Energy Economics 67 (2017) 146–158

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Lifecycle economic analysis of biofuels: Accounting for economic substitution in policy assessment☆

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ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form 1 June 2017
Accepted 4 June 2017
Available online 23 June 2017

JEL classification:
Q16
Q20

Keywords:
Carbon-emission reduction
Carbon tax
Input substitution
Lifecycle analysis
Revenue-neutral carbon tax
Tax policy

ABSTRACT

This paper develops a lifecycle economic analysis (LCEA) model that integrates endogenous input substitution into the standard lifecycle analysis (LCA) of biofuel that typically 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. In a model allowing for input substitution in the cellulosic ethanol feedstock, conversion, and transportation process, we consider energy source substitution (woody biomass for coal in the cellulosic ethanol conversion plant and biodiesel for diesel in feedstock production and feedstock and ethanol transportation) as well as substitution of capital and labor for energy in all stages of the lifecycle. 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. Both tax policies can substantially reduce carbon emissions by inducing substitution among inputs. The revenue-neutral tax-subsidy policy reduces emissions more effectively than the carbon tax policy for carbon tax rates currently in place throughout most of the world. It stimulates substitution of woody biomass for coal and biodiesel for diesel at much lower tax rates when accompanied by corresponding subsidies for reduced emissions from renewable sources.

1. Introduction

Biofuels have become major renewable fuels for transportation. For instance, ethanol made up almost 10% 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 Gal of renewable fuel, of which 16 billion Gal will be produced from cellulosic feedstock.

Policy makers and researchers have pursued cellulosic biofuel for its apparent 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 (USEPA, 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 may mitigate GHG emissions relative to the use of more traditional feedstocks (e.g., Daystar et al., 2012; Bright and Strømman, 2009).

Two widely used categories of LCA frame the analysis used in this paper. For greenhouse gas emissions from a production-consumption system, attributional LCA (ALCA) describes the total or absolute emissions resulting from the production, delivery, and consumption of a specified amount of a good, and consequential LCA (CLCA) describes how emissions change in response to a change in some decision, action, or exogenous system driver (Brander, 2016; Thomassen et al., 2008; Brander et al., 2008).

Consider the following illustration of the relationship between ALCA and CLCA based on their most common definitions (Brander, 2016; Rajagopal et al., 2015; Bento and Klotz, 2014; Zamagni et al., 2012; Earles and Halog, 2011). Let emissions be characterized by a general production relationship as $E = f(\boldsymbol{Y}, \boldsymbol{X})$, where E is emissions, $\boldsymbol{Y}$ is a vector

Abbreviations: ALCA, attributional lifecycle analysis; CLCA, consequential lifecycle analysis; GHG, greenhouse gas; LCA, lifecycle analysis; LCEA, lifecycle economic analysis; RFS, renewable fuel standard.

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

http://dx.doi.org/10.1016/j.eneco.2017.06.002
0140-9883/

of outputs produced and consumed, $\boldsymbol{X}$ is a vector of inputs used to produce $\boldsymbol{Y}$, and the function f defines the physical and economic relationship among them. ALCA describes this static relationship $E=f(\boldsymbol{Y},\boldsymbol{X})$. In contrast, CLCA describes the embedded differential relationship

$$\Delta E=\frac{\partial E}{\partial \boldsymbol{Y}}\Delta \boldsymbol{Y}+\frac{\partial E}{\partial \boldsymbol{X}}\Delta \boldsymbol{X},$$

where $\Delta \boldsymbol{Y}$ and $\Delta \boldsymbol{X}$ are vectors that represent exogenously imposed changes in inputs and outputs. Thus, there is a clear connection between ALCA and CLCA as defined in the literature. CLCA amounts to an analysis of marginal changes in a system in response to changes in system inputs and output given foundational functional relationships described by ALCA.

In the ALCA-CLCA framework, when input substitution and economic decisions about production scale are considered, they are generally imposed by the researcher through exogenous perturbation for comparative analysis.[2] However, there is an embryonic but growing literature that allows input substitution and scale effects to occur endogenously through production input and output supply and demand relationships.[3] To distinguish between exogenous and endogenous substitution and scale effects, consider an augmented economic/production relationship $E=f(\boldsymbol{Y},\boldsymbol{X};\boldsymbol{Z})$, where, as before, E is emissions, $\boldsymbol{Y}$ is a vector of outputs and $\boldsymbol{X}$ is a vector of inputs. In this extension, $\boldsymbol{Z}$ is a vector of exogenous factors affecting the supply and demand functions for $\boldsymbol{Y}$ and $\boldsymbol{X}$, respectively. As before, ALCA describes the static relationship $E=f(\boldsymbol{Y},\boldsymbol{X};\boldsymbol{Z})$. Now, however, if output and inputs respond to elements in $\boldsymbol{Z}$ through market demand and supply shifts, CLCA can describe the embedded differential relationship

$$\Delta E=\left(\frac{\partial E}{\partial \boldsymbol{Y}}\frac{\partial \boldsymbol{Y}}{\partial \boldsymbol{Z}}+\frac{\partial E}{\partial \boldsymbol{X}}\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{Z}}\right)\Delta \boldsymbol{Z},$$

where the new elements $\frac{\partial \boldsymbol{Y}}{\partial \boldsymbol{Z}}$ and $\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{Z}}$ represent the slopes of supply and demand functions, respectively.

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). Liu and Shumway (2016) 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 by Serletis et al. (2010) and Stern (2012).

The present article extends the existing LCA literature by incorporating endogenous substitution of inputs into several stages of the biofuel lifecycle, including production of biofuel feedstock, conversion of the feedstock to biofuel, and transportation for delivering feedstock and distributing biofuel, with a particular focus on energy inputs used in the production of biofuels.[4] In doing so, we begin with what could be considered an ALCA representation of a production system. We then derive implications within the context of the ALCA model's CLCA counterpart of a policy change involving carbon taxes.

We develop and apply this lifecycle economic analysis (LCEA) model for biofuel to analyze the impact of environmental tax policy on cellulosic biofuel lifecycle emission levels. 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 (Weidema et al., 1999), we also consider energy source substitution possibilities in biofuel conversion and in the feedstock and transportation sectors. Our empirical application of the LCEA model examines the impact of alternative carbon 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.[5] 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.[6] Most importantly in terms of policy implications, this article documents that reliance on LCA to infer the potential impacts of a policy such as a carbon tax or renewable fuel subsidy could lead to biased conclusions.

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 the substitution of inputs is accounted for in the ethanol lifecycle. Section 4 concludes.

2. Theoretical foundation of LCEA

The fundamentals of the economic system developed here can be clarified with a simplistic illustration. Consider two types of energy sources: (a) a fossil energy whose combustion leads to emissions of previously sequestered carbon, and (b) a renewable energy source like recently grown feedstock from which there are no net emissions from combustion because feedstock growth sequesters carbon at the same rate as fuel combustion emits it (within a sufficiently short timeframe).[7] Carbon emissions due to biofuels arise due to fossil fuel consumption upstream of biofuel combustion. Thus, lifecycle emissions

[2] As noted by Lundie et al. (2008), most of "these market relations or mechanisms [as implemented in LCA analysis] are generally not endogenized in the model but are derived from economic models and then included as input into LCA". An example of this approach is Earles et al. (2013), who examine the emissions effect of an exogenous shift in the use of wood products for ethanol production along with possible exogenous shifts in energy sources to power the production/conversion processes (e.g., a shift away from the use of mill residues toward natural gas). These input substitutions are motivated by potential changes in relative prices based on the forest products market but are implemented by exogenous changes in input ratios.

[3] For example, Rajagopal and Zilberman (2008a, 2008b) formally integrate endogenous economic input substitution into LCA in a general economic model of corn production and the ethanol biofuel market. 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. Marvuglia et al. (2013) provide partial and general equilibrium modeling perspectives for integrating market substitution and scale effects. Two additional strains of literature implement endogenous input substitution in the context of biofuel production. One is the literature on land-use change in response to biofuel production (e.g., Fargione et al., 2008; Searchinger et al., 2008). Another implements a CLCA model that accounts for endogenous automobile design decisions as "ripple effects" from other (exogenous) design decisions in response to a policy such as a carbon tax (Whitefoot et al., 2011).

[4] To provide focus, we limit input substitution to these sectors and assume fixed input ratios in all other sectors, including other biofuel and fossil fuel sectors.

[5] Besides a focus on 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) we use price elasticities of energy input demands rather than marginal rates of substitution to drive input substitution effects, and (c) we investigate carbon tax levels that can stimulate energy source substitution in ethanol conversion and substitution of biodiesel for diesel in the feedstock and transportation sectors.

[6] Galinato and Yoder (2010) examined optimal taxes and subsidies in the motor fuel and electric power industries and compared welfare gains for a similar policy.

[7] The assumption that carbon emissions associated with the direct burning of biomass (last stage) are offset by the growth of biomass (first stage) implies that net emissions from the biofuel lifecycle are only associated with the productive sectors (e.g., Daystar et al., 2012). Although this assumption is widely accepted in the literature, the "sufficiently short time" assumption is controversial for environmentalists because GHG emissions occur quickly and sequestration can take several months to many years (Cornwall, 2017). While this may have important short-run implications for ramping up cellulosic biofuel industries, sustainable aggregate harvest of cellulosic feedstock would imply that sequestration and emissions would tend to be equal.

of biofuel are only (net) positive if fossil energy is used in its production. If no fossil energy is used, net lifecycle carbon emissions are zero.

If a tax on carbon emissions is imposed on fossil carbon emission, the relative price of carbon-intense fossil energy would increase relative to biofuels and less-carbon-intense fossil fuels. Firms would be incentivized to substitute away from carbon-intense fossil energy and toward low- or no-net emission energy in the production of biofuels, and the lifecycle emissions per unit of biofuel produced would decline.

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.[8] 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. Fig. 1 summarizes the relationship between these sectors and emissions.

Our LCEA approaches accounts for substitution of clean labor and capital inputs for carbon-intensive energy inputs in all stages of the biofuel lifecycle as well as energy source substitution in the biofuel conversion sector and 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 sector 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.[9] Biofuel 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 assumed exogenous and denoted as p_f, $\boldsymbol{p}_n$, p_l, and p_k for feedstock, energy inputs, labor, and capital, respectively. Assuming a perfectly competitive market and a specific quantity of biofuel produced, $\overline{Y}^b$, the cost-minimization problem can be expressed as

$$\min_{\{Y^f, \boldsymbol{N}^b, L^b, K^b\}} p_f\, Y^f + \boldsymbol{p}_n \boldsymbol{N}^b + p_l L^b + p_k K^b$$
$$s.t. Y^b\left(Y^f, \boldsymbol{N}^b, L^b, K^b\right) \geq \overline{Y}^b.$$

The optimal conditions are

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

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

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

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

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

where λ^b is the Lagrange multiplier and subscripts of Y^b represent partial derivatives (e.g., $Y^b_{Y^f}(\cdot) = \partial Y^b / \partial Y^f$). The demand for feedstock and energy inputs in the production of biofuel are determined by the partial equilibrium and denoted as $Y^{f*}(p_f, \boldsymbol{p}_n, p_l, p_k, \overline{Y}^b)$ and $\boldsymbol{N}^{b*}(p_f, \boldsymbol{p}_n, p_l, p_k, \overline{Y}^b)$, 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 $Y^f = Y^f(\boldsymbol{N}^f, L^f, K^f)$. Exogenous input prices are denoted as in the biofuel conversion sector. Similar to the biofuel sector, the cost-minimization conditions under a competitive market determine the optimal quantities of energy inputs, $\boldsymbol{N}^{f*}(\boldsymbol{p}_n, p_l, p_k, Y^{f*})$.

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 output of transportation is measured as transportation-miles produced: the product of distance and quantity transported. 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 $\boldsymbol{p}_n$. For a given distance of transportation, D,the optimal quantities of energy inputs for distributing $\overline{Y}^b$ biofuel and delivering Y^{f*} feedstock are $\boldsymbol{N}^{tb*}(\boldsymbol{p}_n, p_l, p_k, \overline{Y}^{tb})$ and $\boldsymbol{N}^{tf*}(\boldsymbol{p}_n, p_l, p_k, \overline{Y}^{tf})$, respectively, where $\overline{Y}^{tb} = D^* \overline{Y}^b$ and $\overline{Y}^{tf} = D^* Y^{f*}$.

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.

$$E\left(\boldsymbol{p}_n, p_l, p_k, D, \overline{Y}^b, \boldsymbol{e}^i\right) = \sum_i \boldsymbol{e}^i \boldsymbol{N}^i\left(\boldsymbol{p}_n, p_l, p_k, D, \overline{Y}^b\right), \tag{6}$$

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, Eq. (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 CLCA with fixed input ratios 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

[8] The lifecycle of biofuel can be broken into as many as 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). We combine the two transportation stages into a single transportation sector and treat the first and last stages as offsetting. That leaves us with three sectors for analysis.

[9] For convenient reference, all notation used in the paper are also defined in the Notation Appendix.

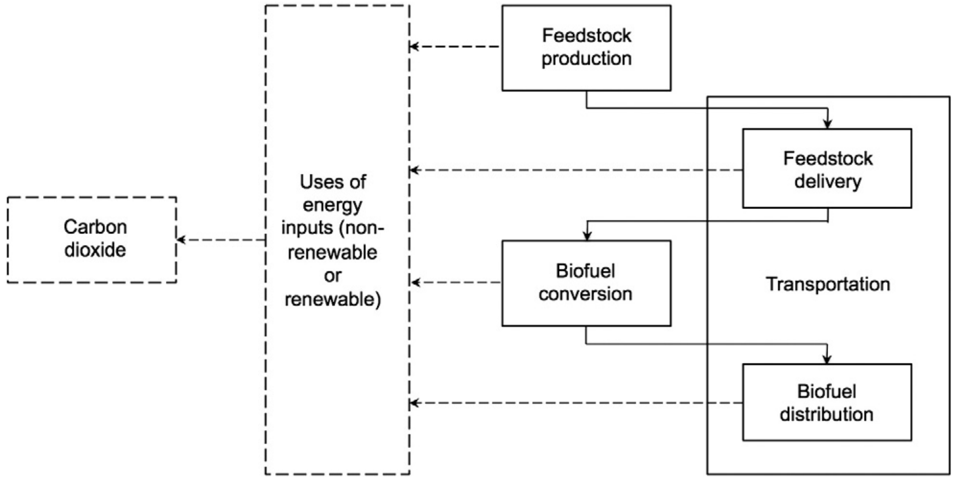

Fig. 1. Relationship of production and transportation sectors and emissions. Note: Solid boxes and arrows represent sectors and their flows, respectively. Dashed boxes and arrows represent carbon emission sources and their flows, respectively.

environmental policies on its lifecycle GHG emissions using the LCEA model.[10]

3.1. Analytical procedure

Liquid fuels for equipment and truck operation are energy inputs in the forest residue production sector and in the transportation sector for the delivery of cellulosic feedstock and ethanol.[11] Diesel is the primary liquid fuel used. We assume that (non-cellulosic) biodiesel is readily available and is a perfect substitute for diesel (adjusted for energy content), so either diesel or biodiesel will be used as the sole liquid fuel for feedstock production and transportation of feedstock and ethanol based on relative prices. Substituting biodiesel for diesel is assumed to occur when the effective price of diesel per unit of energy is higher than the effective price of biodiesel.[12]

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 $Y^j(N^j_{lf}, L^j, K^j)$ $\forall j = f, tf, tb$, 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, $\overline{Y}^b$ are $N^{j*}_{lf}(p_{lf}, p_l, p_k, \overline{Y}^j)$ $\forall j = f, tf, tb$.

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 cellulosic 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 $Y^b_x(Y^f, N^b_{ngx}, N^b_x, L^b_x, K^b_x)$, where $x = c$ or wb represents a plant using natural gas and coal (base case) or natural gas and woody biomass (alternative case), N^b_{ngx} is the quantity of natural gas consumed by the plant using energy x, and N^b_x 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 the other energy source x (coal or woody biomass) are used in fixed proportion to each other in the respective plants.[13] 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 $N^{b*}_{ng}(p_{ng}, p_l, p_k, \overline{Y}^b)$. Then the initial quantity of energy x is $N^{b*}_x = a_x N^{b*}_{ng}$ and a_x denotes a constant proportion of energy x (coal or woody biomass) to natural gas.

Total emission from the production and transportation sectors of cellulosic ethanol using plant x and fu4el lf is

$$E_{x,lf} = e_{lf} \sum\nolimits_{j=f,tf,tb} N^{j*}_{lf} + e_{ng} N^{b*}_{ng} + e_x N^{b*}_x, \tag{7}$$

[10] Indirect emissions from land-use changes in the feedstock sector (Searchinger et al., 2008) are not considered in this study. The value of forest residues is so low that biofuel production is not expected to substantively 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, land-use substitution is one of the many substitution possibilities that LCEA can address.

[11] 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).

[12] 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.

[13] With regard to assumption (a), the amount of feedstock required to produce 1 Gal of cellulosic ethanol depends on conversion method (Pimental 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. With regard to assumption (b), prior estimates of 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).

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.

which is equivalent to

$$E_{x,lf} = e_{lf}\sum\nolimits_{j=f,tf,tb} N_{lf}^{j*} + (e_{ng} + a_x e_x)N_{ng}^{b*}. \tag{8}$$

Emission levels vary as the quantity and composition of energy inputs change in response to market and policy conditions. For a given type of cellulosic ethanol conversion plant, quantities of energy inputs can change due to changes in relative input prices. The amount of change in emission levels for a given cellulosic ethanol conversion technology can be expressed by the following equation:

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

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:

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

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 in lifecycle carbon emissions when prices of energy inputs change. Under the assumption of a fixed-proportions production function implicit in most CLCA 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 CLCA analysis is a special case of this more general LCEA framework.

3.1.1. Energy source substitution

In the ethanol lifecycle, coal is initially used in the cellulosic 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 substitute woody biomass (alternative) depending on which technology provides lower long-run cost. We now derive the conditions under which energy source substitution would occur. 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 (coal or woody biomass) are.

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

which is equivalent to

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

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 (i.e. a carbon tax in this case) 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:

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

where p' is the new effective price for energy ng or x, which accounts for the tax. Producers initially using the base plant switch to the alternative plant and substitute woody biomass for coal 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 Eq. (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 substitution of woody biomass for coal 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 energy source substitution 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.[14] Emission change caused by replacement of diesel with biodiesel is

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

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 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.

The carbon tax is applied to net *combustion* emissions of a fuel. Fossil fuel combustion emissions are taxed proportional to the carbon that was previously sequestered in fossil feedstock. For renewable fuels, combustion emissions are preceded by carbon sequestration in the plant, so net carbon emissions from combustion are close to zero for a sufficiently long time interval.

To focus attention specifically on cellulosic ethanol in model development below, we allow endogenous input substitution only in the cellulosic feedstock production, ethanol conversion, and transportation sectors. We assume a static input mix in the production of other biofuels (biodiesel and non-cellulosic ethanol) and in the collection and transportation of biomass used as an alternative to coal in cellulosic ethanol conversion. A more expansive model would allow for input substitution in all sectors and allow for endogenous lifecycle emissions for all forms of fuels. Given these assumptions, the lifecycle emissions of cellulosic ethanol (and only cellulosic ethanol) are endogenous and dependent on the mix of fossil and renewable feedstocks and fuels used in production.

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 on each unit of emission and lf can be diesel (d) or biodiesel (bd). Price changes are then

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

After accounting for Eqs. (23) and (24), the change in emissions (Eq. (10)), the inequality for substituting woody biomass for coal (Eq. (17)), and the inequality for substituting biodiesel for diesel (Eq. (20)) become, respectively,

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

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

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

The inequalities (Eqs. (26) and (27)) must hold for firms to have an incentive to substitute woody biomass for coal and biodiesel for diesel, respectively.

3.1.3. Revenue-neutral tax-subsidy policy

The integrated revenue-neutral tax-subsidy policy imposes a carbon tax per unit of CO_2 emission from fossil energy and uses the tax revenue to subsidize each unit of emission reduction from renewable energy. For this policy instrument, the carbon tax rate is imposed exogenously, but market outcomes determine the total carbon tax revenue which in turn determines the equilibrium subsidy rate endogenously.

We consider four types of fossil fuels: coal (c), natural gas (ng), diesel (d), and gasoline (g). Renewable energy sources include woody biomass (wb), biodiesel (bd), non-cellulosic ethanol (ne), and cellulosic ethanol (ce). Recall also that for simplicity and focus, we only endogenize input use in the cellulosic ethanol production, processing and distribution sector (so, again, only the cellulosic lifecycle emissions coefficient is endogenous). We associate fixed (positive) lifecycle emissions coefficients with the production and use of fossil fuels, biodiesel, non-cellulosic ethanol, and biomass for use as a substitute for coal in cellulosic ethanol conversion.

The integrated tax-subsidy policy changes the prices of fossil fuels with a tax on each unit of CO_2 emission:

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

We assume that the emission reduction from using woody biomass in cellulosic ethanol conversion is measured by coal emissions minus the net emissions from burning 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:

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

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

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

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

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

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

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

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

Then inequalities for substituting woody biomass for coal and biodiesel for diesel (Eqs. (17) and (20)) become, respectively:

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

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

[14] 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 by assuming technology will resolve the issue in the long-run.

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

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

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,

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

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

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

$$e_{ce,d} = (E_{x,d} + \Delta E_{x,d}) / \overline{Y}^b \quad (41)$$

$$e_{ce,bd} = (E_{x,bd} + \Delta E_{x,bd}) / \overline{Y}^b. \quad (42)$$

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 Gal of renewable fuel to transportation fuel, 16 billion Gal 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% of national liquid fuel, so we examine a scenario in which it produces 2% 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% (160 million Gal) of the U.S. mandate of 16 billion Gal 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.[15] 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 (Pimental 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 Gal of cellulosic ethanol.

Parameter values for price elasticities of energy inputs, initial quantities of energy inputs for producing 160 million Gal 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 labor and capital 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.[16] 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 Shumway (2016), 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.[17] 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 1 Gal of corn-based ethanol reported in Wang et al. (2007) as an approximation for the quantities to produce cellulosic ethanol in the base plant. Then we compute the initial quantities of natural gas and coal required to produce 160 million Gal 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.

In forest residue processing, Johnson et al. (2012) estimate that diesel used for loading and processing residues at log landings is 3.83 l per dry metric ton.[18] We compute the initial quantity of diesel required to produce 2.12 billion kg 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).

For forest residue feedstock 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 l 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 per unit of energy. 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

[15] Multiple conversion pathways for producing ethanol from cellulosic materials are addressed in the literature. Most use biochemical or thermochemical conversion.

[16] The weight on each estimate is equal to the reciprocal of the number of estimates in each paper.

[17] Our elasticity estimate is for the reference case in Liu and Shumway (2016), 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.

[18] 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.

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 to produce 160 million Gal of cellulosic ethanol			
Cellulosic ethanol conversion	Natural gas	8.34	Million MMBtu
	Coal in base plant[b] or	2.54	Million MMBtu
	Woody biomass in alternative plant[c]	3.61	Million MMBtu
Forest residue production	Diesel or	2.14	Million Gal
	Biodiesel[d]	2.29	Million Gal
Forest residue transportation, 145 km	Diesel or	5.22	Million Gal
	Biodiesel	5.59	Million Gal
Ethanol transportation, 145 km	Diesel or	0.992	Million Gal
	Biodiesel	1.06	Million Gal
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/Gal
	Biodiesel[f]	4.31	Dollar/Gal
Emission factors	Natural gas	53.10	kg/MMBtu
	Coal	95.30	kg/MMBtu
	Diesel	11.35	kg/Gal
	Biodiesel	6.13	kg/Gal
	Gasoline	8.90	kg/Gal
	Non-cellulosic ethanol	5.75	kg/Gal
	Woody biomass[g]	1.61	kg/MMBtu
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 Gal
	Biodiesel	114	Million Gal
	Gasoline	2280	Million Gal
	Non-cellulosic ethanol	286	Million Gal
	Cellulosic ethanol	320	Million Gal
Heating value	Diesel	1.33	MMBtu/Gal
	Biodiesel	1.24	MMBtu/Gal
	Gasoline	0.125	MMBtu/Gal
	Ethanol	0.084	MMBtu/Gal
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 7950 Btu of coal to produce 1 Gal of corn ethanol (Wang et al., 2007). We assume that twice this amount is required for 1 Gal 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/kg woody biomass to CO_2/MMBtu of woody biomass. By also using the amount of diesel or biodiesel in the production and transportation of forest residues and the emission factor of diesel and biodiesel, the emission factors of woody biomass when using diesel and biodiesel are 2.04 kg/MMBtu and 1.18 kg/MMBtu, respectively. For use of woody biomass as an alternative energy source for coal in converting cellulosic feedstock to ethanol, we use the mean emission factor of 1.61 kg/MMBtu. We do not account in our analysis for input substitution in the production and transportation of woody biomass as an alternative energy source for coal.
[h] From USEIA (2014b). Refer to Table CT2. Primary energy consumption estimates, 2012.

2012 price of biodiesel on the West Coast is used as a proxy for the 2022 biodiesel price in Washington.[19]

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). 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.

The emission factor of woody biomass production and transportation published in open sources (e.g., The Climate Registry, 2014) is the total amount of CO_2 equivalents from combustion. However, we assume that the emission from combustion of wood is totally offset by emissions absorbed in the growth of the wood. Therefore, we calculate the emission factor of woody biomass in the LCEA model by including only the emissions from harvesting and transporting one unit (MMBtu) of forest residues. In principle, these emissions can vary based on whether diesel or biodiesel is used as the energy input in the collection and transportation of forest residues. However, for the collection and transportation of biomass used as an alternative to coal in ethanol conversion, we assume the ratio of diesel to biodiesel use is exogenous. The emission factor of

[19] 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.

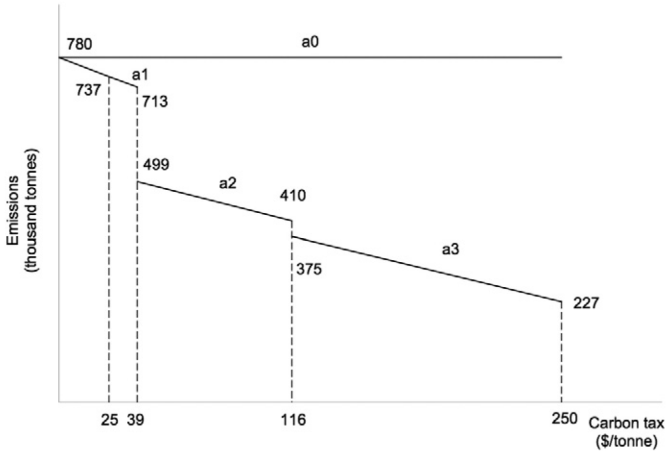

Fig. 2. Estimated impact of a pure carbon tax on lifecycle carbon emissions from Washington cellulosic ethanol production, 2022. Note: *a0* represents the initial lifecycle carbon emissions when assuming fixed-proportions production and transportation of ethanol.

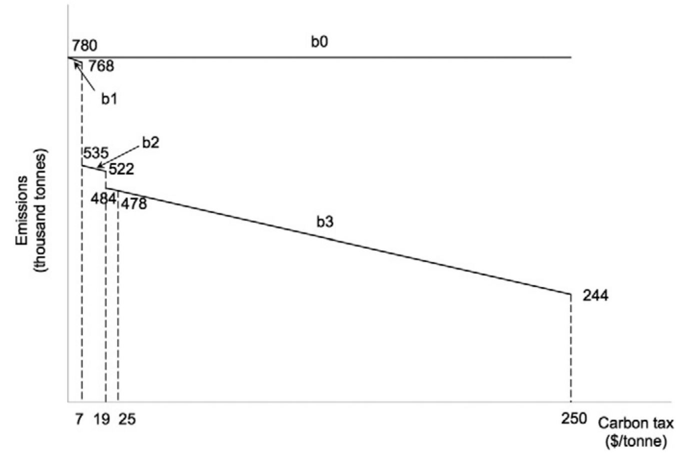

Fig. 3. Estimated impact of a revenue-neutral tax subsidy on lifecycle carbon emissions from Washington cellulosic ethanol production, 2022. Notes: $x1 = 7$, $x2 = 19$, and $x3 = 25$; *b0* represents the initial lifecycle carbon emissions assuming fixed-proportions production and transportation of ethanol.

woody biomass used in the model is proxied by the mean of emissions from using diesel and biodiesel.[20]

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% of each type of biofuel in 2022; (c) cellulosic biofuel consumed in 2022 in Washington will be 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 Gal of biodiesel, non-cellulosic ethanol, and cellulosic ethanol, respectively.[21] The consumption of diesel and gasoline 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 above quantities and prices of coal and woody biomass, coal for the base ethanol conversion plants initially costs $9.11 million less than woody biomass to produce 160 million Gal of forest-residue-derived ethanol.

3.3. Results

By inserting the initial quantities of energy inputs for producing 160 million Gal of cellulosic ethanol and emission factors from Table 2 into Eq. (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 Fig. 2 and *b0* in Fig. 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% and 15%, respectively.[22] Under the assumption of fixed-proportion input combinations, the emission reduction of cellulosic ethanol stays unchanged under any taxes or subsidies on energy inputs. We next examine emission changes under different tax levels for a pure carbon tax and a revenue-neutral tax-subsidy policy allowing for input substitution.

3.3.1. Impact of a carbon tax

Fig. 2 and Table 3 present the estimated long-run impacts of a Pigouvian carbon tax on emissions when input substitution occurs in the Washington State cellulosic ethanol lifecycle. We find that the tax rate that stimulates producers to switch from a coal-based cellulosic ethanol conversion plant to an alternative plant that substitutes woody biomass for coal is lower than the rate that stimulates producers to substitute biodiesel for diesel.

For a tax rate less than \$39/t 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 Fig. 2. Consider a tax rate of \$25/t CO_2.[23] Input substitution of labor and capital for energy causes the emission level to decrease by 43 million kg to 4.61 kg/Gal of cellulosic ethanol. This is a reduction of 6% from that estimated by the standard LCA, which assumes fixed-proportions production (i.e. no input substitution). As the tax rate approaches $39/t (39[−] in Table 3), emissions

[20] Because we don't endogenize the impact of fuel source substitution in production and transportation of biomass used as a substitute for coal in cellulosic ethanol conversion, we underestimate emission reductions from imposition of a carbon tax, with or without the revenue-neutral subsidy.

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

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

[23] This is the tax rate recently proposed for Washington by CarbonWA, a non-partisan grassroots group in a 2016 revenue-neutral citizen's ballot measure to reduce human impacts on climate change. The CarbonWA tax proposal was a revenue-neutral tax-subsidy policy approach that would have imposed a carbon tax on fossil fuels consumed in Washington and use 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/Gal, respectively. The ballot initiative was rejected by Washington voters in the November 2016 election.

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

Pigouvian tax rate ($/t)	Emissions/Gal of cellulosic ethanol (kg)	Total emissions (million kg)	Emission reduction from initial input mix
0.000	4.88	780	0%
25	4.61	737	6%
39[−][a]	4.46	713	9%
39[+]	3.12	499	36%
116[−]	2.56	410	47%
116[+]	2.35	375	52%
250	1.42	227	71%

[a] With [+] and without [−] the energy source substitution that occurs at these values.

are reduced by 67 million kg to 4.46 kg/Gal, which is a 9% reduction due to labor and capital input substitution.

The breakeven price between coal-based and woody biomass-based ethanol conversion technologies is reached at the tax rate of $39/t CO_2 (39[+] in Table 3). At higher rates, the ethanol conversion is based on woody biomass. Emissions are reduced by another 214 million kg to 499 million kg (3.12 kg/Gal), which is 36% lower than the initial emission estimates (Fig. 2, Table 3). Of this reduction, 27% is from substituting woody biomass for coal. Gross prices for all types of energy increase, e.g., the prices of coal and diesel increase by $3.72/MMBtu and $0.44/Gal, respectively.

With carbon tax rates of $39–$116/t CO_2, ethanol conversion uses woody biomass and natural gas, and feedstock production and feedstock and ethanol transportation use diesel as the primary energy input. As the tax rate approaches $116/t CO_2 (116[−] in Table 3), emissions decrease by an additional 89 million kg to 410 million kg (2.57 kg/Gal) due to the substitution of labor and capital for energy inputs (diesel, natural gas, and woody biomass) following line *a2* in Fig. 2. This is 47% 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 $116/t CO_2, at which point biodiesel substitutes for diesel in the feedstock and transportation sectors.[24] At this tax rate (39[+] in Table 3), total emissions drop 405 million kg to 375 million kg (2.35 kg/Gal), which is a 52% reduction from the initial level: 5% due to replacement of diesel with biodiesel, 27% due to substitution of woody biomass for coal in the conversion plant, and 20% due to substitution of labor and capital for energy.

For a carbon tax that exceeds $116/t CO_2, further decreases in emissions are caused by substitution between energy and clean inputs in biofuel production and transportation, following line *a3* in Fig. 2. When the tax rate reaches $250/t CO_2, emissions are reduced by another 148 million kg to 227 million kg (1.42 kg/Gal). This is a remarkable 71% 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 $5/t CO_2 can reduce lifecycle emissions of corn ethanol by 21%. At that tax rate, our estimated reduction from lifecycle emissions of cellulosic ethanol is about 1%. 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.

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

3.3.2. Impact of a revenue-neutral tax-subsidy policy

Fig. 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 $7/t CO_2 on fossil fuels and the endogenous subsidy of $22/t CO_2 reduction on renewables are sufficient to stimulate the ethanol conversion base plant to substitute woody biomass for coal. We also find that biodiesel is an economic substitute for diesel when the tax rate reaches $19/t CO_2 with an endogenous subsidy of $61/t CO_2 reduction.

Up to a tax rate of $7/t 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 Fig. 3. As the tax rate approaches $7/t CO_2, emissions decrease by 12 million kg (1.5% from the initial) to 768 million kg (4.80 kg/Gal 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 $0.67/MMBtu and $0.08/Gal, respectively, and the price of woody biomass decreases by $2.05/MMBtu.

At higher tax-subsidy rates, the ethanol conversion plant substitutes woody biomass for coal as a primary energy source. This substitution of energy source results in an additional drop of 233 million kg CO_2 to 535 million kg (3.35 kg/Gal). At this very low revenue-neutral tax rate, the lifecycle emission level is 31% lower than the initial, with nearly 30% due to energy source substitution.

When the tax rate on fossil fuels is in the range of $7 to $19/t 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 13 million kg to 522 million kg (3.27 kg/Gal) due to further substitution of labor and capital for energy (line *b2* in Fig. 3).

Biodiesel substitutes for diesel when the tax rate reaches $19/t CO_2. This tax rate is just three/fourths the revenue-neutral carbon tax rate recently proposed by CarbonWACarbon Washington, 2014 as a 2016 legislative initiative for Washington. At this tax-subsidy level, prices of diesel and biodiesel are $4.30/Gal and $4.02/Gal. Emissions decrease by 38 million kg because biodiesel replaces diesel. Hence, at the point at which biodiesel replaces diesel, total emissions are reduced by 296 million kg to 484 million. This is a 38% reduction from the initial level, 3% of which is from substitution of labor and capital for energy inputs, 30% from energy source substitution in the conversion plant, and 5% from replacement of diesel with biodiesel.

With a revenue-neutral tax rate higher than $19/t CO_2 on fossil fuels accompanied by an endogenous subsidy higher than $61/t 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 $25/t CO_2 proposed by CarbonWA (Carbon Washington, 2014, the endogenous subsidy for reduced CO_2 emissions by renewable energy sources is $81/t CO_2 reduction. Emissions drop another 6 million kg to 478 million kg (39% from the initial level). If the tax rate on fossil fuels is increased to $250/t CO_2 with an endogenous subsidy of $774/t CO_2 reduction on renewables, emissions are reduced by another 234 million kg to 244 million kg (1.53 kg/Gal) due to further substitution of labor and capital for energy. This is a total reduction from the initial level of 69%, 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. Fig. 4 provides a visual comparison. 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

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

Taxes (subsidies) ($/t)	Revenue-neutral tax-subsidy policy			Carbon tax policy		
	Emission (million kg)		Emission reduction (%)	Emission (million kg)		Emission reduction (%)
Initial emissions	780					
$t=7$	Without substitution of *wb* for *c* [−]	768	2%	768		2%
($s=22$)	With substitution of *wb* for *c* [+]	535	31%			
$t=19$	Without substitution of *bd* for *d* [−]	522	33%	747		4%
($s=61$)	With substitution of *bd* for *d* [+]	484	38%			
$t=25$	478		39%	737		6%
($s=81$)						
$t=39$	463		41%	Without substitution of *wb* for *c* [−]	713	9%
($s=125$)				With substitution of *wb* for *c* [+]	499	36%
$t=116$	383		51%	Without substitution of *bd* for *d* [−]	410	47%
($s=368$)				With substitution of *bd* for *d* [+]	375	52%
$t=250$	244		69%	227		71%
($s=774$)						

Codes: *bd* is biodiesel, *c* coal, *d* diesel, *s* subsidy, *t* tax, *wb* woody biomass, [+] with and [−] without the energy source substitution.

feedstock and transportation sectors. For a tax rate below $116/t CO_2, emission reductions are greater with the integrated tax-subsidy policy. After the tax reaches $116/t 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 $250/t CO_2 reduces emission levels by 2% 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.[25]

Allowing for input substitution in each stage of the ethanol lifecycle, emissions are reduced as the carbon tax is increased due to the gradual substitution of clean inputs (labor and capital) for energy, substituting low GHG-emitting woody biomass for high emitting coal in ethanol conversion, and substituting low GHG-emitting biodiesel for high emitting diesel in the feedstock and transportation sectors. 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 stimulates discrete input substitutions such as woody biomass for coal in ethanol conversion and biodiesel for diesel in feedstock and transportation sectors at a much lower tax rate compared with the pure tax. The pure tax reduces emissions by smaller quantities than does the tax-subsidy policy until the pure tax rate is high enough (a very high $116/t CO_2) to stimulate biodiesel substitution 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–demand elasticities and emission factors

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 input substitution on emissions would change when using the highest (−0.66) and lowest (−0.24) natural gas demand elasticity estimates in the literature.

We also examine the impact of alternative elasticity estimates for fuel used in forest residue production (plus or minus 1 standard deviation from the estimated value) and fuel used in transportation (plus or minus half the base estimate) as well as the impact of higher and lower emission values for woody biomass used as an energy source in the ethanol conversion plant (when it is transported using only diesel or only biodiesel). We consider higher and lower values of each elasticity both singly and collectively.

Table 5 presents total emission reductions from the initial level under the carbon tax policy when using different conditional own-price elasticities for natural gas in the cellulosic ethanol conversion. Emission reductions are positively related to the absolute value of 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 $25–$39/t CO_2. As the carbon tax rate increases, the difference increases. When the tax rate reaches $250/t 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 not as great, but the pattern is similar. The higher the tax rate, the greater the difference in subsidy and in emission reduction, with the latter reaching 21 percentage points at a tax rate of $250/t CO_2.

None of the other alternatives examined has an appreciable impact on emission reductions. The largest difference for any individual elasticity or emission rate alternative is 1 percentage point. When all demand elasticities are increased or decreased, the impact on emissions is virtually identical to the impact of a change in the natural gas demand

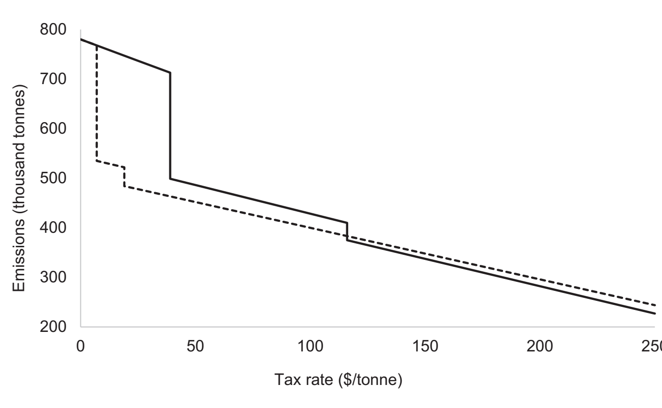

Fig. 4. Comparative impacts of tax policies on lifecycle carbon emissions, Washington cellulosic ethanol production, 2022.

[25] Sweden has the highest carbon tax in the world, which is $137/t CO_2. Carbon taxes in most other countries are much lower (World Bank Group, 2016).

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

Taxes ($/t)	Subsidies ($/t)			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						
25				6%	3%	9%
39				36%	34%	39%
116				52%	45%	62%
250				71%	56%	92%
Revenue-neutral tax rate ($/t)						
7	22	23	20	31%	31%	32%
19	61	65	56	38%	37%	40%
25	81	85	74	39%	37%	41%
250	774	833	691	69%	54%	90%

elasticity. Under all alternatives considered, emissions decrease substantially as the tax or tax-subsidy rates are increased.

4. Conclusions

By failing to allow for economically-induced input substitution, standard lifecycle 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 in all stages of the standard lifecycle analysis of biofuel. The model considers energy source substitution (woody biomass for coal in the cellulosic ethanol conversion plant and biodiesel for diesel in feedstock production and feedstock and ethanol transportation) as well as substitution of capital and labor for energy in each stage of the lifecycle. 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 in the cellulosic ethanol feedstock, conversion, and transportation sectors, we find that input substitution can substantially reduce carbon emissions under both tax policies. The revenue-neutral tax-subsidy policy reduces emissions more effectively than the carbon tax policy for carbon tax rates currently in place throughout most of the world. The tax stimulates substitution of woody biomass for coal and biodiesel for diesel at much lower tax rates when accompanied by corresponding subsidies for reduced emissions from renewable sources. For example, with a $25/t CO_2 tax (as recently proposed for Washington State by CarbonWA (Carbon Washington, 2014), the revenue-neutral tax-subsidy policy reduces emissions by an estimated 39%. Only at very high tax rates do emission reductions under the pure carbon tax policy exceed those from a revenue-neutral tax-subsidy policy.

While the goal of this paper is to examine the importance of accounting for input substitution in LCA when assessing the effectiveness of carbon taxes, it is important to recognize that we implement this concept in our simulations in a constrained way, focusing on endogeneity in the cellulosic ethanol feedstock, conversion, and transportation sectors. Were we to implement endogenous input substitution in the fossil fuel and other biofuel sectors such as corn ethanol, the process-wide differences in LCA and LCEA estimates of carbon tax effects on emissions would likely be substantially larger. In addition, we assume that total fuel consumption and total cellulosic and non-cellulosic biofuel consumption is exogenous and based on the RFS 2022 requirement. This assumption fails to account for additional emission changes from indirect fuel market effects. Because the tax and revenue-neutral tax-subsidy policies would result in an increase in average fuel price, we would expect total fuel consumption to decrease and thus reduce emissions even more than we predict. 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.

Acknowledgements

The authors gratefully acknowledge the constructive comments of Ana Espinola-Arredondo, Phillip R. Wandschneider, Tristan Skolrud, Ben Smith, and an anonymous reviewer on earlier drafts of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2017.06.002.

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