relatively novel. Economy-wide policies such as a moderate carbon cap-and-trade program are unlikely to induce significant GHG reductions from the transport sector, beyond efficiency improvement in the short- to medium-term (*1-3*). By regulating the GHG content of transportation fuel, the LCFS can contribute to both GHG mitigation and energy security. Transportation fuel use in the U.S. is mostly comprised of fossil fuels, predominantly gasoline and diesel, which have high GHG emissions per unit of energy. Unlike the popular biofuel volumetric mandates or blend requirements, such as the Renewable Fuel Standard program in the U.S. and the Biofuel Directive in the European Union, an LCFS is a performance-based standard that seeks to gradually reduce the GHG intensity of transportation fuels. This paper analyzes technologies that could be deployed to meet the requirements of California's proposed LCFS.

In California, Governor Schwarzenegger issued Executive Order S-01-07 in January 2007, which mandates a 10% reduction in lifecycle GHG intensity of transportation fuels by 2020. Lifecycle GHG intensity is defined as grams of carbon dioxide equivalent per megajoule of fuel energy (gCO_2e/MJ). Aside from the predominant GHG emission – CO_2 – other GHG emissions like methane (CH_4) and nitrous oxide (N_2O) are converted into their CO_2 equivalent emissions according to their global warming potential. This measure captures all lifecycle emissions associated with fuels, including emissions from cultivation and extraction, pipeline transport, processing, conversion and production, distribution, and vehicle operation. California's LCFS is the first major regulation of emissions based on lifecycle GHG emissions. It allows for the use of market-based emission-trading mechanisms for compliance, where companies can buy or sell credits with other regulated parties that are below or above their compliance obligations. Credits (in million tonnes) are generated from fuels with lower carbon intensity than gasoline or diesel, the baseline fuels. All low-GHG transportation fuels, which may include low-GHG fossil fuels (e.g., compressed natural gas, oil derived from tar sands with carbon capture and sequestration), biofuels (e.g., ethanol, biodiesel), and other energy carriers (e.g., electricity, hydrogen), can contribute to GHG emission reductions (*4*).

The regulated parties of California's LCFS are refiners, blenders, fuel producers, and importers. Aviation and maritime fuels are excluded because California has limited authority over these areas. Theoretically, the regulated parties have many options to meet the standard. First, refiners can blend low-GHG biofuels, such as those derived from cellulose or waste streams, into gasoline or diesel. Second, fuel providers can sell alternative transport fuels such as high-level blends of biofuels (e.g., ethanol blended in gasoline above 10% by volume, biodiesel in diesel above 20% by volume), compressed natural gas, electricity, and hydrogen fuels. And third, regulated parties can purchase credits from those regulated parties that are over-compliant, or they can apply credits that they banked in previous years. This hybrid of regulation and market mechanism can stimulate innovation and provide incentives for fuel providers to produce more low-GHG fuels at lower costs (*5*).

The final rules of the California LCFS were adopted by the California Air Resources Board (CARB) on April 23 2009 and will be implemented in January 2010 (*4*). Earlier work has focused on the conceptual policy design (*6, 7*) and rationale for a performance-based standard (*5*). This paper tackles the following questions: Are there enough low-GHG fuels available to meet the standard? How much production of in-state resources will be available or necessary to meet the LCFS? Given that the standard is flexible and designed to promote innovation, what are the likely competing technologies for compliance with the standard? What are the costs of compliance from fuel providers' perspective? What are the incentives for lower-GHG fuels?

Because of the known, large-scale applications and large GHG reduction potential before 2020, our evaluation focuses on biofuels (i.e., ethanol and biodiesel) and electricity. We first explore the biofuel resource and GHG reduction potential in California and in the western U.S. states and the potential electrification applications to replace transportation fuels (Section 2). We also estimate the cost-effectiveness of compliance strategies for the regulated parties. In Section 3, we propose a possible portfolio-based scenario utilizing both biofuels and electricity to achieve the LCFS targets. We discuss future research needs and the implication for a national LCFS in Section 4.

2. Resource Potentials: Biofuel and Electricity

2.1 The Design of the LCFS

In California's LCFS, the baseline transportation fuels (gasoline and diesel) and their alternatives have been assigned "carbon intensity" (CI) ratings (gCO_2e/MJ) based on lifecycle GHG intensity, adjusted for associated vehicle drive-train efficiency over conventional gasoline-engine vehicles (*4*). California adopted the default and opt-in approach, adapted from the United Kingdom's Renewable Transport Fuel Obligation (RTFO), which allows companies to "opt in" a lower CI value if they can provide evidence that the fuel they produce has a significantly lower GHG intensity than the default value. California's LCFS has two regulated fuel types – gasoline and gasoline substitutes, and diesel and diesel substitutes – and the average fuel carbon intensity (AFCI) of each fuel type is required to be 10% lower by 2020. Excess emission credits can be traded between these two targets (*4*). It is expected that in 2010, the reference year for California's LCFS, GHG emission from the use of transportation fuels will be 267 million tonnes CO_2e/yr (on a lifecycle basis), of which 76% will come from gasoline fuel, 6%from corn ethanol, and 17% from diesel.

We first examine the resources available in California and other western U.S. states to increase deployment of low-GHG biofuels. Second, we consider the potential of utilizing electricity to displace conventional transportation fuels. Third, in Section 2.4, we discuss the GHG reduction cost-effectiveness of the two pathways.

2.2 GHG Reduction through Expanded Biofuel Use

We evaluate resource availability and explore the potential GHG emission reduction from biofuels, based on the work recently published by University of California, Davis researchers and collaborators for the Western Governors' Association (WGA) (*8-10*). The researchers use a Geographic Information System (GIS) modeling approach in conjunction with a full supply-chain optimization model to develop a set of biofuel supply curves by feedstock within the WGA region, which covers the 18 western U.S. states with an eastern border from Texas in the south to North Dakota in the north. The methodology and results of the study are described in detail in Parker et al. (*10*). The study concluded that biofuels produced from resources in the Western states by 2015 could provide between 5% and 10% of the projected transportation fuel demand in the region at a price between $2.40 and $3.00 per gasoline gallon equivalent (gge), excluding local distribution and marketing costs and taxes. These fuels will rely on a diverse resource base with significant contributions from municipal solid waste, agricultural residue, herbaceous energy crop, forest thinning, corn, and tallow resources. The study attempted to characterize the best available knowledge on biofuel technologies and feedstock supply. However, major uncertainties remain including the economic performance of the different conversion technologies, the adequacy of the supporting feedstock and biofuel delivery infrastructure, and the added costs for biomass feedstocks to meet sustainability requirements. Table 1 shows the potential for biofuel production to contribute toward compliance with the LCFS. Parker et al. (*10*) estimated that the western states have biofuel potential total of 14 billion gge per year (equivalent to approximately 20 billion volumetric gallons of biofuel).

Recent studies have shown that massive consumption of biofuels in the U.S. could lead to expansion of farm lands throughout the world, at the expense of other crop lands and non-crop lands such as forest lands and grass lands (*11-13*). Moreover, when lands with rich soil and biomass carbon deposits are initially converted to agricultural production, a large amount of carbon is emitted. This initial “carbon debt” can take years or even decades of cultivation to pay back (*14-16*).

The conversion of land, induced by market-mediated effect, can be direct or indirect. The indirect effect, or indirect land use change (iLUC), represents the overall impacts from an increased demand for crop-based biofuel production, leading to both extensification (expansion of cultivated land area) and intensification (increasing inputs to increase yields) of agriculture that would not occur in the absence of biofuels production. Extensification modifies global land forms (e.g., farmland, forest, marginal lands) and their carbon stocks. These iLUC effects, which cannot be empirically observed, are estimated from global land use models (*17-19*) and can potentially be mitigated by policy responses (*20*). Attempting to determine the magnitude of the overall market-mediated impact on GHG emissions per MJ of particular biofuels is an intense research area (*21, 22*) but is beyond the scope of this study. Instead we adopt the preliminary iLUC values proposed by CARB for food crop-based biofuels including corn ethanol, Brazilian sugarcane ethanol, and biodiesel from soybean and for energy crops as placeholders to capture the possible iLUC effects on the lifecycle GHG emissions of biofuels (*4*). These placeholders are meant to reflect the consensus that reliance on food crop-based biofuels would have large iLUC effects; energy crop-based biofuels would have more moderate effects; and biofuels from waste streams, agricultural residue, algae, or biomass crops grown on degraded lands would have negligible effects (*23*).

The estimated total GHG reduction (in million tonnes CO_2e per year) is calculated based on the potential biofuel resources by feedstock (in MJ/yr, converted from gge/yr) and multiplied by the difference between the biofuel and the reference fuel GHG intensity levels ($gCO_2e/MJ/10^6$). Fuel providers can use biofuels produced elsewhere, including imports, but the analysis here suggests sufficient quantity of biofuels within the western region to achieve the LCFS carbon reduction target. We found that by including gasoline and diesel fuels together, an estimated 46% of the targeted GHG reduction could be met with California-grown fuels. When the potential biofuel production of all the western states is considered, the potential GHG reduction is equivalent to over twice the targeted California LCFS emission reduction (Table 1).

2.3 GHG Emissions Reduction from Using Electricity-Fuel

There are numerous ways in which electricity generation can be used as an energy source to supplant transportation fuels. Applications for electrification in light-duty vehicles include plug-in hybrid electric vehicles (PHEVs) and full battery electric vehicles (BEVs or EVs). In heavy-duty truck applications, electrification includes the plugging in of long-haul Class 8 trucks that would otherwise idle their main propulsion engines to power accessories in the truck cabin. Another option is to use electrified transport refrigeration units (TRUs) to power the refrigeration cycle for the cooling of cargo space, rather than TRUs powered by diesel-fueled engines. There can also be electrification at ports and in non-road engines, including in industrial (e.g., forklifts) and in smaller (e.g., lawn and garden equipment) applications.

Because electricity used in vehicle technologies is typically more efficient than gasoline or diesel, CARB has assigned proposed "default" energy economy ratio (EER) values for PHEVs, BEVs, and other onroad and offroad electrification. The EER is defined as "*the ratio of the number of miles driven per unit energy consumed for a fuel of interest to the miles driven per unit energy for a reference fuel*" (*4*). The total GHG reduction is estimated based on the following equation:

$$\begin{pmatrix} GHG\ reduction \\ (tonnes\ CO_2e) \end{pmatrix} = \left(\left(Q_{Ref} \cdot CI_{Ref} \right) - \left(Q_{elc} \cdot \frac{CI_{elc}}{EER} \right) \right) \cdot \frac{1\ tonne\ CO_2e}{10^6\ gram\ CO_2e} \qquad \text{(Equation 1)}$$

where:

Q_{Ref} = Quantity reduction of reference fuel, gasoline or diesel (MJ/yr)

Q_{elc} = Quantity increase of electricity use (MJ/yr)

CI_{Ref} = Fuel carbon intensity of reference fuel (gCO_2e/MJ)

CI_{elc} = Fuel carbon intensity of electricity (gCO_2e/MJ)

EER_i = Energy Economy Ratio (dimensionless)

The PHEVs, which can use both grid-supplied electricity and liquid fuels, offer substantial potential GHG emission reductions (*24-27*). Based on a widely cited Electric Power Research Institute (EPRI) study, PHEV20 (those vehicles with a battery capacity of 20 miles of all-electric range) efficiency when in all-electric (i.e., "charge-depleting") mode is about 4.3 miles/kWh for a compact car and 2.6 miles/kWh for a mid-size sport utility vehicle (*24*). Over the lifecycle, the use of electricity in light-duty vehicles offers an estimated 57–64% improvement in carbon intensity over gasoline fuel. This improvement is based on 35–41 gCO_2e/MJ for electricity (after EER adjustment) for average and marginal additions to the California grid electricity mix (which is 43% natural gas, 27% renewable, 15% nuclear, 15% coal) (*4, 28*), compared to 96 gCO_2e/MJ for gasoline.

A summary of potential applications for expanded use of electricity to supplant higher carbon fuels is shown in Table 2. Of the electricity applications investigated here, PHEVs and forklifts offer the greatest potential for decreased GHG emissions. The PHEV category includes 90% PHEV20 (which are assumed to cover 36% of their distance in all-electric mode) and 10% PHEV40 (64% all-electric mileage) (*24*). Electrification of truckstops and marine ports also offer relatively high potential GHG reductions. Together, the electrification actions examined here would equate to a 2.3 to 5.3 million tonnes CO_2e, an 8% to 19% contribution toward the total required LCFS target for 2020.

Based on estimates from the full use of all the electrification applications from Table 2, these new electric demands could result in an additional 2 GW of "summer peak load before mitigation" (*29*). The required amount of annual electricity usage (about 11 TWh/yr) and peak capacity increase (about 2 GW) are 3–4% of the California electricity demand and peak capacity, respectively. Provided that peak-time charging is avoided, several million PHEVs could be deployed in California without requiring new generation capacity (*30*). However, issues related to the future grid capacity, the specific charge timing of the different electric applications, and the local distribution network would need to be examined.

2.4 Cost-effectiveness of Compliance from Fuel Providers' Perspective

The "cost-effectiveness" of compliance is defined as the relative cost of the alternative fuel compared with reference petroleum, per amount of GHG abatement. For the same level of abatement cost, it is more cost-effective (i.e., lower cost per tonne of GHG reduction) to adopt measures that achieve higher GHG reductions. A performance-based LCFS provides higher economic incentives (i.e., lower abatement cost per tonne of CO_2e reduction) for lower-GHG fuels than for fuels that have only marginal GHG reduction potential. A cost-effectiveness ratio that is below zero would deliver a net financial benefit while reducing GHG emissions. This is consistent with several studies on lower GHG technologies (see, e.g., (*31*)).

The cost-effectiveness of any expansion of the use of alternative fuels for transportation, from the perspective of fuel providers, is subject to the uncertainties of the prices of the biomass feedstocks, the cost of electricity, and the costs of competing petroleum products. We compare the costs of the biofuels and electricity against petroleum costs of \$2 and \$3 per gge (crude and refining cost, excluding distribution, marketing, and taxes, which add another 50–70 cents) to estimate the cost-effectiveness of utilizing these two abatement strategies to reduce the GHG emission contribution of transportation fuels under an LCFS. The finished gasoline production cost of \$2.00/gge corresponds to about \$2.60/gge retail in California and roughly \$60 per barrel at the world oil price. The GHG-reduction cost-effectiveness of compliance is calculated by the following equation:

$$\begin{pmatrix} Cost\ effectiveness \\ (\$/tonne\ CO_2e) \end{pmatrix} = \frac{(Cost_{LCF} / EER - Cost_{Ref})}{(CI_{\mathrm{Re}f} - CI_{LCF} / EER)} \cdot \frac{10^6\ gram\ CO_2e}{1\ tonne\ CO_2e} \qquad \text{(Equation 2)}$$

where:

$Cost_{Ref}$ = Cost of reference fuel, gasoline or diesel (\$/MJ)

$Cost_{LCF}$ = Cost of low carbon fuel (\$/MJ)

CI_{Ref} = Fuel carbon intensity of reference fuel (gCO$_2$e/MJ)

CI_{LCF} = Fuel carbon intensity of low carbon fuel (gCO$_2$e/MJ)

EER_i = Energy Economy Ratio (dimensionless)

2.4.1 Cost-Effectiveness of Compliance Using Biofuels

The cost-effectiveness of biofuels is determined by the cost difference between the production cost of biofuels (based on the WGA study (*8-10*)) and the production costs of reference petroleum fuels, divided by the resulting emission reduction from the use of the alternative fuels for a fixed amount of energy required by vehicles. For example, at a price difference of \$0.50/gge between the gasoline fuel and the biofuels, the compliance costs are \$276/tonne CO$_2$e for today's low-GHG corn ethanol (CI = 80.7 gCO$_2$e/MJ including indirect emissions of 30 gCO_2e/MJ (*32*)) versus $57/tonne CO_2e for cellulosic biofuel from forest waste (CI = 22.2 gCO_2e/MJ). Figure 1 shows fuel providers' GHG-reduction compliance cost curves for biofuels produced in California and from the western states. Based on the cost assumptions presented in Parker et al. (*10*), an 18–50 million tonnes CO_2e reduction (63–180% of the target LCFS reduction) could be met at a cost less than or comparable to that of conventional petroleum fuels at $2 to $3 per gallon (or $2.6 to $3.6 per gallon including distribution, marketing, and taxes).

Even though the estimated costs of LCFS compliance for the regulated parties range from -125 to 24 $/tonne CO_2e depending on the assumptions of gasoline and diesel costs, there are significant uncertainties associated with technologies, feedstock costs, and infrastructure availability, as well the environmental impacts of large-scale biofuel feedstock production such as excess nitrous oxide emissions, feedstock water use, and water pollution (*33*). The CO_2e compliance cost curves depend critically on many cost assumptions, including those related to the costs of feedstock and production. The biomass feedstock and production costs are based on engineering cost estimates (*10*) that do not account for more dynamic market effects. Many reasons might explain higher prices of feedstock and production costs. For example, the increased demand for corn ethanol contributed to increased corn prices in the U.S. from 2006 to summer of 2008, when high oil prices, government subsidies, and industry growth made corn ethanol a cost-competitive substitute for gasoline. High oil prices also increase the costs of fertilizer and energy. In reality, the actual supply curves are likely to start from lower feedstock costs when biofuel demands are lower and to move toward higher feedstock and production costs as demand for biofuel increases. The resource supply curves presented here also assume production cost at significant economies of scale, although experience suggests that the cost at the beginning of production is likely to be higher due to technology uncertainties and the lack of economy of scale (*34, 35*).

2.4.2 Cost-Effectiveness of Compliance Using Electricity

We calculate the cost-effectiveness of compliance of electricity use strictly from a fuel provider's perspective. The cost-effectiveness from a vehicle user's perspective, which would also account for the additional cost of batteries and other electric components, has been addressed in many studies [e.g., (*24, 36*)] and is outside the scope of this study. Figure 2 shows the GHG abatement cost – from a fuel provider's perspective – of replacing transportation fuels with electricity as an energy source. Over the ranges of gasoline prices and electricity rates (which can vary depending on the time-of-use (hourly and seasonally)) that we examined, the abatement costs of using electricity are negative (i.e., it is cheaper to provide electricity to replace gasoline fuels) in most cases. So long as electricity rates were at or below \$0.18/kWh and \$0.27/kWh with petroleum prices at \$2.00 per gallon and \$3.00 per gallon, respectively, the fuel providers' LCFS compliance cost by substituting electricity for petroleum use is below zero.

Many industrial electrification applications (e.g., forklifts, ports, truckstops) may predominantly charge during the night and therefore benefit from off-peak electricity prices. Electric or plug-in light-duty vehicles, however, may be charging at both residential and workplace locations (if available), and thus be subject to variable and uncertain timing and electricity rates. In addition to time-of-day variation, seasonal, sectoral (residential, commercial, industrial), and usage-level differences also contribute to variation in electricity rates. For the California electricity rates we examined (ranging from 13.3 ¢/kWh in non-peak winter hours to 17.8 ¢/kWh in peak summer hours) (*37, 38*), electricity is an advantageous replacement for gasoline, with -230 to -160 \$/tonne CO_2e for \$3/gge petroleum fuel and -80 to 0 \$/tonne CO_2e for \$2/gge petroleum fuel. If electricity is produced from renewable sources, the carbon abatement costs are even more advantageous than calculated above.

The above cost-effectiveness assessment from a fuel provider's compliance perspective excludes the equipment costs (e.g., incremental vehicle costs for batteries, motors, charging equipment for grid-connection-capable vehicles) and the consumer fuel-saving impacts (e.g., cost-per-mile reductions for consumers using electricity versus gasoline) that would be critical for a broader, more inclusive cost-effectiveness assessment.

3. A Portfolio Scenario for Lower GHG Intensity

Acknowledging that challenges and uncertainties may be associated with drastic scale-up of both the biofuel and battery electric-vehicle technologies, we analyze a scenario in which both biofuels and electricity fuels contribute to compliance with the California LCFS. Figure 3 shows the fuel use change (million gge) from business-as-usual (BAU) in the portfolio scenario that achieves the 10%-AFCI reduction targets. The BAU scenario incorporates California's AB1493 (Pavley), which requires a 30% reduction in GHG emissions rate from new light-duty vehicles by 2016 (*39*). Conventional and advanced gasoline and hybrid electric vehicles are projected to be 90.7% of the total fleet in 2020, with the rest being E85 flex-fuel vehicles (5.8%), diesel and diesel hybrid vehicles (3.2%), and plug-in, electric, and other vehicles (0.3%). The portfolio scenario assumes that a mix of second-generation biofuels and advanced electric-vehicle technologies, primarily HEVs, hybrid flex-fuel E85 vehicles, and PHEVs, will be needed by 2020. Growth of PHEVs from 2010–2020 would be slightly higher the current sales growth trend of HEVs in California (which is twice as high as the national average), reaching 20% of new vehicle sales and a total of 1.7 million PHEVs on the road by 2020. The total electric vehicles would reach 49,000 by 2020. The combined electricity use from PHEV and electric vehicles would reach 3,950 GWh/yr and reduce 473 million gallons of gasoline use by 2020. These PHEV and electric-vehicle penetration rates represent an optimistic technology deployment. Other policies, such as California's zero emission vehicle (ZEV) program, may provide additional incentives for adoption. In addition, other electrification options listed in Table 2 can substitute PHEV and electric vehicles and achieve the same desired outcome.

Total advanced ethanol use and renewable biodiesel use would reach 2.06 billion gge/yr (bgge/yr) and 0.73 bgge/yr, respectively, by 2020. This level can vary because the performance-based LCFS does not specify a minimum amount of energy that alternative fuels must provide: the more low-GHG fuels used, the smaller quantity needed to meet the target. Although this scenario was developed for a 10% reduction in both gasoline and diesel types, trading between the two categories could result in differing levels of compliance for each category – but with overall aggregate compliance remaining at 10%.

4. Discussion

The portfolio scenario presented here is intended to illustrate the contribution of alternative transportation fuels from a variety of possible pathways and the changes needed to attain these targets. Although the portfolio scenario as well as biofuel and electricity pathways are treated as feasible compliance strategies and analyzed as such, many other technologies and fuels can significantly reduce transportation GHG emissions. Fuels from other states or countries, such as sugarcane ethanol from Brazil, can contribute toward meeting California's LCFS. The methodology illustrated here does not assert the carbon reduction benefits or costs of specific feedstock, which are subject to uncertainties. Rather, we intended to demonstrate feasible pathways to meet a performance-based LCFS based on the best available science. Our paper does not explicitly address the sustainability issues except the consideration of carbon emissions associated with land-use conversion due to the market-mediated effect. Ongoing work elsewhere has begun to consider policy options to address the sustainability issues within the LCFS (*4, 40*).

The implications of this study are broad. The European Union adopted the LCFS-like Fuel Quality Directive on December 17, 2008 (*23*). The Canadian provinces of British Columbia and Ontario, the 11 northeast and mid-Atlantic states, and the U.S. government (e.g., the April 2009 Waxman-Markey bill) have all considered an LCFS (*5*). We estimate that if the U.S. were to adopt an LCFS similar to California's (10% AFCI reduction by 2020), CO_2e could be reduced roughly 251 million tonnes from its reference

2020 emissions of 3.1 billion tonnes (on a lifecycle-basis), whereas the biofuel mandate in the Energy Independence and Security Act (*41*) would reduce the average transport-fuel carbon intensity by 5% by 2020 and 6.3% by 2023 (See the Supporting Information). Even though more research is needed to carefully examine whether the 10% target by 2020 is feasible for the U.S., an LCFS provides a more flexible framework compared to the RFS as it encourages the participation of other low-carbon fuels, such as electricity and hydrogen, economically rewards the use of ultra-low carbon fuels, provides flexibility by allowing companies to choose their own implementation strategy, and encourages innovation by allowing companies to provide opt-in values for truly low-GHG biofuels.

The success of the policy will also partly depend on consumers' adoption of vehicles and transportation applications that use alternative fuels. As with other biofuel programs, the implementation of an LCFS also faces several key challenges, especially with regard to sustainability, such as competition between biofuel crops and food crops for land and water. Additional policies may be needed to address the sustainability issues (*4, 40*).

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authors alone and do not necessarily represent those of any sponsoring organization or outside reviewer.

Supporting Information Available

Detailed information on transportation fuel carbon intensity, the vehicle and fuel assumptions, and GHG emission calculations for the California LCFS can be found in the Supporting Information (SI). The underlying assumptions of bioenergy conversion technology and resulting supply curves of the WGA study are summarized in the SI. The SI also includes a first-order calculation of a national LCFS. This material is available free of charge via the Internet at http://pubs.acs.org.

Table 1. Potential resources and greenhouse gas reductions from use of biofuels in California's transportation sector.

Biofuel resources		Potential resource level [a] (million gge/yr)	GHG reduction [b] (thousand tonnes CO_2e/yr)	Percentage of California LCFS target for 2020
Resources within California	Corn	210	370	1.7%
	LCE-Forest	250	2,230	11%
	LCE-Orchard/vineyard waste	130	1,100	5%
	LCE-Agricultural residue	51	450	2%
	LCE-Municipal solid waste	440	3,880	18%
	Subtotal - Gasoline substitutes	1,080	8,040	39%
	FAHC-Tallow	15	150	2%
	FAHC-Grease	23	220	3%
	FT-Municipal solid waste	450	4,400	65%
	Subtotal - Diesel substitutes	490	4,760	71%
	Total estimated biofuel substitutes within California	1,570	12,800	46%
Total estimated biofuel substitutes from western U.S. states [c]		14,100	63,400	230%
2020 gasoline target [d]			21,200	
2020 diesel target [d]			6,700	
Total LCFS reduction target			27,900	

Abbreviations: LCE=lignocellulosic ethanol; FAHC=fatty acid to hydrocarbon; FT=Fischer-Tropsch

[a] *Based on Parker et al. (10).*

[b] *GHG emissions of 30, 46, and 42 gCO_2e/MJ from indirect land use change are added to corn ethanol, Brazilian sugarcane ethanol, and soybean biodiesel, respectively, and 18 gCO_2e/MJ to energy crops.*

[c] *Includes 18 western states that are part of the WGA region of the U.S.*

[d] *Based on projected demand of 18.5 billion gge gasoline and gasoline substitutes and 5.4 billion gge diesel and diesel substitutes in 2020. This estimate varies depending on the projections of fuel uses in the BAU case and in the compliance scenario.*

Table 2. Potential applications and greenhouse gas reductions from replacing transportation fuel with electricity.

Category	Technology	Scenario	Additional electricity use in 2020 [a] (GWh/yr)	Greenhouse gas emission reduction toward LCFS [b] (thousand tonnes CO_2e/yr)	Calculated Energy Economy Ratio (EER)[c]
Light-duty vehicles	Plug-in hybrid EVs	2.1 million new vehicles by 2020	4,750	1,070	3.7
	Full-size, city, and neighborhood BEVs	455k vehicles by 2020; ~20x increase from expected 2010	990	240	4.1
Marine	Ports: cold ironing (alternative marine power)	115 new berths, 1200 new vessels by 2020	1,770	330 to 770	2.5
Transport - non-road	Electrified transportation refrigeration units (eTRUs)	29k units by 2020; ~7x increase from expected 2010	76	14 to 130	2 to 6.4
	Truck stop electrification (TSE)	35k spaces, 26k trucks by 2020; ~5x increase from expected 2010	310	58 to 470	6
	Electric forklifts (Classes 1-3)	37k units by 2020; ~10x increase from expected 2010	2,360	440 to 1090	2.3 to 3.8
	Tow tractors / industrial tugs	7k new units by 2020	140	26 to 240	6
	Electric personnel and burden carriers	13k new units by 2020	120	22 to 170	6
	Turf trucks	27k new units by 2020	81	15 to 170	7
	Miscellaneous	Electric sweepers/scrubbers, lawn and garden equipment, golf carts, airport ground-support equipment	410	76 to 900	6
Total - all applications			11,000	2,290 to 5,250	4.4 to 7.4

[a] *Adapted from TIAX analyses* (*29, 42-46*).

[b] *The range in GHG values is based on whether the GHG accounting of CARB (lower values) or the TIAX (higher value) is applied. ARB assigns EER = 3.0 for light/medium-duty vehicles and 2.7 for heavy-duty vehicles and off-road applications. We also assume an average California electricity carbon intensity of 124.1 gCO_2e/MJ (4).*

[c] *Calculated based on the estimated petroleum use reduction divided by the estimated electricity use (converted to MJ/yr) for off-road application for which ARB has not specifically developed EERs* (*29, 42-46*).

Figure Captions

Figure 1. Fuel providers' biofuel GHG compliance cost curves in California and from western states at gasoline fuel costs of \$2/gge and \$3/gge (production cost, excluding distribution, marketing, and taxes).

Figure 2. Fuel providers' abatement costs of reducing GHG emissions (\$/tonne CO_2e) with the use of electricity as a transportation energy source, as a function of electricity rate and gasoline production costs.

Figure 3. Fuel use change (million gge) between the business-as-usual (BAU) and the portfolio scenario.

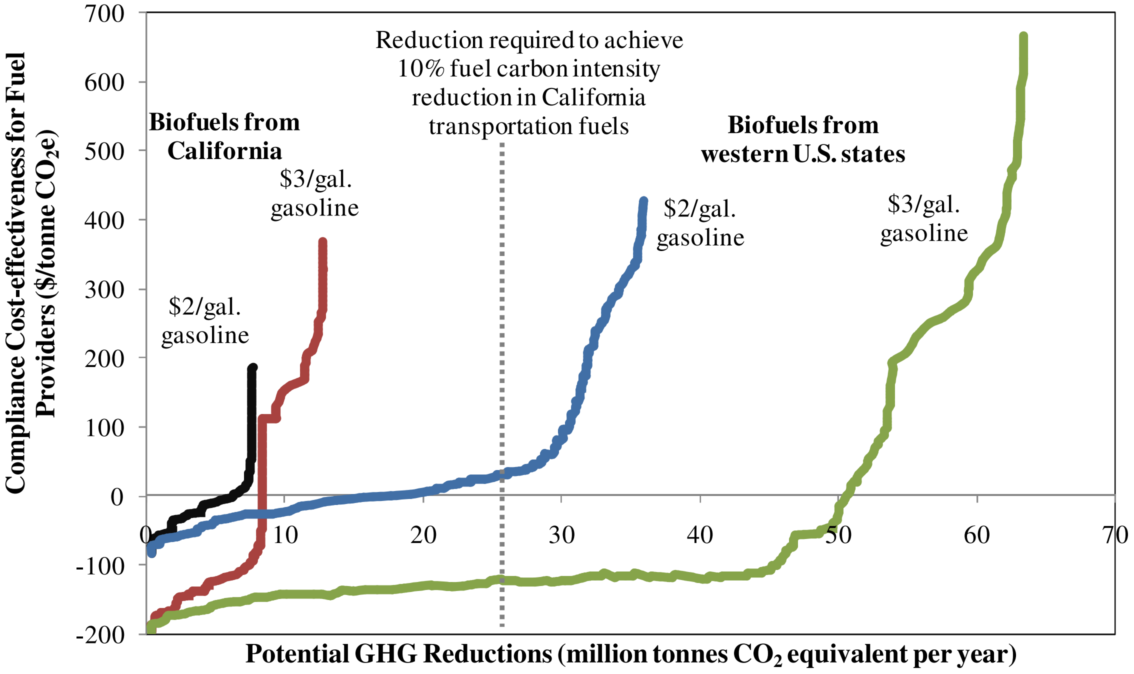
Compliance Cost-effectiveness for Fuel Providers ($/tonne CO_2e)
700
600
500
400
300
200
100
0
-100
-200
0
10
20
30
40
50
60
70
Potential GHG Reductions (million tonnes CO_2 equivalent per year)
Reduction required to achieve 10% fuel carbon intensity reduction in California transportation fuels
Biofuels from California
$3/gal. gasoline
$2/gal. gasoline
Biofuels from western U.S. states
$2/gal. gasoline
$3/gal. gasoline

Figure 1.

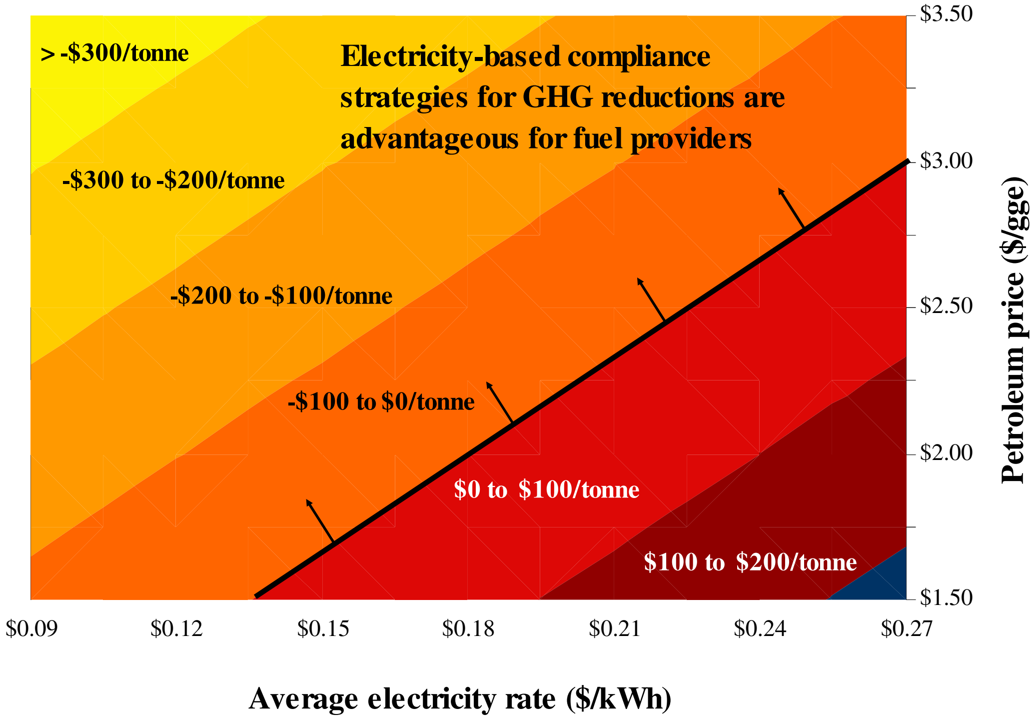
> -$300/tonne
-$300 to -$200/tonne
-$200 to -$100/tonne
-$100 to $0/tonne
$0 to $100/tonne
$100 to $200/tonne
Electricity-based compliance strategies for GHG reductions are advantageous for fuel providers
$3.50
$3.00
$2.50
$2.00
$1.50
Petroleum price ($/gge)
$0.09
$0.12
$0.15
$0.18
$0.21
$0.24
$0.27
Average electricity rate ($/kWh)

Figure 2.

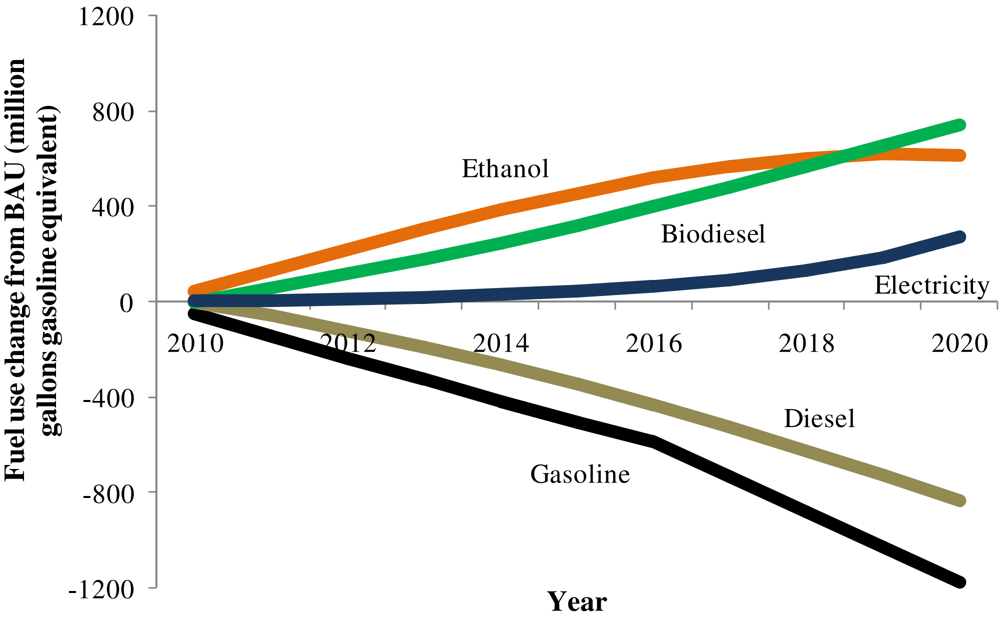
1200
800
400
0
-400
-800
-1200
Fuel use change from BAU (million gallons gasoline equivalent)
2010
2012
2014
2016
2018
2020
Year
Ethanol
Biodiesel
Electricity
Diesel
Gasoline

Figure 3.

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