Climate Policy Decisions Require Policy-based Lifecycle Analysis

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Lifecycle analysis (LCA) metrics of greenhouse gas emissions are increasingly being used to select technologies supported by climate policy. However, LCAs typically evaluate the emissions associated with a technology or product, not the impacts of policies. Here, we show that policies supporting the same technology can lead to dramatically different emissions impacts per unit of technology added, due to multimarket responses to the policy. Using a policy-based consequential LCA, we find that the lifecycle emissions impacts of four US biofuel policies range from a reduction of 16.1 gCO2e to an increase of 24.0 gCO2e per MJ corn ethanol added by the policy. The differences between these results and representative technology-based LCA measures, which do not account for the policy instrument driving the expansion in the technology, illustrate the need for policy-based LCA measures when informing policy decision making.

Introduction

Policymakers increasingly rely on lifecycle analysis (LCA) metrics of greenhouse gas (GHG) emissions to establish which technologies should be supported in major climate initiatives, including the US Renewable Fuel Standard (*1*), the European Union Renewable Energy Directive (*2*), and the Low Carbon Fuel Standard in California (*3*). However, the vast majority of LCA studies are technology-based, and evaluate GHG emissions associated with a technology, not the impact of a policy on GHGs. If policies supporting the same technology result in different market adjustments and therefore GHG impacts, per unit of the technology added to the economy, then technology-based LCA metrics may result in estimates of emissions savings that are misleading. A policy-based consequential LCA that analyzes how policies affect GHGs within an economic framework that captures the adjustments in the markets affected by the policies, may be more informative for policy applications.

LCA metrics of GHG emissions attempt to determine the total emissions associated with a particular technology, including all phases of its production and use. LCA studies have broadly been assigned to one of two approaches: attributional and consequential (*4*–*8*). This delineation is based on the application and context being studied, and determines the allocation procedures used to assign emissions to a technology, data choice, and the treatment of market-induced, or indirect, adjustments (*9*, *10*). Attributional LCA, which is the more prevalent approach (*11*–*17*), aggregates emissions across sectors using the flow of materials and energy to the production and use of a technology, and often relies on average data to characterize these flows. Consequential LCA is a more recent and rapidly evolving approach (*18*) that evaluates how a change or decision, typically an expansion of a technology, will affect emission levels in sectors associated with that technology, either through supply chain or economic linkages. Most recent consequential LCAs rely on estimates from economic models, with varying levels of sophistication (*7*, *18–20*), to predict the market and GHG implications of the change in the technology being studied. For evaluating changes, consequential LCA offers distinct advantages over the attributional approach, particularly in recognizing that market adjustments and indirect effects can be as important as the physical flows captured by attributional LCA, with indirect land use change (LUC) resulting from expanded biofuel production being a key example (*21–23*). In either approach, the lifecycle emissions savings of a technology are typically calculated as the difference between the lifecycle emissions of the technology of interest and the lifecycle emissions of an equivalent quantity of an alternative technology.

While the integration of economic models into LCA has created frameworks well suited for evaluating the emissions impacts of policies, most consequential LCA studies are technology-based, and evaluate a change in a technology without direct reference the policy driving the change, with (*24*) being a notable exception. However, studies in the economics literature demonstrate that technology-based analyses could generate misleading emissions savings estimates because policies that trigger similar expansions in a particular technology can have dramatically different impacts on markets and, consequently, on resulting emissions (*25*, *26*). Further, within policy classes, such as mandates, the details of implementation can affect the incentives facing regulated agents and the resulting market adjustments and emissions (*27*, *28*). Even the emissions resulting from low carbon fuel standards, which incorporate emissions ratings for the regulated fuels and set emissions targets, are determined by market adjustments and policy details (*29*). A related thread of literature points out that policies in related markets can affect the impacts of the policy being evaluated (*30–32*).

A policy-based consequential LCA evaluates how policy instruments, or changes in policy instruments, impact GHGs within a framework that explicitly models the policy instrument being studied and the markets affected directly or indirectly by the policy instrument. The resulting LCA metrics inform policy decisions because policymakers can change policy instruments, not quantities of specific technologies. A range of analyses can be conducted with a policy-based consequential LCA. To evaluate the implementation of, or a change in, a policy instrument, the total change in emissions resulting from this change could be established. Alternatively, the emissions resulting from a unit increase in a technology induced by a change in a policy instrument could be analyzed. Both metrics could prove useful in quantifying the economy wide impact of a policy decision on emissions for policymakers' cost-benefit analyses.

The economic framework underlying a policy-based consequential LCA must explicitly account for the policies being studied and be capable of capturing adjustments in markets affected by these policies. The impact of the policies on affected markets drives the differences in emissions across policies. Identification of affected markets for policy-based LCA, and therefore the system boundaries of the analysis, can follow the same guidelines established in the broader consequential LCA literature (*33*, *34*), but would be subject to the same critiques (*18*). At minimum, the economic framework used as the basis for a policy-based LCA should integrate the market or sector regulated by the policy and any market or sector that is affected by the technology being supported and any technologies being displaced. For example, an economic framework used to evaluate biofuel policies in the US should at least incorporate fuel blenders, which is the sector regulated by biofuel policies, domestic and international agriculture and land markets, which are impacted by expansions in biofuels, and domestic and international fuel markets, which are affected by reduced demand for gasoline. Increasing the sectoral and regional detail of the economic framework would increase the precision of the policy-based metrics, provided that the policy instruments remain explicitly modeled.

In contrast to authors who have made similar recommendations (*8*, *20*, *35*, *36*) and to LCA guidelines that discuss the analysis of policies (*10*), we develop a framework that quantifies how sensitive lifecycle emissions savings are to policy instruments. Biofuels are an ideal context for our analysis because these technologies have been extensively studied using technology-based attributional (*11*, *12*, *15*, *37*, *38*) and consequential LCA methods (*21*, *23*). In particular, corn ethanol provides a useful case study because it has the largest market share of any biofuel in the US, and has been supported by two large-scale federal policies that can be evaluated: the Renewable Fuel Standard (RFS) and the Volumetric Ethanol Excise Tax Credit (VEETC).

Previous technology-based consequential LCAs of biofuels have relied on models of agriculture and land use (*21*, *23*). For example, the EPA (*23*) conduct a detailed analysis of the land and agricultural market impacts resulting from an expansion in biofuel demand mimicking the RFS, but do explicitly model how the policy impacts fuel blenders' decisions and therefore fuel markets. However, biofuel policies—the RFS and VEETC being current examples—expand biofuel use by altering the fuel blenders' incentives to include biofuels in blended fuel. If policies differentially alter the price of blended fuel, then the rate at which gasoline is displaced by the policy will vary across policies. The resulting variation in emissions could be dramatic because decreases in gasoline use are the primary source of emissions reductions resulting from biofuel policies. Although the differences in fuel market impacts across policies are noted elsewhere (*39*, *40*), LCAs of biofuels have instead relied on an implicit assumption that each unit of ethanol displaces an energy equivalent unit of gasoline (*11*, *21*, *23*, *37*), sometimes accounting for vehicle efficiency (*38*, *41*), or focused on the displacement of gasoline due to an exogenous shock in biofuel demand (*42*). Relative to these frameworks, a policy-based LCA requires more than just the addition of fuel markets, although this is necessary because biofuel policies regulate fuel production. The crucial aspect of a policy-based analysis is that the policy instruments being evaluated are explicitly modeled, and changes in these instruments are evaluated.

Our work is most closely related to a set of papers (*43*, *44*) that integrate the GTAP economic model with an LCA model to evaluate the impacts of increased in EU bioenergy demand scenarios, which reflect an overall EU bioenergy policy, on land and fuel markets and a variety of environmental and health outcome. These analyses suggest that non-marginal demand changes will lead to indirect market adjustments that need to be captured in a lifecycle assessment. Unlike these studies, our framework analyzes the indirect market adjustments and lifecycle emissions implications of changes in policy instruments, rather than changes in demand. We find that the lifecycle emissions implications of an expansion in biofuel are critically determined by the policy instrument driving the expansion and the presence of interacting policies. Approaches to LCA that do not explicitly account for the policy driver in the underlying economic framework may result in over or under-estimates relative to the policy-based emissions savings, depending on the policy configuration. These results suggest that technology-based LCAs may be limited for policy evaluation, and that a policy-based LCA would be more informative.

Materials and Methods

A policy-based consequential LCA framework. Our analysis relies on an integrated economic and emissions model (See SI Methods for a complete description of the model and the data used for calibration). The economic model is a multi-market general equilibrium model of the US economy that links fuel, food, and land markets and accounts for trade in crops and crude oil. Total emissions are calculated based on production and consumption levels predicted by the economic model.

The impact of a policy on ethanol and emissions is calculated by comparing the model outcomes with the policy in place to a baseline simulation. The baseline simulations establish the counterfactual level of emissions and ethanol that would occur if the policy of interest were not implemented. Our primary lifecycle emissions estimates are the change in emissions between baseline and policy cases per unit ethanol added between the two cases. We focus on this metric because it is similar to the metrics commonly reported by technology-based LCA studies and used by policymakers and because it allows for comparison across policies that have different impacts on ethanol quantities. We also report and briefly discuss the total change in emissions due to each policy.

Economic Model. The economic agents in the equilibrium model are a representative consumer, an agricultural producer who manages a land endowment, and producers of fuel, gasoline, and ethanol. The behavior of each agent is represented by a set of supply or demand equations that depend on prices and are derived from underlying production or utility functions. The consumer demands blended fuel, food, and a composite good that represents all other consumption. The consumer's income consists of returns to its endowments of labor and land. Taking prices as given, the household chooses quantities of blended fuel, food, and the composite good to maximize utility, subject to its income constraint.

Blended fuel is produced from gasoline and ethanol, which is subsidized when the VEETC is in place. The RFS mandates a quantity of ethanol that must be used in blended fuel production. In the production of blended fuel, gasoline and ethanol are assumed to be energy-equivalent perfect substitutes. The fuel blender chooses quantities of gasoline and ethanol to minimize production costs, inclusive of the VEETC, subject to its production constraint and the RFS mandate. Ethanol and gasoline are produced from corn and imported crude oil, respectively. Ethanol is jointly produced with co-products, which substitute for corn and soybeans in food production.

Returns to the land endowment are maximized by allocating land to the production of crops (corn, soybeans, wheat, hay, and cotton), or setting land aside to the Conservation Reserve Program (CRP). Reductions in the land allocated to CRP represent domestic land use change. Crop yields and the CRP rental payment are assumed to be decreasing in the quantity of land allocated to each use. Corn can be used to produce ethanol or food, or exported; other crops can be used to produce food or exported. Food is produced from crops and co-products.

The behavior of the rest of the world is treated more simply. Rest of world demand for US crops is specified according to excess demand functions for US crop exports. Rest of world land use change is estimated under the assumption that for each unit reduction in crop exports, a quantity of additional land, which is a composite of forest, grassland, shrubland, and savanna among other land types, is brought into agricultural production. The rest of the world supplies crude oil to the US according to an excess supply function. Crude oil use in the rest of the world responds to changes in the world price of crude oil.

Aggregating supply and demand equations across agents yields total supply and demand for each good. Equilibrium consists of prices for each good such that supply equals demand in each market. Equilibrium prices are determined by solving the system of non-linear equations given by these market clearing conditions.

An equilibrium represents the state of the economy in a given year. The model is calibrated to data from the year 2003 and is solved annually through 2015, although results are reported only for 2011, 2013 and 2015. To account for dynamic trends, we allow domestic and international income, crop yields, ethanol production technology, average fuel economy, and average annual crude oil prices to adjust exogenously between years.

Emissions Model. Greenhouse gas emissions are modeled by assigning per unit emissions factors (see table SI.15 for values and sources) to each GHG generating activity, which is sufficient to map all adjustments in the economic model into changes in greenhouse emissions. We estimate emissions generated during ethanol production and combustion, the lifecycle of gasoline, which include emissions from crude oil recovery, gasoline refining, and gasoline combustion, as well as consumption of crude oil in the rest of the world. We calculate emissions from agricultural production using crop-specific emissions factors, which account for direct and indirect N_2O emissions, emissions from agricultural energy use and lime application and the emissions from the production of fertilizers, pesticides and other farm inputs. Finally, we assess the amount of carbon from above- and below-ground biomass and soils released to the atmosphere as a result of the conversion of land to agricultural production, both domestically and in the rest of the world. We convert greenhouse gases to units of carbon dioxide equivalent (CO2e) based on 100-year global warming potentials (*45*), although this approach is not without critics (*46*). The time path of emissions discharges is a chief concern because biofuel expansions yield large upfront emissions from land use change (*47*). Although there have been a number of attempts to rectify the treatment of time in LCA (*48*, *49*), we take the global warming potential approach to maintain consistency with most prior LCA studies (*11*, *21*, *23*).

Policy context. We analyze the RFS, the VEETC, and the interactions between these two policies, through 2015. The RFS, which was established by the Energy Independence and Security Act of 2007, mandates the use of various classes of biofuel in the production of blended fuel. The classes are defined primarily on the basis of lifecycle emissions savings relative to gasoline or diesel. To qualify for the RFS, a biofuel must achieve 20% emissions savings. A portion of the RFS must be met by advanced biofuels that achieve emissions savings of 50%. The EPA determined that corn ethanol, which does not qualify for the RFS for advanced biofuel, just achieves the 20% lifecycle emissions savings requirement and is expected to fill the vast majority of the RFS for conventional biofuels (*23*). We focus on the implied RFS mandate for conventional biofuels, the national RFS target less the RFS for advanced biofuels, which expands from 321 billion MJ (15.1 billion liters) in 2006 to 1,206 billion MJ (56.7 billion liters) in 2015 (*1*). We do not consider the RFS for advanced biofuels in our analysis because the technologies used to meet this mandate face significant challenges to expansion through 2015 (see SI Text). The VEETC, established by the American Jobs Creation Act of 2004 and updated in the 2008 Farm Bill, is a tax credit of 0.06 $/MJ (0.12 $/liter) to fuel blenders for each unit of ethanol used to produce blended fuel. The VEETC maintained the continuous subsidization of ethanol by the federal government that began with the 1978 Energy Tax Act. Primarily due to budgetary concerns (*50*), the VEETC was allowed to expire in 2011, which motivates the need to evaluate the RFS both with and without the VEETC in place.

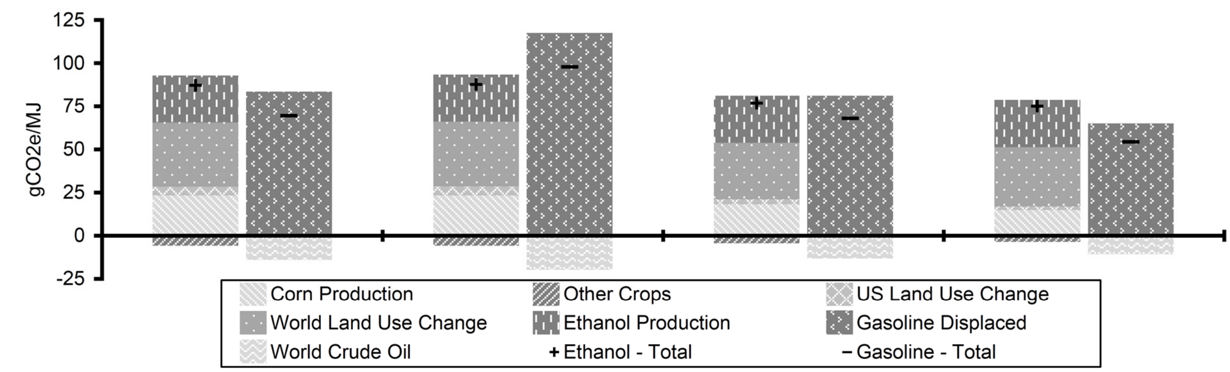
To disentangle the emissions resulting from the individual policies and interactions between the two, we calculate policy-based lifecycle emissions savings under four policy cases. The first two policy cases evaluate the RFS relative to a baseline with the VEETC in place (VEETC Baseline) to reflect the policy context when the RFS was established. Relative to the VEETC Baseline, we consider the impacts of the RFS when the VEETC is renewed (RFS, VEETC Renewed) and when the VEETC is phased out (RFS, VEETC Phased Out), which allows us illustrate the interactions between the RFS and the VEETC. The final two policy cases isolate the impacts of the RFS and the VEETC relative to a baseline with neither policy in place (No-policy Baseline).

Results and discussion

Our results show that lifecycle emissions savings vary considerably across policy scenarios under a range of parameter assumptions. Technology-based LCA methods that do not directly analyze policies or that do not account for adjustments in affected markets are unable to capture these differences across policies.

a. Policy-based Consequential Lifecycle Emissions Savings, 2015

	VEETC Baseline		No-policy Baseline	
	RFS, VEETC Renewed	RFS, VEETC Phased Out	RFS	VEETC
Ethanol (billion MJ)				
Baseline	971.3	971.3	556.0	556.0
Change	236.4	229.7	657.0	406.0
Displacement Ratio	0.90	1.26	0.87	0.70
GHG Savings				
Total (TgCO2e)	-4.1	2.3	-5.8	-8.4
Per unit (gCO2e/MJ)	-17.5	10.2	-8.8	-20.7



b. Comparison of Policy-based and Technology-based Lifecycle Emissions Savings, 2015

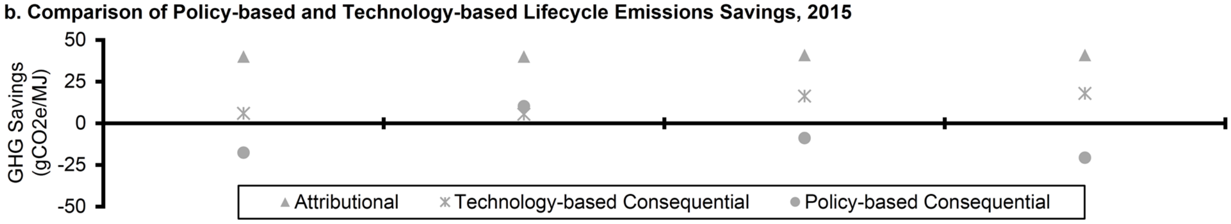


Figure. 1. Policy-based LCA emissions savings and comparison with technology-based LCA estimates of four policy cases in 2015. Relative to a baseline with the VEETC in place, the RFS is assessed when the VEETC is renewed (first set of results) and when the VEETC is phased out (second set of results). Against a baseline with no ethanol policies in place, the RFS (third set of

results) and the VEETC (fourth set of results) are assessed in isolation. The displacement ratio is the MJs of gasoline displaced per MJ of ethanol added to the economy. The displacement ratio varies with the impact of each policy on the price and demand for blended fuel. **a**. Policy-based LCA emissions savings. The left-hand column of each pair of columns decomposes the lifecycle emissions of ethanol by sector, while the right-hand column decomposes the emissions savings from displaced gasoline. **b.** Comparison of policy-based and technology-based estimates of lifecycle emissions savings. Technology-based LCA metrics are calculated using 2015 data and results from the policy-based economic model. Tabular results are available in Tables SI.7 and SI.8 for the year 2015, as well as 2011 and 2013.

The lifecycle emissions savings generated by an ethanol policy can be decomposed into the lifecycle emissions of ethanol and the lifecycle emissions of displaced gasoline. Policy-based consequential lifecycle emissions savings metrics for the four policy cases are displayed in Panel A of Figure 1. For each pair of columns, the left-hand column decomposes the lifecycle emissions of ethanol, while the right-hand column decomposes the lifecycle emissions of displaced gasoline. The difference between the lifecycle emissions of displaced gasoline and the lifecycle emissions of ethanol is the policy-based lifecycle emissions savings.

The lifecycle emissions of ethanol include emissions resulting from ethanol production and adjustments in domestic and international land markets (Panel A of Figure 1). Increased ethanol production causes the prices of all crops to increase, with the price of corn increasing most dramatically (Table SI.2), and causes additional land to be allocated to corn production at the expense of other crops. Emissions from additional corn production are only partially offset by reduced emissions from the production of other crops. In addition, elevated returns to cropland cause an expansion of cropland in the US, and reduced US crop exports, while higher world crop prices induce the clearing of land for agriculture outside the US.

The lifecycle emissions of displaced gasoline arise from adjustments in gasoline and crude oil use. The displacement of gasoline is the primary source of emissions reductions for each policy, but increased emissions from world crude oil consumption erode some of these reductions (Panel A of Figure 1). As ethanol policies reduce the demand for gasoline, the world price of crude oil falls, inducing additional crude oil consumption in the rest of the world (Tables SI.4 and SI.5), an effect that has been noted by others (*51–53*).

Policies that support the same technology can have dramatically different impacts on emissions, both in total magnitude and per unit of technology added. The total emissions impacts of the four ethanol policy cases considered here range from a modest reduction (2.3 TgCO2e) to a modest increase (-8.4 TgCO2e). While the magnitude of these total changes are determined largely by the quantity of ethanol added to the economy, there are also drastic differences in the emissions impacts per unit ethanol added. Relative to a baseline that includes the VEETC, the introduction of the RFS increases lifecycle emissions by 17.5 gCO2e/MJ if the VEETC is renewed. However, if the VEETC is phased out, the RFS reduces emissions by 10.2 gCO2e/MJ. In contrast, the VEETC increases emissions by 20.7 gCO2e/MJ. As discussed below, the differences in lifecycle emissions savings are primarily driven by the policies' differing impacts on fuel markets.

To accurately quantify the differences in emissions across policies, the economic framework underlying an LCA must explicitly account for the policies being evaluated. The differences in emissions savings across policies are primarily driven by the rate at which gasoline is displaced by ethanol in the blended fuel market. Agricultural production, land use, and rest of world crude oil consumption, in contrast, are relatively constant across policies.

The rate at which ethanol displaces gasoline, the displacement ratio, depends on the impact of the policy on blended fuel demand, and therefore on the policy's impact on the price of blended fuel. In turn, the change in the price of blended fuel depends on the policy's impact on prices of ethanol and gasoline. The displacement ratio will be less than one if a policy reduces the price of blended fuel. In this case, total fuel demand increases, so each unit of ethanol added by the policy will displace less than one unit of gasoline. If a policy increases the price of blended fuel, blended fuel consumption will fall and the displacement ratio will be greater than one.

The displacement ratio varies across the four policy cases, pointing to the need to model policies directly and to consider how related policies may interact. The RFS can result in displacement ratios greater than or less than one. Relative to a baseline that includes the VEETC, the introduction of the RFS causes the price of blended fuel to fall when the VEETC is renewed. This is because the decrease in the price of gasoline, due to the reduced demand for gasoline, dominates the increase in the price of ethanol, due to the increased demand for ethanol (Table SI.4). As a result, only 0.90 MJ of gasoline is displaced for each MJ of ethanol added, and the emissions of displaced gasoline are 83.6 gCO2e/MJ. When the VEETC is phased out, the resulting increase in the price of ethanol overwhelms the fall in the price of gasoline, and the RFS increases the price of blended fuel. In this case, each MJ of ethanol added by the RFS displaces 1.26 MJ of gasoline, and the emissions of displaced gasoline are 117.5 gCO2e/MJ. The introduction of the RFS relative to a baseline without the VEETC generates a similar displacement ratio to that associated with the RFS when the VEETC is renewed, because in both cases the RFS is imposed while the VEETC remains unchanged. The emissions of gasoline displaced due to the VEETC (65.2 gCO2e/MJ) are well below those of the three RFS cases. The VEETC subsidizes and therefore lowers the price of ethanol, which combines with a reduction in the price of gasoline to accentuate the reduction in the price of blended fuel.

Despite being large sources of emissions for each policy, the emissions from agricultural production, land use, and rest of world crude oil differ only slightly across policies. Agricultural and land use emissions are slightly higher in policy cases that have larger impacts on ethanol and that compare to baselines with larger quantities of ethanol. These two trends occur because domestic land supply tightens and crop exports contract more severely as the quantity of ethanol in the economy increases. Emissions from increased rest of world crude oil consumption are somewhat more severe for policies that displace more gasoline, because these policies cause a greater reduction in the world price of crude oil (Table SI.4).

Interactions between policies can significantly affect the lifecycle emissions savings of a policy. The importance of accounting for interactions between policies can be illustrated by comparing the two RFS cases relative to the VEETC baseline in Panel A of Figure 1. Despite having the same impact on ethanol, emissions savings due to the RFS are positive when the VEETC is phased out, but negative when the VEETC is renewed. Phasing out the VEETC causes the price of blended fuel to increase in response to the RFS, as opposed to the decrease that occurs when the VEETC is renewed. Since it is the RFS that sets the quantity of ethanol in the economy, this leads to larger quantities of gasoline displaced for the same change in ethanol quantity, and greater emissions savings per unit of ethanol added.

Technology-based LCA metrics calculated within our framework are broadly consistent with previous research and vary only slightly across policies. In Panel B of Figure 1, we compare our estimates of the policy-based consequential lifecycle emissions savings with estimates of technology-based attributional and consequential LCA savings for a MJ of ethanol based on the same assumptions and data as in our policy-based analysis. The technology-based attributional LCA estimates follow (*11*) and represent the difference between the lifecycle emissions of a MJ of gasoline and the lifecycle emissions of a MJ of ethanol. The attributional lifecycle emissions of ethanol are the sum of the emissions from the production of the corn required for ethanol production, less a co-product credit, and the emissions from ethanol production, including emissions from relevant inputs (see SI Text).

Consequential LCA has been used to describe a range of studies, from those that use data on the assumed marginal technologies in an attributional framework (*5*, *19*), to those that rely on economic models to evaluate large expansions in the technology being analyzed (*21*, *23*). We calculate a technology-based consequential LCA emissions savings metric following (*23*), by adding emissions from ethanol production to the per MJ ethanol emissions impacts in domestic and international land markets calculated in our policy-based analysis and comparing this to the lifecycle emissions of a MJ of gasoline. We use the methods of (*23*) to represent a technology-based consequential LCA because its framework has been deemed appropriate for evaluating the impacts of expanded biofuel production (*19*, *20*), despite its exogenous treatment of biofuel expansions and lack of integrated fuel markets.

Emissions savings are positive for both technology-based LCA methods, relative to a MJ of gasoline, and are broadly consistent with previous estimates in the literature (see SI Text). In sharp contrast to the policy-based estimates, the technology-based LCA estimates vary only slightly across policies. The attributional estimates vary due to small differences in corn yields, which are affected by the quantity of ethanol in the baseline. The technology-based consequential LCA estimates exhibit more variability across policies because the policies have different impacts on ethanol quantities and, therefore, on the agricultural and land use emissions.

Attributional LCA metrics are unlikely to reflect a change in emissions due to a policy. Panel B of Figure 1 shows that attributional LCA overstates emissions savings relative to the policy-based LCA for each policy case, reinforcing the well-known limitations of attributional LCA methods for evaluating changes and decisions (*7*, *19*, *20*) or policies (*54*).

Technology-based consequential LCAs of corn ethanol are inadequate for evaluating the emissions impacts of policies. Our technology-based consequential LCA estimates of emissions savings are of the opposite sign as the policy-based LCA emissions savings for three of the four policy cases. As the technology-based and policy-based consequential LCA metrics incorporate the same agricultural and land use adjustments, the difference in sign is caused by the explicit modeling of policies and the resulting impacts on fuel markets. The largest difference between policy-based and technology-based consequential emissions savings, 38.6 gCO2e/MJ, occurs for the VEETC alone. The technology-based lifecycle emissions savings are 20.7 gCO2e/MJ, while the policy-based LCA estimates that emissions increase by a similar magnitude. For both the RFS when the VEETC is renewed, and the RFS alone, there is roughly a 25 gCO2e/MJ difference between technology-based and policy-based estimates. In both cases, technology-based savings are positive, but policy-based savings are negative. Emissions savings estimates based on economic frameworks that do not explicitly account for policies should be interpreted with caution for policy applications. The assumption that the displacement ratio is one is especially problematic in the case of corn ethanol policies, since it effectively removes the market adjustment that generates the differences in emissions savings across policies.

Policy-based and technology-based consequential estimates roughly match for the RFS when the VEETC is phased out. These estimates are similar only because impacts of the policies on fuel markets captured in the policy-based approach, but not in technology-based approach, approximately cancel each other out. The policy-based and technology-based estimates do not match in the years prior to 2015, when technology-based consequential LCA estimates emissions savings are well below those obtained from the policy-based approach (Table SI.8), because the phase-out of the VEETC causes a stronger increase in the price of blended fuel per unit of ethanol added by the RFS (Table SI.4).

The differences in policy-based emissions savings across policies, and between policy-based and technology-based LCA methods for the same policy, are robust to a range of parameter assumptions. As noted by others (*55–57*), there is great uncertainty associated with both the economic and emissions models, particularly with regard to the magnitude and emission intensity of land use change (*8*, *58*) and fuel market adjustments. Policy-based LCA estimates provided to policymakers should include error bounds around the point estimates of emissions savings in order to quantify these uncertainties. One approach to obtaining these error bounds would be through Monte Carlo methods (*38*, *55–57*). A different sensitivity analysis is required to support the results of this paper. Our conclusions depend on comparing the policy-based lifecycle emissions savings across policy scenarios and comparing the policy-based and technology-based LCA metrics for a given policy. Since the parameter assumptions are not independent across policies or across LCA metrics, both sets of comparisons need to take place under the same parameter assumptions. Therefore, we conducted both sets of comparisons under a range of assumptions for the parameters that alter the emissions from agriculture and land use change and the excess supply elasticity of crude oil, which affects how fuel markets respond to the policies (see SI Text).

Figure 2 shows that the differences in emissions savings across policy cases persist under a wide range of parameter values. The parameter assumptions do affect the level of emissions savings generated by the policies, with emissions savings increasing when smaller agricultural and land use emissions factors or a higher elasticity of crude oil are used. Despite this, the differences across policies are largely unaffected by parameter choice. The rank of the three RFS cases are maintained across all parameter assumptions, with the RFS when the VEETC is phased out always leading to the greatest emissions savings, although these savings can be negative. The relative rank of the VEETC case is more sensitive to the parameter assumptions because the VEETC has smaller impacts on land use than the RFS cases.

The full results of our sensitivity analysis for all policy cases, parameter assumptions, and LCA methods are reported in Table SI.9 and Figure SI.1. In the vast majority of cases, attributional LCA estimates emissions savings are far above the estimates of policy-based or technology-based consequential methods because market-induced adjustments are ignored. Only the elasticity of crude oil supply will have an impact on the difference between policy-based and technology-based consequential LCA estimates, since these metrics are constructed using the same land use emissions estimates. The differences between policy-based and technology-based emissions savings estimates diminish as the elasticity of crude oil supply increases, but there are still important differences between the estimates in the high elasticity case.

As a further robustness check, differences between policy-based and technology-based LCA estimates for each policy in 2011 and 2013 are reported in Table SI.8. The differences in policy-based emissions savings across policy cases and between policy-based and technology-based LCA estimates are clearly evident.

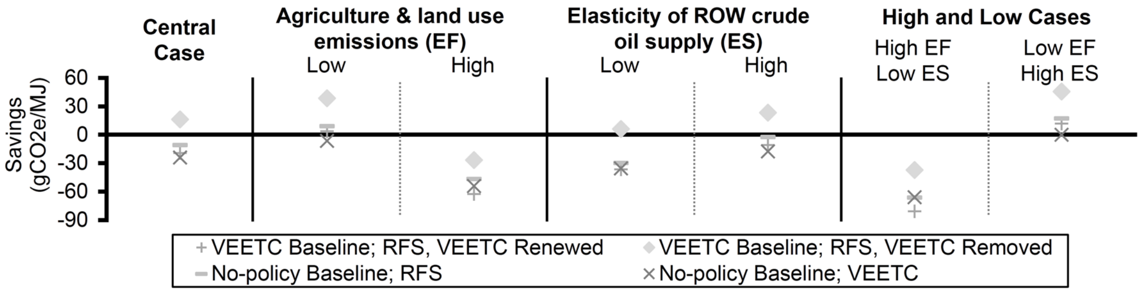


Figure. 2. Comparison of policy-based consequential LCA emissions savings metrics under varying parameter assumptions in 2015. Groups of markers shows estimated emissions savings from four policy cases for a set of parameter assumptions. The elasticity of ROW crude oil supply is 0.25, 0.5, and 0.75 in the low, central, and high cases, respectively. The corresponding values for the elasticity of world crude oil demand are –0.01, –0.02, and –0.03, respectively. The low agricultural and land use emissions case sets the emissions factors for these sectors to low values reported in supplementary material, and lowers the world land use conversion ratios by 20%. The high agriculture and land use emissions case sets all emissions factors in these sectors to high values, and increases the world land use conversion ratios by 20%. Tabular results for this sensitivity analysis are presented in Table SI.9.

Discussion

Our analysis highlights the advantages of policy-based LCA over technology-based LCA for evaluating the GHG implications of first-generation biofuel policies. The policy-based LCA approach is likely to offer similar advantages for the evaluation of policies supporting second-generation biofuels, such as the RFS for advanced biofuels. Technology-based lifecycle analyses typically find that cellulosic and second-generation biofuels, which would be used to meet the RFS for advanced biofuels, can generate larger greenhouse gas reductions than corn-based ethanol, mainly because the feedstock and fuel production phases of the cellulosic biofuel lifecycle are less emissions intensive than those of corn ethanol (*11*, *15*, *17*, *23*) and because cellulosic feedstocks may be grown on marginal land not used for food crops (*15*). However, our analysis shows that variation in fuel market emissions is the main driver behind the differing emissions impacts of alternative corn ethanol policies. The emissions consequences of alternative cellulosic ethanol policies are likely to exhibit similar patterns that could not be captured by technology-based LCA.

Renewable electricity is another context in which the policy-based LCA method could offer distinct advantages over technology-based LCA. Consequential LCA has been used to assess the impacts of large changes in the demand for renewable electricity (*43*, *44*). However, a variety of policies may be used to support renewable electricity production, including mandates such as renewable portfolio standards (RPS) or clean energy standards (CES), and price instruments such as production subsidies. Our results suggest that expansions in renewable electricity generation driven by these policies could have very different emissions implications. Like biofuel policies, renewable electricity policies rely on displacing fossil-fuel based energy sources to reduce emissions. Therefore, comparisons of the technology-based LCA emissions estimates of renewable and fossil electricity, which do not account the impacts of a policy on the demand for electricity or fossil fuels, are likely to provide inaccurate assessments of GHG savings resulting from expansions in renewable electricity.

Our numerical results should be taken as an illustration of the limitations of technology-based LCA, rather than precise estimates of the emissions savings of current US biofuel policies. Admittedly, our point estimates of emissions savings could be improved with a more sophisticated treatment of rest of the world land use, following (*21*, *23*), and fuel markets, following (*52*). Further, we do not address other well-known issues surrounding the implementation of consequential LCA, such as the identification of affected sectors and system boundaries, so our framework could be criticized due to the omission of potentially important market or economic effects, such as worldwide income effects due to US biofuel policies.

Concerns have also been raised regarding the uncertainties inherent in the economic models that would be required for the policy-based approach. However, our analysis illustrates that capturing the economic adjustments resulting from a policy is key to understanding how emissions impacts vary across policies. Our position is that potentially ignoring the variation in emissions across policy settings by leaving sectors out of the analysis is more problematic than the uncertainties surrounding the economic effects. Quantifying uncertainties around these estimates is undoubtedly important. When applying the policy-based approach we encourage analysts to consider the uncertainty in the key parameters of the economic and emissions models and to establish the confidence intervals for the lifecycle emissions savings metrics. Our goal here is only to highlight how consequential LCA estimates can vary across policy instruments and to point out a significant limitation of technology-based LCA.

Our results should not, however, be used to denigrate the importance of technology-based LCA. Technology-based LCA methods remain crucial for many applications, such as consumption-based emissions accounting (*59*), carbon footprinting and carbon labeling of consumer products (*60*), and for identifying the emissions-intensive phases of a production process (*61*). Rather, our results suggest that when evaluating the impacts of climate mitigation options and policies that promote alternative technologies, LCA methods should analyze policies rather than technologies.

ASSOCIATED CONTENT

Supporting Information. Supplementary numerical results for additional years and sensitivity cases; complete description of numerical model and calibration data; additional details regarding policies and calculations of lifecycle metrics. This material is available free of charge via the Internet at http://pubs.acs.org

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