School of Economic Sciences

Working Paper Series
WP 2015-16

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August 26, 2015

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Abstract

This paper develops a lifecycle economic analysis (LCEA) model that integrates input substitution, technology switching, and substitution of biodiesel for diesel into the standard (typically attributional) lifecycle analysis (LCA) of biofuel that assumes fixed-proportions production. We use the LCEA model to examine impacts of a pure carbon tax and a revenue-neutral tax-subsidy policy on lifecycle greenhouse gas emissions from cellulosic ethanol using forest residues as feedstock in Washington State. We find that ignoring endogenous input substitution by using standard LCA leads to substantial underestimation of the impact of carbon tax policies on carbon emissions. A pure carbon tax higher than \$0.039/kg CO_2 stimulates technology switching from coal to woody biomass in a cellulosic ethanol conversion plant and a pure carbon tax higher than \$0.116/kg CO_2 induces substitution of biodiesel for diesel in the feedstock and transportation sectors. Estimated emissions are 36 percent and 52 percent lower, respectively, compared to the standard LCA. In the latter case, 2/5 of the reduction is due to substitution of capital and labor inputs for energy. The revenue-neutral tax-subsidy policy reduces emissions more effectively than the carbon tax policy for a carbon tax lower than \$ 0.116/kg CO_2 because it can stimulate both technology switching and substitution of biodiesel for diesel at much lower tax rates when accompanied by corresponding subsidies for reduced emissions from renewable sources.

Keywords: carbon-emission reduction, input substitution, lifecycle analysis, tax policy, technology switching

JEL classification: Q16, Q20.

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The authors gratefully acknowledge the constructive comments of Ana Espinola-Arredondo, Phillip R. Wandschneider, Tristan Skolrud, and Ben Smith on earlier drafts of this paper. This research was supported by Agriculture and Food Research Initiative Competitive Grant 2012-67009-19707 from the USDA National Institute of Food and Agriculture, by the Washington Agricultural Research Center, and by the USDA National Institute of Food and Agriculture Hatch grant WPN000275.

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1 Introduction

Biofuels have become major renewable fuels for transportation. For instance, ethanol made up almost 10 percent of U.S. gasoline consumption by volume in early 2012 (U.S. Energy Information Administration (USEIA), 2012). Environmental mandates have promoted the development of biofuels, especially cellulosic biofuels. The Renewable Fuel Standard (RFS) mandates that by 2022 liquid fuel consumed in the United States will include 36 billion gallons of renewable fuel, of which 16 billion gallons will be produced from cellulosic feedstock.

Policy makers and researchers have pursued cellulosic biofuel for its advantages in mitigating lifecycle greenhouse gas (GHG) emissions, which the 2007 U.S. Energy Independence and Security Act defines as the aggregate quantity of all types of GHG emissions related to the full fuel lifecycle (EPA, 2010).[1] The act requires the U.S. Environmental Protection Agency to determine and enforce lifecycle GHG reduction thresholds for renewable fuels. The tool primarily used to assess the lifecycle emissions from fuels is lifecycle analysis (LCA). Recent findings based on LCA suggest that the use of cellulosic feedstocks has clear benefits for mitigating GHG emissions (e.g., Daystar *et al*., 2012; Bright and Strømman, 2009).

Most of the existing work using standard LCA is from the engineering field and generally is limited by the implicit or explicit assumption that inputs are used in fixed-proportions in each stage of the biofuel lifecycle. This is true for the common attributional LCAs (ALCA) that

[1] The mass values of all types of GHG emissions are adjusted to CO_2-equivalent emissions according to their global warming potential.

aggregate emissions based on the flow of materials and energy across sectors, and often relies on averaged data. It is also true for most of the newer generation of consequential LCAs (CLCA) that evaluate how a change or decision affects emissions within a sector, and are typically based on supply chain or economic linkages (Bento and Klotz 2014; Rajagopal *et al*. 2015; Zamagni *et al*. 2012). As a result, the emission estimates from those models are only based on current market conditions and do not account for any input mix response to changing market prices or policy incentives. However, input substitutability is likely to exist in the production of feedstock and biofuel and in their transportation. For example, Liu and Shumway (2015) find substantial substitutability between GHG polluting and non-polluting inputs in agricultural production relevant to biofuel feedstock. Significant substitution potential among energy sources has also been found (e.g., Serletis *et al.*, 2010; Stern, 2012).

Input substitutability can lead to substantial differences in estimated lifecycle GHG emissions. In particular, when a price-based regulation (e.g., a carbon tax) is imposed on an input that generates GHG emissions, it could induce substitution away from that input and alter emission measures and environmental policy consequences (Rajagopal and Zilberman, 2008a).

Two types of literature integrate input substitution into LCA. One is the literature on land-use change in response to biofuel production (e.g., Fargione *et al.*, 2008; Searchinger *et al.*, 2008), but these papers integrate economic substitution into LCA in only a very limited sense – focusing on land-use response. The other is a smaller body of work (e.g., Rajagopal and Zilberman 2008a, 2008b) that formally integrates economic input substitution into LCA in a general economic model of production and biofuel markets. Rajagopal and Zilberman (2008a, 2008b) develop an LCA model that includes production of corn and corn-based ethanol conversion in which producers can change optimal input combinations in response to changes in policy and prices. They derive a functional relationship between input prices and lifecycle emissions and use it to analyze sensitivity of the lifecycle emission estimates to a carbon tax. Rajagopal *et al*. (2011) extend their work by accounting for indirect emissions induced in the fuel markets.

The present article develops and applies a lifecycle economic analysis (LCEA) model for biofuel and uses this model to analyze the impact of environmental tax policy on cellulosic biofuel lifecycle emission levels. The term "economic" in LCEA refers to allowing for economic input substitution in production and transportation sectors through the biofuel lifecycle. In this model, emission level is a function of optimal quantities of inputs that generate emissions, which are determined by partial equilibrium conditions in each sector. Hence, market conditions are formally incorporated into the lifecycle emission calculations. Because lifecycle analysis is concerned with long-run impacts, we also consider technology-switching possibilities in biofuel conversion and replacement of diesel with biodiesel in the feedstock and transportation sectors.

Our empirical application of the LCEA model examines the impact of alternative tax policies on the emission estimates of forest-residues-derived ethanol in the State of Washington. We first analyze the effects of a pure carbon tax imposed on each unit of emission, as Rajagopal and Zilberman (2008a) did for corn-based ethanol. Besides empirically addressing cellulosic rather than corn-based biofuel, our analysis differs from theirs in three aspects: (a) we include a transportation sector for both feedstock and cellulosic ethanol delivery and distribution to make the biofuel lifecycle more complete, (b) in our analysis of emission changes, we capture the effects of input substitution due to price changes by using conditional cross-price elasticities of energy input demand, and (c) we investigate carbon tax levels that can stimulate technology switching in ethanol conversion (from a base plant that uses coal and natural gas to an alternative plant that uses woody biomass and natural gas) and substitution of biodiesel for diesel in the feedstock and transportation sectors.

Perhaps most importantly in terms of policy implications, this article documents the extent to which LCA analysis underestimates emission reductions that can follow from emission tax policies by failing to account for economically-induced input substitution, technology switching, and fuel substitution. A pure carbon tax higher than \$0.039/kg CO_2 stimulates technology switching from coal to woody biomass in a cellulosic ethanol conversion plant, and a carbon tax higher than \$0.116/kg CO_2 induces substitution of biodiesel for diesel in the feedstock and transportation sectors. At these tax rates, estimated emissions are 36 percent and 52 percent lower, respectively, compared to the standard LCA; the emission reductions include 9 and 20 percent, respectively, due to the substitution of clean inputs of labor and capital for carbon-intensive energy inputs in the production and transportation of cellulosic ethanol.

We also analyze the impact of an integrated carbon tax-subsidy policy on the lifecycle emission level of ethanol that is revenue-neutral within the energy sector. It taxes nonrenewable energy sources based on the amount of carbon emitted and uses the tax revenues to subsidize renewable energy sources based on the amount of carbon emissions they save. Galinato and Yoder (2010) previously developed and examined a similar policy. They simulated optimal taxes and subsidies in the motor fuel and electric power industries and compared welfare gains under different environmental policy settings. Our research differs from theirs by examining how the revenue-neutral tax-subsidy policy would alter lifecycle emissions of cellulosic biofuel when integrating input substitution, technology switching, and fuel substitution.

The policy implications on emissions of a revenue-neutral tax-subsidy policy are even more profound than those of a pure carbon tax. The revenue-neutral policy leads to technology switching and fuel substitution at much lower tax rates. For example, technology switching in the conversion plant occurs at a tax on fossil fuels of only \$0.006/kg CO_2 when accompanied by a subsidy on renewable fuels higher than \$0.023/kg CO_2 reduction. Biodiesel substitutes for diesel when the tax on fossil energy exceeds \$0.017/kg CO_2 with a corresponding subsidy for renewable energy that exceeds \$0.065/kg CO_2 reduction. At these low tax-subsidy rates, emissions are reduced by 31 and 38 percent, respectively.

Cumulative emission reductions resulting from an integrated tax-subsidy policy are greater than those caused by the pure carbon tax at all tax rates until the pure carbon tax rate is high enough (i.e., \$0.116/kg CO_2) to stimulate replacement of diesel with biodiesel in the feedstock and transportation sector. This is because the revenue-neutral tax-subsidy policy can stimulate both technology switching and replacement of diesel with biodiesel at relatively low tax rates. When the tax exceeds \$0.116/kg CO_2, the pure carbon tax becomes more effective in reducing emissions than the revenue-neutral policy with the same tax level. When the tax approaches \$0.25/kg CO_2, emission reduction caused by the pure carbon tax is 71 percent compared to 68 percent by the revenue-neutral policy.

The rest of the article is organized as follows. Section 2 develops a theoretical LCEA model. Section 3 implements the LCEA model for ethanol that uses forest residues as feedstocks and examines the impact of a carbon tax and a revenue-neutral tax-subsidy policy on emissions when input substitution, technology switching, and fuel substitution are accounted for in the ethanol lifecycle. Section 4 concludes.

2 Theoretical foundation of LCEA

In the lifecycle of biofuel, there are three sectors that generate GHG emissions from the use of energy inputs: feedstock production, biofuel conversion, and transportation.[2] The feedstock sector produces feedstock that is purchased by a biofuel conversion sector as an input for processing into biofuel. The transportation sector provides services for delivering feedstock to biofuel plants and distributing biofuel to the sites where it is combusted. Figure 1 summarizes the relationship between these sectors and emissions.

Our LCEA incorporates input substitution in feedstock production, biofuel conversion, and transportation sectors as well as technology switching in the biofuel conversion sector and changes in energy source in the feedstock and transportation sectors. The LCEA model relaxes the standard LCA assumption of fixed-proportions production in each sector and allows market conditions to guide producers' choices about the quantities and ratios of inputs used. We determine input quantities and ratios of inputs by a partial equilibrium analysis of each sector. To describe the LCEA model, we begin from the biofuel conversion and move backward to the feedstock production and transportation sectors.

2.1 Biofuel conversion sector

The biofuel conversion sector, indexed by $b,$ uses feedstock Y^f, a vector of non-renewable and renewable energy inputs $\boldsymbol{N}^b$, labor L^b, and capital K^b to produce biofuel. Biofuel

[2] The lifecycle of biofuel could be broken into six stages –absorption of GHG emissions by feedstock growth, production of feedstock, transportation of feedstock to a biofuel plant, conversion to biofuel, transportation of biofuel to end users, and combustion of biofuel (Wang *et al.*, 2007; Neupane *et al.*, 2011; Daystar *et al.*, 2012). An assumption with wide acceptance in the literature is that carbon emissions associated with the direct burning of the biomass (last stage) are offset by the growth of biomass (first stage). Consequently, net emissions from the biofuel lifecycle are only associated with the productive sectors (e.g., Daystar *et al*., 2012). We combine the two transportation stages into a single transportation sector.

output is based on the sectoral production function $Y^b = Y^b(Y^f, \boldsymbol{N}^b, L^b, K^b)$. The production function is increasing and concave in all arguments. Input prices are denoted as p_f, $\boldsymbol{p}_n$, p_l, and p_k for feedstock, energy inputs, labor, and capital, respectively, and are assumed to be exogenous. Assuming a perfectly competitive market and a pre-specified quantity of biofuel, $\bar{Y}^b$, the cost-minimization problem can be expressed as

$$\min_{\{Y^f, \boldsymbol{N}^b, L^b, K^b\}} p_f\ Y^f + \boldsymbol{p}_n^b \boldsymbol{N}^b + p_l L^b + p_k K^b$$

$$s.t. Y^b(Y^f, \boldsymbol{N}^b, L^b, K^b) \geq \bar{Y}^b.$$

The optimal conditions are

$$p_f - \lambda^b Y^b_{Y^f}(Y^f, \boldsymbol{N}^b, L^b, K^b) = 0 \tag{1}$$

$$\boldsymbol{p}_n^b - \lambda^b Y^b_{N^b}(Y^f, \boldsymbol{N}^b, L^b, K^b) = 0 \tag{2}$$

$$p_l - \lambda^b Y^b_{L^b}(Y^f, \boldsymbol{N}^b, L^b, K^b) = 0 \tag{3}$$

$$p_k - \lambda^b Y^b_{K^b}(Y^f, \boldsymbol{N}^b, L^b, K^b) = 0 \tag{4}$$

$$Y^b = \bar{Y}^b, \tag{5}$$

where λ^b is the Lagrange multiplier and subscripts of Y^b represent partial derivatives (e.g., $Y^b_{Y^f}(.) = \partial Y^b / \partial Y^f$). The demand for feedstock and energy inputs in the production of biofuel are determined by the partial equilibrium and denoted as $Y^{f*}(p_f, \boldsymbol{p}_n^b, p_l, p_k, \bar{Y}^b)$ and $\boldsymbol{N}^{b*}(p_f, \boldsymbol{p}_n^b, p_l, p_k, \bar{Y}^b)$, respectively.

2.2 Feedstock production sector

Production in the feedstock sector f uses non-renewable and renewable energy inputs $\boldsymbol{N}^f$, labor L^f, and capital K^f, and is characterized by the sectoral production function $Y^f = Y^f(\boldsymbol{N}^f, L^f, K^f)$. Input prices are denoted as in the biofuel conversion sector and are treated as exogenous. Similar to the biofuel sector, the cost-minimization conditions under a competitive market determine the optimal quantities of energy inputs, $\boldsymbol{N}^{f*}(\boldsymbol{p}_n^f, p_l, p_k, Y^{f*})$.

2.3 Transportation sector

The transportation sector delivers feedstock to biofuel production plants and distributes biofuel to the combustion sector. We assume that the transportation sector uses labor, capital, and energy inputs. The same inputs are used to transport feedstock and biofuel. The product of distance and quantity transported is treated as the output of transportation. The outputs of biofuel transportation, Y^{tb}, and feedstock transportation, Y^{tf}, are determined by the sectoral production functions $Y^{tb} = Y^{tb}(\boldsymbol{N}^t, L^{tb}, K^{tb})$ and $Y^{tf} = Y^{tf}(\boldsymbol{N}^t, L^{tf}, K^{tf})$, respectively, where inputs are denoted as in the other sectors with corresponding prices $\boldsymbol{p}_n^t$. For a given distance of transportation, D, the optimal quantities of energy inputs for distributing $\bar{Y}^b$ biofuel and delivering Y^{f*} feedstock are $\boldsymbol{N}^{tb*}(\boldsymbol{p}_n^t, p_l, p_k, \bar{Y}^{tb})$ and $\boldsymbol{N}^{tf*}(\boldsymbol{p}_n^t, p_l, p_k, \bar{Y}^{tf})$, respectively, where $\bar{Y}^{tb} = D * \bar{Y}^b$ and $\bar{Y}^{tf} = D * Y^{f*}$.

2.4 Lifecycle carbon emissions

Direct lifecycle emissions are calculated in the LCEA model from the use of energy inputs in the feedstock production, biofuel conversion, and transportation sectors. Assuming the quantity of emissions from the use of each type of energy input is proportional to the quantity of the energy input, total direct emissions can be specified as

$$E(\boldsymbol{p}_n^b, \boldsymbol{p}_n^f, \boldsymbol{p}_n^t, p_l, p_k, D, \bar{Y}^b, \boldsymbol{e}^i) = \sum_i \boldsymbol{e}^i \boldsymbol{N}^i (\boldsymbol{p}_n^b, \boldsymbol{p}_n^f, \boldsymbol{p}_n^t, p_l, p_k, D, \bar{Y}^b), \quad (6)$$

where $\boldsymbol{e}^i$ denotes a vector of emission factors for energy inputs in process $i = b, f, tb, tf$. Unlike the lifecycle emission estimates in most previous LCA papers that are fixed for a process, equation (6) reflects a relationship between emission levels and market prices for producing a given amount of biofuel. Because optimal quantities and proportions of inputs can change when input prices change, total emissions can also change. This is the defining distinction between standard LCA and LCEA. We next use this LCEA model to analyze the impact of alternative tax policies on lifecycle emissions from ethanol that is produced using forest residues as feedstock.

3 LCEA for ethanol derived from forest residues

Cellulosic biomass is a potential feedstock for biofuel in the Pacific Northwest. This region produces high-value crops, many under irrigation, so it has a comparative disadvantage in using agriculture crops and cropland for biofuel feedstocks. However, it does have an abundance of cellulosic biomass in the form of forest residues (Yoder *et al.*, 2010). Forest residue comes from logging, tree thinning, milling, and land clearing. While forest residues can be refined to produce several types of biofuel, we focus on ethanol and examine the impact of environmental policies on its lifecycle GHG emissions using the LCEA model.[3]

3.1 Analytical procedure

Liquid fuels, which are required for equipment and truck operation, are energy inputs in the forest residue production sector and in the transportation sector.[4] Diesel is the primary liquid fuel used. We assume that non-cellulosic biodiesel is readily available and is a perfect substitute

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[3] Indirect emissions from land-use changes in the feedstock sector (Searching *et al*., 2008) are not considered in this study. The value of forest residues is so low that biofuel production is not expected to change optimal commercial timber harvest decisions. Hence, the environmental impacts of land-use change or deforestation due to timber harvest decisions are allocated to the main forestry products like timber and wood pulp (Daystar *et al*., 2012). Indirect emissions can also come from fuel consumption changes caused by changes in the quantity of biofuel adopted in the fuel market (Rajagopal *et al*., 2011). Because we focus on forest residues to produce the amount of cellulosic ethanol prescribed by the RFS mandate for 2022, these indirect emissions from land use change are taken to be inconsequential. However, it is worth reiterating that land-use substitution is indeed one of the many substitution possibilities that LCEA highlights.

[4] In forest residues production, forestry equipment is used to collect and process forest residues into deliverable sizes. In the transportation sector, a combination truck (tractor and trailer) is used to deliver forest residues and distribute ethanol (Daystar *et al*., 2012).

for diesel (adjusted for energy content), so either diesel or biodiesel will be used as the sole liquid fuel based on relative prices. Substituting biodiesel diesel is assumed to occur when the effective price of diesel per unit of energy is higher than the effective price of biodiesel.[5]

The production of forest residues, transportation of forest residues, and transportation of ethanol allows input substitution among labor, capital, and liquid fuel; these are characterized by the production function $Y^j\left(N_{lf}^j, L^j, K^j\right) \forall j = f, tf, tb$, respectively, where the subscript lf represents liquid fuel that can be diesel (d) or biodiesel (bd). In the absence of environmental policy, the cost-minimizing quantities of liquid fuels used in the production of feedstock, transportation of feedstock, and transportation of a given amount of ethanol, $\bar{Y}^b$ are $N_{lf}^{j*}\left(p_{lf}, p_l, p_k, \bar{Y}^j\right) \forall j = f, tf, tb.$

The energy required for cellulosic ethanol conversion is similar to that for corn ethanol conversion but with an additional step required to break cellulosic material into simple sugars (Goffman, 2009). Energy inputs used for corn ethanol conversion are typically fossil energy such as natural gas and coal, or renewable energy like wood chips and corn syrup (Wang *et al*., 2007). We examine two technological types of ethanol conversion plants based on the energy inputs used. The base plant uses both natural gas and coal as energy inputs, while the alternative plant uses natural gas and woody biomass. Energy and non-energy inputs used in each stage of cellulosic ethanol production and transportation are summarized in Table 1.

Ethanol output for each conversion plant is based on the production function $Y_x^b\left(Y^f, N_{ngx}^b, N_x^b, L_x^b, K_x^b\right)$, where $x = c$ or wb represents a plant using coal (base case) or woody

[5] Because LCA focuses on the long run, we allow perfect substitutability between diesel and biodiesel. This assumes that any short-run limits on substitutability are resolved in the long run. For the remainder of the paper we use the term biodiesel to mean non-cellulosic biodiesel.

biomass (alternative case), N_{ngx}^{b} is the quantity of natural gas consumed by the plant using energy x, and N_{x}^{b} is the quantity of energy x. We allow substitution between energy inputs and clean inputs of labor and capital and assume (a) the forest feedstock is used in fixed proportion to the aggregate of other inputs and (b) natural gas and energy, x, are used in fixed proportion in the respective plant.[6] Therefore, the optimal quantity of natural gas in both plants is the same and the initial quantity of natural gas to produce a given amount of ethanol can be denoted as $N_{ng}^{b*}(p_{ng}, p_{l}, p_{k}, \bar{Y}^{b})$. Then the initial quantity of energy x is $N_{x}^{b*} = a_{x} N_{ng}^{b*}$ and a_{x} denotes a constant proportion of energy x to natural gas.

The total emission from the production and transportation sectors of cellulosic ethanol using plant x and fuel lf is

$$E_{x,lf} = e_{lf} \sum_{j=f,tf,tb} N_{lf}^{j*} + e_{ng} N_{ng}^{b*} + e_{x} N_{x}^{b*}, \quad (7)$$

which is equivalent to

$$E_{x,lf} = e_{lf} \sum_{j=f,tf,tb} N_{lf}^{j*} + (e_{ng} + a_{x} e_{x}) N_{ng}^{b*}. \quad (8)$$

Emission levels vary as the quantity and composition of energy inputs change in response to market and policy conditions. For a given type of ethanol conversion plant, quantities of energy inputs can change due to changes in relative input prices. The amount of change in

[6] The amount of feedstock required to produce one gallon of cellulosic ethanol depends on conversion methodology (Pimentel and Patzek, 2005; Thomas, 2008; Sims *et al.*, 2010). It will require much improvement in technology to substitute feedstock with other inputs, so we make assumption (a) and focus on the substitution of labor and capital for energy. In the existing literature, estimates for the long-run conditional cross-price elasticities between natural gas and coal for the whole U.S. economy and for the industrial sector include both positive and negative estimates (Jones, 1995; Urga and Walters, 2003; Serletis et al., 2010). Since the positive estimates are very small and the mean of the estimates is negative, we treat the cross-price elasticities as zero, which implies that natural gas and coal are used in fixed proportions. In ethanol conversion, woody biomass can be used as an energy source to substitute for coal (Wang *et al*., 2007). Because LCA focuses on the long run, we assume that any short-run limits on the extent to which woody biomass can be substituted for coal are resolved in the long run. Thus, we treat them as perfect substitutes as energy sources in ethanol conversion, i.e., assumption (b).

emission levels for a given ethanol conversion technology can be expressed by the following equation:

$$\Delta E_{x,lf} = e_{lf} \sum_{j=f,tf,tb} \Delta N_{lf}^{j*} + (e_{ng} + a_x e_x)\Delta N_{ng}^{b*}. \tag{9}$$

Holding capital and labor prices constant, changes in quantities of liquid fuel and natural gas due to changes in their prices can be obtained by taking the total differentials:

$$\Delta E_{x,lf} = e_{lf} \sum_{j=f,tf,tb} \frac{\varepsilon_{lf}^{j} N_{lf}^{j*}}{p_{lf}} \Delta p_{lf} + (e_{ng} + a_x e_x) \frac{\varepsilon_{ng}^{b} N_{ng}^{b*}}{p_{ng}} \Delta p_{ng}, \tag{10}$$

where ε_{lf}^{j} is the conditional own-price elasticity of liquid fuel used in sector j, and ε_{ng}^{b} is the conditional own-price elasticity of natural gas used in ethanol conversion. Thus, it is clear that the conditional input demand elasticities play a pivotal role in determining changes to lifecycle carbon emissions when the prices of energy inputs change. Under the assumption of a fixed-proportions production function implicit in most LCA analyses, conditional input demand elasticities are assumed equal to zero, and emissions remain unchanged even when environmental policies cause changes in energy prices. Instead, non-zero conditional input demand elasticities imply that input ratios will change as input prices change. Thus, standard LCA analysis is a special case of this more general LCEA framework.

3.1.1. Technology switching and liquid fuel changes

In the ethanol lifecycle, coal is initially used in the ethanol conversion plant, and diesel is used in the production of feedstock and the transportation of feedstock and ethanol. Environmental policy could cause producers using coal in the ethanol plant (base) to switch to woody biomass (alternative) depending on which technology provides lower long-run cost. For simplicity, we assume that the construction costs for base and alternative plants are the same. The initial input costs for plants using energy source x are

$$C_x = p_{ng}N_{ng}^{b*} + p_x N_x^{b*} + p_l L_x^{b*} + p_k K_x^{b*}, \tag{11}$$

which is equivalent to

$$C_x = (p_{ng} + p_x a_x)N_{ng}^{b*} + p_l L_x^{b*} + p_k K_x^{b*}. \tag{12}$$

Assuming that quantities of labor and capital used in both plants are the same, the initial input cost difference between the alternative and base plants in the absence of environmental policy is

$$\overline{\Delta C} = C_{wb} - C_c = (p_{wb}a_{wb} - p_c a_c)N_{ng}^{b*}. \tag{13}$$

When environmental policy affects the relative prices of carbon intensive and less carbon intensive energy sources, the cost changes in the alternative plant and the base plant can be determined as follows:

$$\Delta C_x = (p'_{ng} + p'_x a_x)\Delta N_{ng}^{b*} + (\Delta p_{ng} + \Delta p_x a_x)N_{ng}^{b*} + p_l \Delta L_x^{b*} + p_k \Delta K_x^{b*}, \tag{14}$$

where p'_x is the new effective price for energy, *x*, which accounts for the tax. Producers initially using the base plant switch to the alternative plant if input costs for the alternative plant are lower than for the base plant in the long-run:

$$C_c + \Delta C_c > C_{wb} + \Delta C_{wb}, \tag{15}$$

which is equivalent to

$$\Delta C_c - \Delta C_{wb} > \overline{\Delta C}. \tag{16}$$

Assuming changes in quantities of labor and capital are the same for both plant types (i.e., $\Delta L_c^{b*} = \Delta L_{wb}^{b*}$ and $\Delta K_c^{b*} = \Delta K_{wb}^{b*}$), inserting equation (14) into inequality (16) and differentiating ΔN_{ng}^{b*} with respect to p_{ng}, we have

$$(p'_c a_c - p'_{wb} a_{wb})\Delta p_{ng} \frac{\varepsilon_{ng}^{b} N_{ng}^{b*}}{p_{ng}} + (\Delta p_c a_c - \Delta p_{wb} a_{wb})N_{ng}^{b*} > \overline{\Delta C}. \tag{17}$$

The emission change caused by the technology switching when keeping diesel as the primary liquid fuel is

$$\Delta E_{cwb} = (E_{wb,d} + \Delta E_{wb,d}) - (E_{c,d} + \Delta E_{c,d}), \tag{18}$$

and total emission reduction from the initial emission level at the technology switching point is

$$\Delta E = E_{wb,d} + \Delta E_{wb,d} - E_{c,d}. \tag{19}$$

Additionally, the price of diesel per unit of energy is currently lower than the price of biodiesel in the absence of any environmental policy. When environmental policy affects relative prices of diesel and biodiesel, biodiesel substitutes totally for diesel in feedstock production and in transportation of the feedstock and ethanol if

$$\frac{p_d+\Delta p_d}{HV_d} > \frac{p_{bd}+\Delta p_{bd}}{HV_{bd}}, \tag{20}$$

where HV denotes heating values.[7] Emission change caused by replacement of diesel with biodiesel is

$$\Delta E_{dbd} = (E_{wb,bd} + \Delta E_{wb,bd}) - (E_{wb,d} + \Delta E_{wb,d}), \tag{21}$$

and total emission change from the initial level when substituting biodiesel for diesel is

$$\Delta E = E_{wb,bd} + \Delta E_{wb,bd} - E_{c,d}. \tag{22}$$

We next analyze the impact of environmental policy on the cellulosic ethanol lifecycle emissions. Two policy regimes are considered: a carbon tax and an integrated tax-subsidy policy within the fuel industry. The former refers to a tax that is imposed on each unit of emission. The latter refers to a revenue-neutral tax policy on energy sources with higher carbon intensities and offsetting subsidies on energy sources with lower carbon intensities.

[7] This assumes that diesel and biodiesel are perfect substitutes in their working relationship with engines, which is not entirely accurate (Fazal et al. 2011, Washington State Department of Enterprise Services, 2012). We abstract from this complication for simplicity.

3.1.2 Carbon tax

The prices of liquid fuels, natural gas, coal, and woody biomass after imposing the carbon tax are as follows:

$$p_h' = p_h + \tau e_h \ \ \forall h = lf, ng, c, wb, \tag{23}$$

where τ denotes the carbon tax and lf can be diesel (d) or biodiesel (bd). Price changes are then

$$\Delta p_h = \tau e_h \ \ \forall h = lf, ng, c, wb. \tag{24}$$

Accounting for equations (23) and (24), the change in emissions (equation (10)), the inequality for technology switching (equation (17)), and the inequality for fuel switching (equation (20)) become, respectively,

$$\Delta E_{x,lf} = \tau\left(e_{lf}\right)^2 \sum_{j=f,tf,tb} \frac{\varepsilon_{lf}^{j} N_{lf}^{j*}}{p_{lf}} + \tau e_{ng}\left(e_{ng} + a_x e_x\right) \frac{\varepsilon_{ng}^{b} N_{ng}^{b*}}{p_{ng}} \tag{25}$$

$$\tau e_{ng}\left(a_c(p_c + \tau e_c) - a_{wb}(p_{wb} + \tau e_{wb})\right) \frac{\varepsilon_{ng}^{b} N_{ng}^{b*}}{p_{ng}} + \tag{26}$$

$$\tau(e_c a_c - e_{wb} a_{wb}) N_{ng}^{b*} > \overline{\Delta C}.$$

$$\frac{p_d + \tau e_d}{HV_d} > \frac{p_{bd} + \tau e_{bd}}{HV_{bd}} \tag{27}$$

The inequalities (equations 26 and 27) must hold for firms to have an incentive to switch processing technology and fuel source, respectively.

3.1.3. Revenue-neutral tax-subsidy policy

The integrated revenue-neutral tax-subsidy policy imposes a carbon tax on fossil fuels and uses the tax revenue to subsidize each unit of emission reduction from renewable energy. We consider four types of fossil fuels: coal (c), natural gas (ng), diesel (d), and gasoline (g). Renewable fuels include woody biomass (wb), biodiesel (bd), non-cellulosic ethanol (ne), and cellulosic ethanol (ce). The integrated tax-subsidy policy changes the prices of fossil fuels with a tax on each unit of CO_2:

$$p'_q = p_q + \tau e_q \ \ \forall q = c, ng, d, g. \tag{28}$$

We assume that the emission reduction of woody biomass is measured by the emission of coal minus the emission of woody biomass. We treat the emission of diesel and gasoline, respectively, as the baseline for measuring the emission reduction of biodiesel and ethanol. Effective prices of renewable fuels then become:

$$p'_{wb} = p_{wb} + s(e_{wb} - e_c) \tag{29}$$

$$p'_{bd} = p_{bd} + s(e_{bd} - e_d) \tag{30}$$

$$p'_n = p_n + s(e_n - e_g) \ \forall n = \ ne, ce, \tag{31}$$

where s represents the subsidy on each unit of emission reduction. The changes in prices are

$$\Delta p_q = \tau e_q \ \ \forall q = c, ng, d, g \tag{32}$$

$$\Delta p_{wb} = s(e_{wb} - e_c) \tag{33}$$

$$\Delta p_{bd} = s(e_{bd} - e_d) \tag{34}$$

$$\Delta p_n = s(e_n - e_g) \ \forall n = \ ne, ce. \tag{35}$$

Then inequalities for technology and fuel switching (equations (17 and 20)) become, respectively:

$$\tau e_{ng}(a_c(p_c + \tau e_c) - a_{wb}(p_{wb} + s(e_{wb} - e_c)))\frac{\varepsilon_{ng}^{b} N_{ng}^{b*}}{p_{ng}} + (\tau e_c a_c - s a_{wb}(e_{wb} - e_c))N_{ng}^{b*} > \overline{\Delta C}. \tag{36}$$

$$\frac{p_d + \tau e_d}{HV_d} > \frac{p_{bd} + s(e_{bd} - e_d)}{HV_{bd}} \tag{37}$$

The revenue-neutral tax-subsidy instrument ensures that tax receipts equal tax subsidies by satisfying the constraint:

$$\tau \sum_q e_q Y_q + s(e_{wb} - e_c)Y_{wb} + s(e_{bd} - e_d)Y_{bd} + \ s\sum_n (e_n - e_g)Y_n \ = 0, \tag{38}$$

where Y_q, Y_{wb}, Y_{bd}, and Y_n represent the total quantities of fuel q, wb, bd, and n, respectively, consumed by Washington in the target year of 2022 under a binding RFS mandate. In this equation, the emission factor of cellulosic ethanol is not static because the emission of cellulosic ethanol is changed by taxes and subsidies due to the incorporation of input substitution in its lifecycle. For a given type of conversion technology, x, changes in emissions when diesel or biodiesel, respectively, are used are,

$$\Delta E_{x,d} = \tau(e_d)^2 \sum_{s=f,tf,tb} \frac{\varepsilon_d^s N_d^{s*}}{p_d} + \tau e_{ng}(e_{ng} + a_x e_x) \frac{\varepsilon_{ng}^b N_{ng}^{b*}}{p_{ng}} \tag{39}$$

$$\Delta E_{x,bd} = s e_{bd}(e_{bd} - e_d) \sum_{s=f,tf,tb} \frac{\varepsilon_{bd}^s N_{bd}^{s*}}{p_{bd}} + \tau e_{ng}(e_{ng} + a_x e_x) \frac{\varepsilon_{ng}^b N_{ng}^{b*}}{p_{ng}}. \tag{40}$$

Accordingly, based on a given amount of forest residues-derived ethanol ($\bar{Y}^b$), the emission factors of ethanol can be computed depending on the least-cost liquid fuel type and conversion technology by the following equations:

$$e_{ce,d} = \left(E_{x,d} + \Delta E_{x,d}\right)/\bar{Y}^b \tag{41}$$

$$e_{ce,bd} = \left(E_{x,bd} + \Delta E_{x,bd}\right)/\bar{Y}^b. \tag{42}$$

The emission factors of other types of energy are treated as constants.

3.2 Parameter values

Parameter values used in our analysis are based on the assumption that Washington State will meet the RFS 2022 mandate. For the purpose of this research, we focus on production of cellulosic ethanol from forest residues in Washington. By 2022, the RFS requires the blending of 36 billion gallons of renewable fuel to transportation fuel, 16 billion gallons of which must be from cellulosic materials. We consider the case in which Washington is self-sustaining in its production of cellulosic biofuel. It currently consumes 2 percent of national liquid fuel, so we examine a scenario in which it produces 2 percent of the 2022 RFS mandate for cellulosic biofuel, with half of cellulosic feedstocks coming from the forestry sector and converted into cellulosic ethanol. Under these conditions, Washington would produce 1 percent (160 million gallons) of the U.S. mandate of 16 billion gallons of ethanol using forest residues as feedstock in 2022. The quantity of forest residues required for a given amount of cellulosic ethanol depends on the conversion process. We do not focus on a particular conversion technology.[8] Instead, we use the mean of estimates in the existing literature for the amount of woody biomass required to produce one liter of cellulosic ethanol (Pimentel and Patzek, 2005; Thomas, 2008; Sims *et al.*, 2010). Thus, a gallon of cellulosic ethanol is estimated to require 13.25 dry kilograms of cellulosic feedstock. Based on this estimate, we extrapolate that 2.12 billion dry kilograms of forest residues would be required to produce 160 million gallons of cellulosic ethanol.

Parameter values for price elasticities of energy inputs, initial quantities of energy inputs for producing 160 million gallons of cellulosic ethanol in Washington, energy prices, emission factors, initial energy consumption in Washington State in 2022 if the requirements of RFS 2022 are met, heating value of each energy source, and initial input cost difference between alternative and base plants are presented in Table 2. They are based on prior literature. Information on capital and labor is not required for the analysis.

No information is available about input price elasticities for cellulosic ethanol plants. We use the weighted average of long-run conditional own-price elasticities of natural gas in the relevant literature (Jones, 1995; Urga and Walters, 2003; Serletis *et al*., 2010) as a proxy.[9] No prior estimates exist for conditional own-price elasticities of liquid fuel used in the forestry sector or biodiesel used in transportation. Using the same data and procedures as Liu and

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[8] Multiple conversion pathways for producing ethanol from cellulosic materials are addressed in the literature. Most use biochemical or thermochemical conversion.
[9] The weight on each estimate is equal to the reciprocal of the number of estimates in each paper.

Shumway (2015), we obtained a meta-regression estimate of the conditional own-price elasticity of GHG-polluting inputs in agricultural production relevant to biofuel feedstock production. We use this estimate as a proxy for the conditional own-price elasticity of liquid fuel used in the forestry sector for biofuel feedstock production.[10] We use Dahl's (2012) estimate of the conditional own-price elasticity of diesel in the transportation sector for the own-price elasticity of diesel in transportation of both forest residues and ethanol. We also use it as a proxy for the own-price elasticity of biodiesel.

The conversion process for cellulosic ethanol is similar to that for corn ethanol with the additional step of breaking cellulosic materials into simple sugars (Goffman, 2009). Pimental and Patzek (2005) indicate that the conversion process for wood ethanol uses twice as much electricity as that for corn ethanol. Therefore, we double the quantities of natural gas and coal required for producing one gallon of corn-based ethanol in Wang *et al.* (2007) as an approximation for cellulosic ethanol produced in the base plant. Then we compute the initial quantities of natural gas and coal required to produce 160 million gallons of cellulosic ethanol. The initial quantity of woody biomass in the alternative plant is computed based on the relative heating values of coal and woody biomass.

[10] Our elasticity estimate is for the reference case in Liu and Shumway (2015), which is regarded as the most relevant case for LCA models. This model is a long-run conditional input demand price elasticity for the polluting input of energy, fertilizer, and manure with prices of labor, land, and capital included as non-polluting input categories in the estimation equation. It is based on a static translog cost function that permits non-neutral technological change and non-constant returns to scale, treats U.S. aggregate agriculture as a single output, includes post-1981 time series data, and uses a maximum likelihood estimator.

In forest residue processing, Johnson *et al*. (2012) estimate that diesel used for loading and processing residues at log landings is 3.83 liters per dry metric ton.[11] We compute the initial quantity of diesel required to produce 2.12 billion kilograms of forest residues using their estimate. As an alternative energy source, we compute the initial quantity of biodiesel that can substitute totally for diesel based on the mean of lower and higher heating values of diesel and biodiesel, respectively, from the U.S. Department of Energy (USDOE, 2013).

In transportation, we follow Johnson *et al.* (2012) and set the average delivery distance from the forest to the ethanol conversion plant at 145 km. Their analysis indicates that 9.33 liters of diesel is required to transport a metric ton of forest residues this distance. The LCA model of ethanol developed by Daystar *et al.* (2012) implies that the fuel used for ethanol transportation is 0.19 times as much as for forest residue transportation. We follow this result to extrapolate the initial diesel quantities for the distribution of ethanol and assume an average distribution distance of 145 km. Then the initial quantity of biodiesel that can substitute totally for diesel is computed based on the relative heating values of diesel and biodiesel.

We use 2012 prices of natural gas, coal, woody biomass, and diesel in Washington as proxies for their price estimates in 2022. The average 2012 price of biodiesel on the West Coast is used as a proxy for the 2022 biodiesel price in Washington.[12]

Emission factors are in units of CO_2 equivalents. The emission factors of natural gas and coal are from the U.S. Energy Information Administration (USEIA, 2013). The emission factor of woody biomass is proxied by the mean emission of harvesting and transporting one unit

[11] Johnson et al. (2012) model production for grinding residues at log landings in the Inland West. This is the most similar case to forest residue collection in Washington available in the existing literature.
[12] The prices are retail prices. We use 2012 data because this is the latest year for which complete information about both energy price and consumption are available for the State of Washington.

(MMBtu) of forest residues using diesel and biodiesel.[13] We consider only harvesting and transportation emissions of woody biomass since emissions from burning woody biomass are totally offset by emissions absorbed in producing the woody biomass.[14] We follow Galinato and Yoder (2010) to determine the amount of emission generated per gallon of diesel and biodiesel. Emission factors of gasoline and non-cellulosic ethanol are also required when analyzing emission reductions under the integrated tax-subsidy policy. They are obtained from the USEIA (2013) and The Climate Registry (2014), respectively.

We extrapolate the initial total consumption of each energy source in Washington in 2022 in the absence of environmental policy that could impact energy prices. Our estimates are based on the following assumptions: (a) the consumption of non-liquid fuels (coal, natural gas, and woody biomass) will be the same as in 2012; (b) the national use of non-cellulosic and cellulosic biofuel will meet the RFS 2022 mandate and Washington will consume 2 percent of each type of biofuel in 2022; (c) cellulosic biofuel consumed in 2022 in Washington is cellulosic ethanol; (d) the proportion of biodiesel to non-cellulosic ethanol consumed will be the same as the proportion of diesel to gasoline consumed in 2012; (e) the total consumption of diesel and biodiesel will remain the same as in 2012; and (f) the total combined consumption of gasoline, non-cellulosic ethanol, and cellulosic ethanol will remain the same as in 2012. Based on assumptions (b) – (d), Washington will use 114 million, 286 million, and 320 million gallons of biodiesel, non-cellulosic ethanol, and cellulosic ethanol, respectively.[15] The consumption of diesel and gasoline

[13] We check the sensitivity of our results by using both the lower bound and the upper bound of emission factors for woody biomass. We find no appreciable differences in the results.

[14] The emission factor of woody biomass in current literature is often much higher since carbon absorption by woody biomass production is not taken into account (*e.g.*, The Climate Registry, 2014).

[15] RFS 2022 requires 20 and 16 billion gallons of non-cellulosic and cellulosic biofuels, respectively. The ratio of diesel to gasoline consumption in 2012 was 0.4.

in 2022 are computed by the quantities consumed in 2012 minus the quantities of biodiesel and ethanol (adjusted by energy content), respectively, based on assumptions (e) and (f).

The initial input cost difference between alternative and base plants in the absence of environmental policy is computed based on input quantities and prices. Assuming that construction costs and labor and capital use are the same for both types of plants, the only difference in costs is the source of energy. Using the quantities and prices of coal and woody biomass discussed above, coal for the base ethanol conversion plants initially costs $9.11 million less than woody biomass in alternative plants for producing 160 million gallons of forest-residue-derived ethanol.

3.3 Results

By inserting the initial quantities of energy inputs for producing 160 million gallons of cellulosic ethanol and emission factors from Table 2 into equation (7), the total amount of CO_2 emissions from producing cellulosic ethanol in the State of Washington in 2022 is estimated to be 780 million kg when the base ethanol conversion plant is used and diesel is the only liquid fuel used in forest-residue production and transportation and in ethanol transportation. This value is indicated as *a0* in Figure 2 and *b0* in Figure 3. Accordingly, the average emission level per gallon (emission factor) of cellulosic ethanol is 4.87 kg. Thus, in the absence of input substitution, substituting cellulosic ethanol for an energy-equivalent amount of gasoline or corn ethanol would reduce carbon emissions by 19 percent and 15 percent, respectively.[16] Under the assumption of fixed-proportion input combinations, the emission reduction of ethanol stays unchanged under any taxes or subsidies on energy inputs. We next examine emission changes

[16] Gasoline and corn ethanol have emission factors of 8.90 kg CO_2/gallon and 5.75 kg CO_2/gallon (USEIA, 2013), respectively. Energy content of gasoline and ethanol is 0.125 and 0.084 MMBtu/gallon, respectively (The Climate Registry, 2014).

under different tax levels for a pure carbon tax and a revenue-neutral tax-subsidy policy allowing for input substitution, technology switching, and fuel substitution.

3.3.1 Impact of a carbon tax

Figure 2 and Table 3 present the estimated long-run impacts of a Pigouvian carbon tax on emissions when input substitution, technology switching, and fuel substitution occurs in the Washington state cellulosic ethanol production and transportation sectors (i,e., feedstock production, ethanol conversion, and transportation of feedstock and ethanol). We find that the tax rate that stimulates producers to switch from the base ethanol conversion plant that uses coal to an alternative plant that uses woody biomass is lower than the rate that stimulates producers to substitute biodiesel for diesel.

For a tax rate less than \$0.039/kg CO_2, changes in emissions result from substitution of labor and capital for energy (diesel, natural gas, and coal) in each of the ethanol production and transportation stages. Emissions follow line *a1* in Figure 2. Consider a tax rate of \$0.025/kg CO_2.[17] Input substitution of labor and capital for energy causes the emission level to decrease by 43 million kg, or 4.61 kg/gallon of cellulosic ethanol. This is a reduction of 6 percent from that estimated by the standard LCA, which assumes fixed-proportions production (i.e. no input substitution). As the tax rate approaches \$0.039/kg (0.039[-] in Table 3), emissions are reduced by 67 million kg, or 4.46 kg/gallon, which is a 9 percent reduction due to input substitution.

[17] This is the tax rate currently proposed for Washington by CarbonWA, a non-partisan grassroots group developing a 2016 revenue-neutral citizen's ballot measure to reduce human impacts on climate change. The CarbonWA tax proposal is a revenue-neutral tax-subsidy policy approach that imposes carbon tax on fossil fuels consumed in Washington and uses the tax revenues to reduce sales tax, fund the Working Family Rebate, and eliminate the Business and Occupation tax (Carbon Washington 2014). At this tax rate, gross prices (including the carbon tax) of coal and diesel increase by \$2.38/MMBtu and \$0.28/gallon, respectively.

The breakeven price between ethanol conversion technologies that use coal (base) and those that use woody biomass (alternative) as a primary energy source is reached at the tax rate of \$0.039/kg CO_2 (0.039[+] in Table 3). At higher rates, the ethanol conversion plant switches technology, from using coal to woody biomass. Emissions are reduced by another 214 million kg to 499 million kg (3.12 kg/gallon), which is 36 percent lower than the initial emission estimates (Figure 2, Table 3). Of this reduction, 27 percent is from technology switching. Gross prices for all types of energy increase, e.g., the prices of coal and diesel increase by \$3.72/MMBtu and \$0.44/gallon, respectively.

With carbon tax rates of \$0.039–\$0.116/kg CO_2, ethanol conversion uses woody biomass and natural gas, and production and transportation of feedstock and ethanol use diesel as the primary energy input. As the tax rate approaches \$0.116/kg CO_2, emissions decrease by an additional 89 million kg to 410 million kg (2.56 kg/gallon) due to the substitution of labor and capital for energy inputs (diesel, natural gas, and woody biomass) following line *a2* in Figure 2. This is 47 percent lower than under the assumption of no input substitution.

Based on inequality (27) and parameter values in Table 2, the breakeven price between diesel and biodiesel (per unit of energy) is reached at a tax rate of \$0.116/kg CO_2, at which point biodiesel substitutes for diesel in the feedstock and transportation sectors.[18] At this tax rate, total emissions drop 404 million kg to 376 million kg, or 2.35 kg/gallon, which is a 52 percent reduction from the initial level: 5 percent due to replacement of diesel with biodiesel, 27 percent due to technology switching in the conversion plant, and 20 percent due to substitution of labor and capital for energy.

[18] Gross prices of diesel and biodiesel increase by \$1.32 and \$0.71 per gallon, respectively at this point.

For a carbon tax that exceeds \$0.116/kg CO_2, further decreases in emissions are caused by substitution between energy and clean inputs in biofuel production and transportation, following line *a3* in Figure 2. When the tax rate reaches \$0.250/kg CO_2, emissions are reduced by another 148 million kg to 228 million kg, or 1.43 kg/gallon. This is a remarkable 71 percent total reduction from the initial level, of which more than half is due to substitution of labor and capital for energy sources.

Although we find that emissions can be substantially reduced through a carbon tax, our estimates of emission reduction from cellulosic ethanol due to a carbon tax follow a less steep path than do Rajagopal and Zilberman's (2008a) estimates for corn ethanol. For example, they estimate that a tax rate of \$0.005/kg CO_2 can reduce lifecycle emissions of corn ethanol by 21 percent. At that tax rate, our estimated reduction from lifecycle emissions of cellulosic ethanol is about 1 percent. One reason for the big difference is that they treat natural gas and coal used in the ethanol conversion plant as substitutes while we treat them as complements. They also use different sources for their parameter values because they focus on corn-based ethanol, while we consider forest-residue-derived ethanol.

3.3.2 Impact of a revenue-neutral tax-subsidy policy

Figure 3 presents the estimated long-run impacts of a revenue-neutral carbon tax-subsidy on emissions. By inserting parameter values from Table 2 into inequalities (36) and (37) and constraint (38), we find that a very low tax rate of \$0.006/kg CO_2 on fossil fuels and a corresponding subsidy of \$0.023/kg CO_2 reduction on renewables are sufficient to stimulate the ethanol conversion base plant to switch from coal to the alternative technology using woody biomass. We also find that biodiesel is an economic substitute for diesel when the tax rate reaches \$0.017/kg CO_2 and is associated with a subsidy of \$0.065/kg CO_2 reduction.

Up to a tax rate of \$0.006/kg CO_2 on fossil fuels, the impact of a revenue-neutral tax-subsidy policy on the emission change is equivalent to that of a carbon tax since there are no renewable fuels initially used in producing and transporting ethanol. The change in emission follows line *b1* in Figure 3. As the tax rate approaches \$0.006/kg CO_2, emissions decrease by 11 million (1.4 percent from the initial) to 769 million kg (4.8 kg/gallon of cellulosic ethanol) as a result of substitution between energy inputs of diesel, coal, and natural gas and clean inputs of labor and capital. Prices of coal and diesel increase by \$0.57/MMBtu and \$0.07/gallon, respectively, and the price of woody biomass decreases by \$2.15/MMBtu.

At higher tax-subsidy rates, the ethanol conversion plant switches technology to using woody biomass instead of coal as a primary energy source. The technology switching results in an additional drop of 232 million kg CO_2 to 537 million kg (3.36 kg/gallon). At this very low revenue-neutral tax rate, the lifecycle emission level is 31 percent lower than the initial, with 1 percent stemming from substitution of labor and capital for energy and 30 percent from technology switching.

When the tax rate on fossil fuels is in the range of \$0.006 to \$0.017/kg CO_2, the ethanol conversion plant uses woody biomass and diesel is the only liquid fuel used in the feedstock and transportation sectors. Emissions drop by another 23 million kg to 514 million kg (3.21 kg/gallon) due to further substitution of labor and capital for energy (line *b2* in Figure 3).

Biodiesel substitutes for diesel when the tax rate reaches \$0.017/kg CO_2. This tax rate is just two-thirds the revenue-neutral carbon tax rate currently proposed by CarbonWA (Carbon Washington 2014) as a 2016 legislative initiative for Washington. At this tax-subsidy level, the prices of diesel and biodiesel are \$4.27/gallon and \$3.97/gallon. Emissions decrease by 28 million kg because biodiesel replaces diesel. Hence, at the point at which biodiesel replaces diesel, total emissions are reduced by 294 million kg to 486 million. This is a 38 percent reduction from the initial level, 4 percent of which is from substitution of labor and capital for energy inputs, 30 percent from technology switching in the conversion plant, and 4 percent from replacement of diesel with biodiesel.

With a revenue-neutral tax rate higher than \$0.017/kg CO_2 on fossil fuels accompanied by a subsidy higher than 0.065/kg CO_2 reduction on renewable energy sources, further changes in emissions are due to substitution of labor and capital for natural gas, woody biomass, and biodiesel (line *b3*). For the revenue-neutral tax rate of \$0.025/kg CO_2 proposed by CarbonWA (Carbon Washington 2014), the corresponding subsidy for reduced CO_2 emissions by renewable energy sources is \$0.096/kg CO_2 reduction. Prices of biodiesel and woody biomass decrease by \$0.50/gallon and \$8.99/MMBtu, respectively, from their initial prices, while natural gas, coal, and diesel prices increase by \$1.33/MMBtu, \$2.38/MMBtu, and \$0.28/gallon, respectively, from their initial prices. Emissions drop another 8 million kg to 478 million kg (39 percent from the initial level). If the tax rate on fossil fuels is increased to \$0.250/kg CO_2 associated with a subsidy of \$0.927/kg CO_2 reduction on renewables, emissions are reduced by another 227 million kg to 251 million kg (1.57 kg/gallon) due to further substitution of labor and capital for energy. This is a total reduction from the initial level of 68 percent, of which half is due to substitution of labor and capital for energy inputs.

3.3.3 Comparison of a pure carbon tax and revenue-neutral tax-subsidy policy

Table 4 summarizes the changes in emissions just before and after pivotal changes in the carbon tax and revenue-neutral tax-subsidies. The cumulative emission reduction caused by the integrated tax-subsidy policy is greater than that caused by the pure carbon tax at all tax rates until the pure carbon tax rate is high enough to stimulate replacement of diesel with biodiesel in the feedstock and transportation sectors. Up to a tax rate of \$0.039/kg CO_2, emission reductions are much higher with the integrated tax-subsidy policy. After the tax reaches \$0.116/kg CO_2, the degree of substitution between clean inputs (labor and capital) and energy inputs (natural gas, woody biomass, and biodiesel) is greater under the pure tax than under the revenue-neutral tax-subsidy policy. At such high rates, the pure carbon tax becomes more effective than the revenue-neutral tax-subsidy policy in reducing emissions. A pure carbon tax of \$0.250/kg CO_2 reduces emission levels by 3 percent more than the revenue-neutral policy with the same level of tax. But it should be noted that these are very high tax rates on carbon when judged by current carbon market prices worldwide.[19]

Allowing for input substitution in ethanol production and transportation, lifecycle emissions are reduced as the carbon tax is increased due to the gradual substitution of clean inputs (labor and capital) for energy, switching ethanol conversion technology from using high GHG-emitting coal to low emitting woody biomass, and changing feedstock and ethanol transportation fuel from high-GHG emitting diesel to low emitting biodiesel. The impact of a tax on carbon emissions is very sensitive to the way the tax is implemented. A pure tax on carbon alters the relative prices of non-renewable and renewable energy inputs but raises the prices of both. A tax-subsidy policy that is revenue neutral within the energy sector raises prices of non-renewable energy sources while reducing the prices of lower-GHG emitting renewable energy sources. Therefore, the tax-subsidy policy can stimulate technology switching from using coal to woody biomass in ethanol conversion and replacement of diesel with biodiesel in feedstock and transportation sectors at a much lower tax rate compared with the pure tax. The pure tax reduces

[19] Sweden has the highest carbon tax in the world, which is \$0.168/kg CO_2 (The Carbon Brief, 2014). Carbon taxes in other countries are much lower (World Bank, 2014).

emissions by smaller quantities than does the tax-subsidy policy until after the pure tax rate is high enough (a very high \$0.116/kg CO_2) to stimulate substituting biodiesel for diesel. Then the emissions decrease more rapidly under the pure tax because it stimulates a more rapid substitution of labor and capital for energy than does the revenue-neutral tax-subsidy policy.

3.3.4 Robustness check – natural gas demand elasticity

Emission changes due to input substitution depend crucially on conditional energy input demand price elasticities in the production and transportation of cellulosic ethanol in the LCEA model. Since a prior estimate for the long-run conditional own-price elasticity of natural gas in the cellulosic ethanol conversion sector does not exist, we applied the weighted average of natural gas elasticity estimates in relevant literature (Jones, 1995; Urga and Walters, 2003; Serletis *et al*., 2010) in the above analysis. In this robustness check, we examine how the impact of incorporating input substitution into ethanol conversion on emissions would change when using the lowest (-0.24) and highest (-0.66) natural gas demand elasticity estimates in the literature.

Table 5 presents total emission reductions from the initial level under the carbon tax policy when using three different conditional own-price elasticities for natural gas in the cellulosic ethanol conversion. Emission reductions are positively related to the natural gas elasticity estimate. For relatively low carbon tax rates, the differences in emission reductions from using different natural gas elasticity estimates are small. The difference between using the lowest and the highest elasticity estimates is 6 percentage points at tax rates of \$0.025 - \$0.039/kg CO_2. As the carbon tax rate increases, the difference increases. When the tax rate reaches \$0.250/kg CO_2, the differences between using the lowest and highest elasticity estimates under the pure tax policy is 36 percentage points. The impact of alternative natural gas elasticity estimates under the revenue-neutral tax-subsidy policy is similar. The higher the tax rate, the greater the difference in subsidy and in emission reduction, with the latter reaching 33 percentage points at a tax rate of \$0.250/kg CO_2.

4 Conclusions

By failing to allow for economically-induced input substitution and technology adoption, standard life cycle analyses underestimate the effectiveness of carbon tax and subsidy policies in reducing carbon emissions.

This paper develops a lifecycle economic analysis model (LCEA) that integrates input substitution and technology switching into the standard lifecycle analysis of biofuel. We use this model to estimate lifecycle emissions from cellulosic ethanol that uses forest residues as feedstocks. We examine emission reductions under both a pure carbon tax and a revenue-neutral tax-subsidy policy in the State of Washington for the year 2022.

Compared to emission estimates from a standard lifecycle analysis that assumes fixed-proportions production, a pure carbon tax reduces emissions by 9 percent as it approaches \$0.039/kg CO_2, at which point it can stimulate cellulosic ethanol conversion plants using coal to switch to woody biomass as a primary energy input, resulting in total emission reductions of 36 percent. Biodiesel substitutes for diesel in the forest residue and transportation sectors when the tax is greater than \$ 0.116/kg CO_2, resulting in a 52 percent emission reduction from the initial level.

A revenue-neutral tax-subsidy policy can lead a conversion plant using coal to use woody biomass at the very low tax rate of \$0.006/kg CO_2 accompanied by a subsidy of \$0.023/kg CO_2 reduction on renewable fuels. Emissions decrease by 31 percent from the initial level. Biodiesel replaces diesel when the tax exceeds \$0.017/kg CO_2 with a subsidy that exceeds \$0.065/kg CO_2

reduction, which results in a 38 percent total emission reduction. Both of these energy substitutions occur at a revenue-neutral tax rate lower than the \$0.025/kg CO_2 currently proposed for Washington State by CarbonWA (Carbon Washington 2014), a nonpartisan grassroots group developing a 2016 citizens' ballot measure to reduce human impacts on climate change.

The potentially large differences between LCA and LCEA results indicate the policy relevance and importance of accounting for economic incentives in the production of fuels, and energy in general, when anticipating the impact of climate policies.

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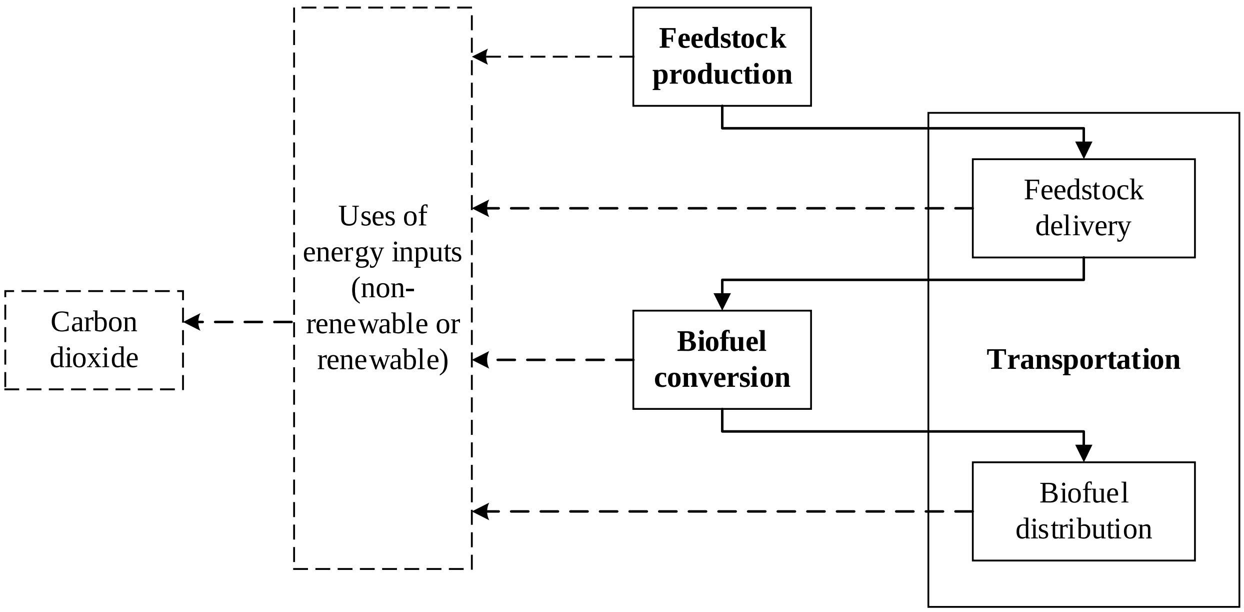
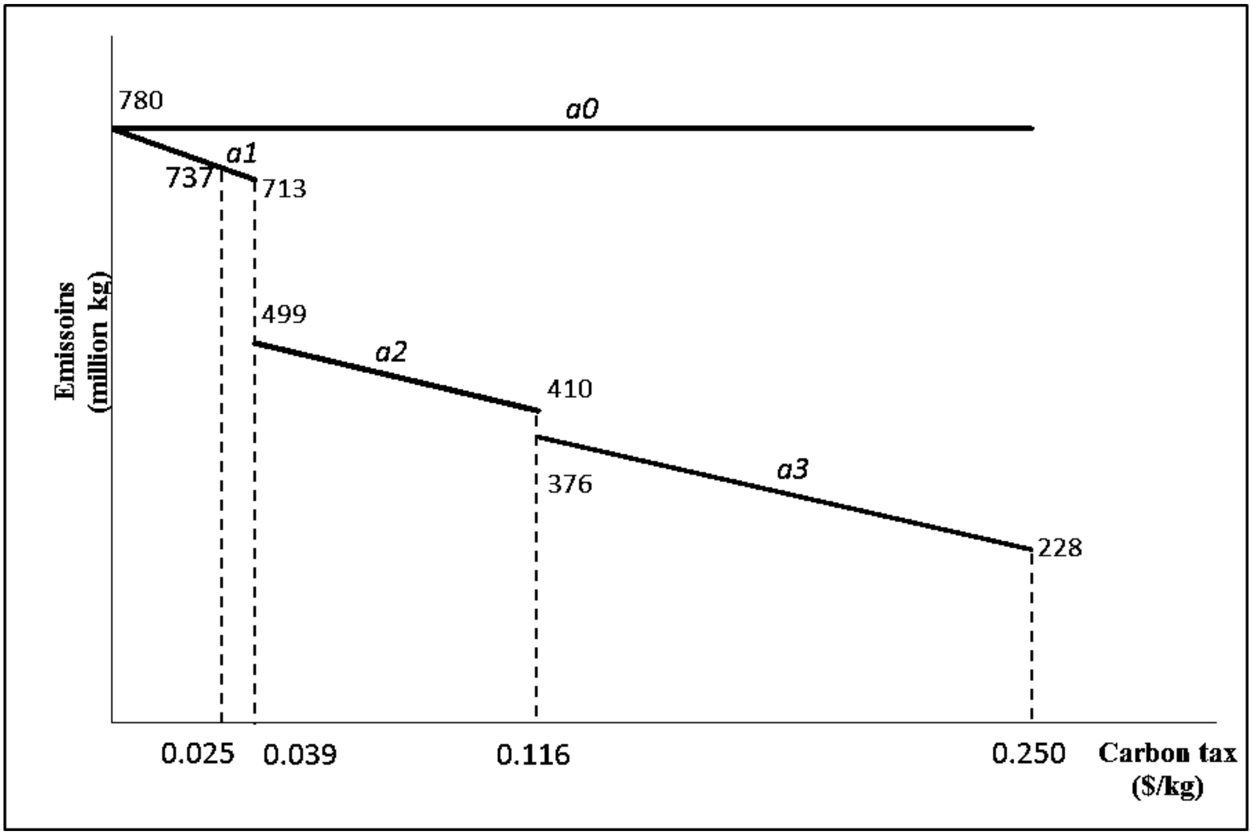
Figure 1: Relationship of production and transportation sectors and emissions



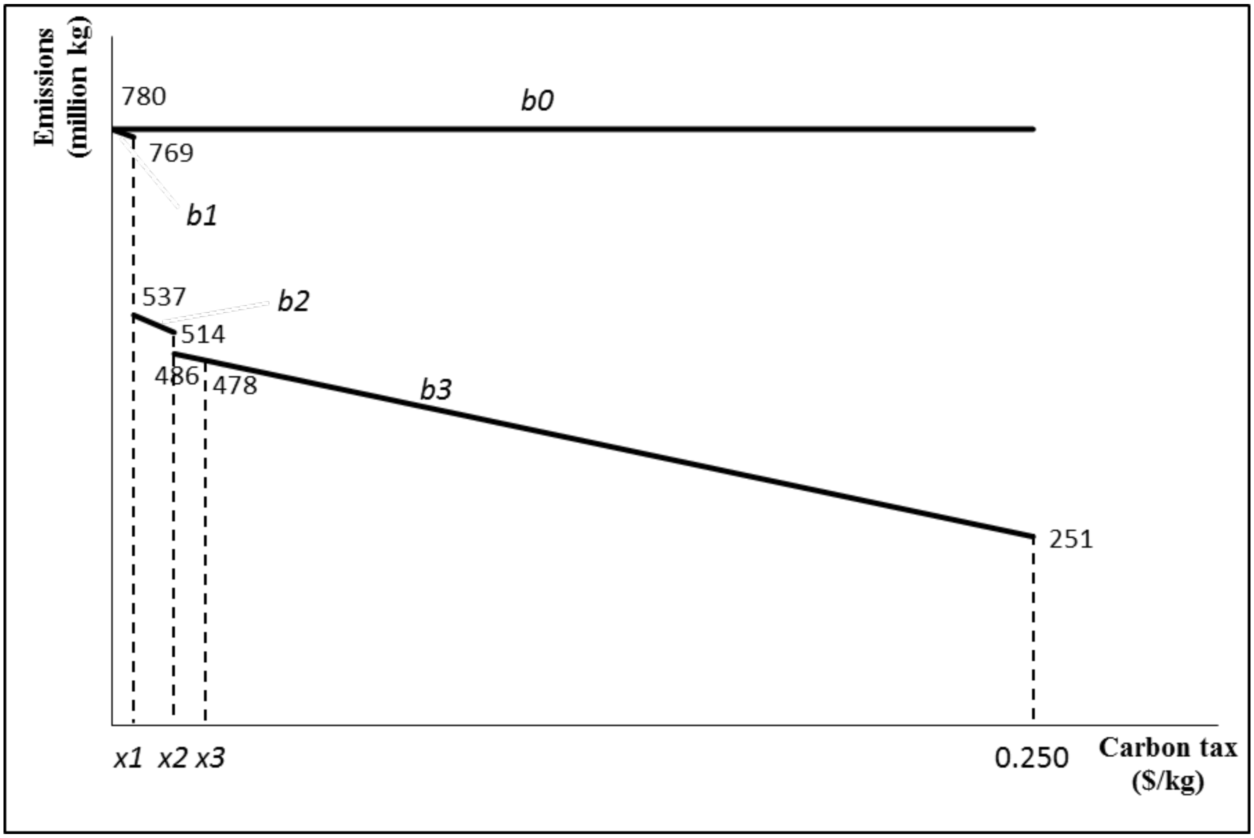
Note: Solid boxes and arrows represent sectors and their flows, respectively. Dashed boxes and arrows represent carbon emission sources and their flows, respectively.

Figure 2: Estimated impact of a pure carbon tax on lifecycle carbon emissions from Washington cellulosic ethanol production, 2022



Note: *a0* represents the initial lifecycle carbon emissions when assuming fixed-proportions production and transportation of ethanol.

Figure 3: Estimated impact of a revenue-neutral tax subsidy on lifecycle carbon emissions from Washington cellulosic ethanol production, 2022



Notes: *x1* = 0.006, *x2* = 0.017, and *x3* = 0.025; *b0* represents the initial lifecycle carbon emissions assuming fixed-proportions production and transportation of ethanol.

Table 1: Input uses in production and transportation sectors for forest-residues-derived ethanol

Production and transportation sectors	Energy inputs	Other inputs
Forest residues production	Liquid fuels (diesel or biodiesel)	Labor and capital
Ethanol conversion	Base: natural gas and coal Alternative: natural gas and woody biomass [a]	Labor, capital, and forest residues [b]
Transportation	Liquid fuels (diesel or biodiesel)	Labor and capital

[a] Woody biomass can be used as an alternative energy source to coal in the ethanol conversion process.
[b] Forest residues, which are one type of woody biomass, are used as a cellulosic feedstock for producing ethanol.

Table 2: Parameter values

Parameters	Energy Type	Value	Unit
Energy input demand own-price elasticities	Natural gas in cellulosic ethanol conversion [a]	−0.41	
	Fuel (i.e. diesel or biodiesel) in forest residues production	−0.73	
	Diesel in transportation	−0.07	
	Biodiesel in transportation	−0.07	
Initial quantities of energy inputs for producing 160 million gallons of cellulosic ethanol			
Cellulosic ethanol conversion	Natural gas	8.34	Million MMBtu
	Coal in base plant [b]	2.54	Million MMBtu
	Woody biomass in alternative plant [c]	3.61	Million MMBtu
Forest residue production	Diesel or	2.14	Million gallons
	Biodiesel [d]	2.29	Million gallons
Forest residue transportation, 145km	Diesel or	5.22	Million gallons
	Biodiesel	5.59	Million gallons
Ethanol transportation, 145km	Diesel or	0.992	Million gallons
	Biodiesel	1.06	Million gallons
Prices	Natural gas [e]	9.00	Dollar/MMBtu
	Coal [e]	2.10	Dollar/MMBtu
	Woody biomass [e]	4.00	Dollar/MMBtu
	Diesel [e]	4.08	Dollar/gallon
	Biodiesel [f]	4.31	Dollar/gallon
Emission factors	Natural gas	53.10	Kg/MMBtu
	Coal	95.30	Kg/MMBtu
	Woody biomass [g]	1.61	Kg/MMBtu
	Diesel	11.35	Kg/gallon
	Biodiesel	6.13	Kg/gallon

	Gasoline	8.90	Kg/gallon
	Non-cellulosic ethanol	5.75	Kg/gallon
Initial total energy consumption in Washington State in 2022 under the RFS mandate	Coal [h]	43	Million MMBtu
	Natural gas [h]	272	Million MMBtu
	Woody biomass [h]	96	Million MMBtu
	Diesel	785	Million gallons
	Biodiesel	114	Million gallons
	Gasoline	2280	Million gallons
	Non-cellulosic ethanol	286	Million gallons
	Cellulosic ethanol	320	Million gallons
Heating value	Diesel	1.33	MMBtu/gallon
	Biodiesel	1.24	MMBtu/gallon
	Gasoline	0.125	MMBtu/gallon
	Ethanol	0.084	MMBtu/gallon
Initial input cost difference for base and alternative plant		9.11	Million dollars

a. For the conditional own-price elasticity of natural gas, Jones (1995) has two estimates for the industrial sector, Urga and Walters (2003) have three estimates for the industrial sector, and Serletis *et al.* (2010) have one estimate for the national economy.
b. In 2010, the typical corn ethanol conversion plant used 26,050 Btu of natural gas and 7,950 Btu of coal to produce one gallon of corn ethanol (Wang *et al.*, 2007). We assume that twice this amount is required for one gallon of cellulosic ethanol conversion.
c. The heating value of coal is about 1.42 times that of woody biomass (The Climate Registry, 2014), so we assume that the quantity of woody biomass required is 1.42 times that of coal. The use of natural gas is held constant.
d. The average heating value generated by diesel is about 1.07 times the heating value generated by biodiesel per gallon (USDOE, 2013). We extrapolate the quantity of biodiesel by multiplying the quantity of diesel by 1.07.
e. From USEIA (2014a). Refer to Table ET1. Primary Energy, Electricity and Total Energy Price and Expenditure Estimates, Selected Years, 1970–2012, for the year 2012.
f. From USDOE (2012). This is the average estimate of biodiesel price on the West Coast of the United States in 2012.
g. The heating value of dry woody biomass is 17.48 MMBtu per short ton (The Climate Registry, 2014). It is used to convert CO_2 per kg woody biomass to CO_2 per MMBtu of woody biomass.
h. From USEIA (2014b). Refer to Table CT2. Primary Energy Consumption Estimates, 2012.

Table 3. Emission changes in response to a standard Pigouvian carbon tax policy

Pigouvian Tax rate ($/Kg)	Emissions/gallon of cellulosic Ethanol (Kg)	Total emissions (Millions Kg)	Emission reduction from initial input mix
0.000	4.88	780	0%
0.025	4.61	737	6%
0.039[-][a]	4.46	713	9%
0.039[+]	3.12	499	36%
0.116[-]	2.56	410	47%
0.116[+]	2.35	376	52%
0.250	1.43	228	71%

[a]With [+] and without [-] the technology switch or fuel substitution that occurs at these values.

Table 4: Emission changes comparison between revenue-neutral tax-subsidy policy and carbon tax policy

Taxes (Subsidies) ($/kg)	Revenue-neutral tax-subsidy policy			Carbon tax policy		
	Emission (million kg)		Emission reduction (%)	Emission (million kg)		Emission reduction (%)
Initial emissions	780					
$t = 0.006$ $(s = 0.023)$	Without switch from *wb* to *c* [-]	769	1%		769	1%
	With switch from *wb* to *c* [+]	537	31%			
$t = 0.017$ $(s = 0.065)$	Without switch from *bd* to *d* [-]	514	34%		746	5%
	With switch from *bd* to *d* [+]	486	38%			
$t = 0.025$ $(s = 0.096)$		478	39%		737	6%
$t = 0.039$ $(s = 0.150)$		464	41%	Without switch from *wb to c* [-]	713	9%
				With switch from *wb* to *c* [+]	499	36%
$t = 0.116$ $(s = 0.439)$		385	51%	Without switch from *bd* to *d* [-]	410	47%
				With switch from *bd to d* [+]	376	52%
$t = 0.25$ $(s = 0.927)$		251	68%		228	71%

Codes: *bd* is biodiesel, *c* coal, *d* diesel, *s* subsidy, *t* tax, *wb* woody biomass, [+] with and [-] without the technology switch or fuel substitution.

Table 5: Robustness check on the natural gas conditional own-price elasticity in cellulosic ethanol conversion for alternative carbon tax policies

Taxes ($/kg)	Subsidies ($/kg)			Emission reduction from initial (%)		
	$\varepsilon_{ng}^{b} = -0.41$	$\varepsilon_{ng}^{b} = -0.24$	$\varepsilon_{ng}^{b} = -0.66$	$\varepsilon_{ng}^{b} = -0.41$	$\varepsilon_{ng}^{b} = -0.24$	$\varepsilon_{ng}^{b} = -0.66$
Pure carbon tax rate						
0.025				6%	3%	9%
0.039				36%	33%	39%
0.116				52%	45%	62%
0.250				71%	56%	92%
Revenue-neutral tax rate ($/kg)						
0.006	0.02314	0.02315	0.02312	31%	30%	32%
0.017	0.0654	0.0655	0.0653	38%	37%	39%
0.025	0.0961	0.0963	0.0959	39%	38%	41%
0.250	0.9266	0.9431	0.9033	68%	56%	89%

Notation Appendix

Notation	Meaning	Notation	Meaning
a	Constant proportion	lf	Liquid fuel (*b* or *bd*)
b	Biofuel sector	n	Represents *be, cbe*
bd	Biodiesel	N	Energy input
c	Coal	ne	Non-cellulosic ethanol
ce	Cellulosic ethanol	ng	Natural gas
cwd	Technology switching (coal to woody biomass)	q	Represents c, ng, d, g
d	Diesel	t	Transportation
D	Distance	s	Subsidy
dbd	Liquid fuel substitution (diesel to biodiesel)	tb	Transportation of biofuel
e	Emission factor	tf	Transportation of feedstock
E	Emission level	wb	Woody biomass
f	Feedstock sector	x	Represents *c* or *wb*
g	Gasoline	Y	Quantity
j	Represents *f, tf, tb*	ε	Conditional price elasticity
K	Capital	τ	Carbon tax
L	Labor	*	Cost minimizing level