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WELFARE IMPLICATIONS OF THE RENEWABLE FUEL STANDARD WITH AN INTEGRATED TAX SUBSIDY POLICY

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Abstract

This paper derives the optimal integrated tax-subsidy policy where one input is taxed and revenues are used to subsidize the use of a substitute input to reduce greenhouse gas emissions given the existing policies under the Renewable Fuel Standard policies. We measure the welfare effects and impact on cellulosic ethanol production after implementing the tax-subsidy policy using a general equilibrium model. A revenue-neutral integrated tax-subsidy scheme would lead to a small positive tax rate for crude oil and a large positive subsidy for cellulosic ethanol because the former has a larger emissions coefficient than the latter. The overall welfare effects of an integrated tax subsidy scheme are less than a 1% increase for the economy but the growth in the cellulosic ethanol industry could range from 28% to 238% because the revenues from taxing crude oil are directly used to subsidize cellulosic ethanol production.

Keywords: Renewable Fuel Standard, Carbon Tax, Revenue-neutral
JEL Codes: H23, Q48, Q16, Q43

1. Introduction

A carbon tax is one of the many programs that have been considered and developed to reduce greenhouse gas (GHG) emissions. Several countries have implemented national carbon taxes such as Denmark (IEA 2002), Sweden (Hammar and Jagers 2007), Finland (Vourc'h and Jimenez 2000) and parts of Canada (British Columbia Ministry of Small Business and Revenue 2008). Carbon taxes are touted by economists as an effective instrument in addressing climate change (Tol 2005). However, political concerns have hindered any significant traction at the federal level in the United States (Metcalf 2009).

When the tax revenue from a carbon tax is used to offset an existing distortionary tax policy or it is used to subsidize relatively cleaner technology, public support for carbon taxes across political groups increase drastically (Amdur et al. 2014). Feebates are an example of a pollution tax where the revenues are used to subsidize the use of less polluting or clean good. In the energy market in Gainesville, Florida, a surcharge on consumption of electricity is collected and the ensuing revenues are used to fund the purchase of electricity generated by privately owned solar panels (New York Times 2009). In the automotive market, taxes are imposed on low mileage cars and a tax rebate is imposed on high mileage cars (Greene et al. 2005). Such policies that tax high polluting goods and subsidize low polluting goods shift consumption toward goods that are relatively less polluting (Johnson 2006).

The US government has enacted the Energy Independence and Security Act (EISA) of 2007 as an attempt to reduce fossil fuel dependence by increasing renewable fuel and as a way to reduce GHG emissions by substituting for energy feedstock that has a relatively lower emissions coefficient. The law provides incentives to increase conventional biofuel production from feedstocks such as sugar or starch as well as advanced biofuels using cellulosic feedstocks such as woody crops or agricultural residue. EISA mandates an increasing role for cellulosic biofuel use such that by 2022, 16 billion gallons are required to be used which is larger than the 15-billion-gallon consumption mandate for conventional biofuel (GPO 2011).

Even though there is a growing emphasis on cellulosic biofuels relative to conventional biofuels, the production of the cellulosic biofuel had been slow. Only 20,069 gallons of cellulosic biofuel were produced in 2012, despite an original mandate of 0.5 billion gallons (EPA 2013). There are two relevant Renewable Fuel Standard (RFS) policies relating to the cellulosic biofuel requirement: the input ratio requirement which imposes a lower bound on the amount of cellulosic fuel used in production and the price of waivers which can be used to circumvent the input requirement (Skolrud and Galinato 2015). Given the political feasibility of establishing pollution taxes where the revenues can be used to subsidize less polluting substitute goods, an interesting question arises: How will such a tax-subsidy system affect welfare in the presence of the existing RFS policies that incentivize cellulosic fuel production?

The objective of this paper is to determine the effect on welfare and cellulosic fuel production from an integrated tax-subsidy policy that reduces GHG emissions given the existing RFS policies related to the cellulosic biofuel requirements. We develop a general equilibrium model of GHG based subsidies for low carbon emitting energy inputs such as cellulosic fuel that are funded solely by taxes on high energy carbon emitting sources such as crude oil. This approach alleviates concerns regarding implementation of taxes only or subsidies only since the policy can be revenue-neutral where aggregate additional tax revenues is zero and no new expenditures are added.

We contribute to the literature in two ways. First, this is the first paper that solves for the optimal integrated tax-subsidy policy in a general equilibrium framework. Galinato and Yoder (2010) developed a partial equilibrium framework that analyzed the optimal derivation of taxes and subsidies across various energy output sources. We extend their model by using a general equilibrium framework with multiple sectors and incorporating the integrated tax-subsidy framework in the use of inputs that are blended in the production of fuel. Second, by incorporating the integrated tax-subsidy framework on top of the current RFS policies, we are able to determine the extent to which the integrated tax-subsidy policy can boost cellulosic biofuel production. We calibrate and simulate the model for Washington State, Idaho and Oregon – states with varying abundance of cellulosic feedstock in the form of woody biomass (Yoder et al. 2010).

In a partial equilibrium framework, the standard Pigouvian tax rate is equal to marginal damages created by the pollutant and independent of emissions from other sectors in the economy (Sandmo 1975; Kopczuk 2003). Galinato and Yoder (2010) was the first paper to model the feebate structures by formally deriving the optimal output tax-subsidy schedules from an optimization model. They show that output taxes and subsidies across sectors are not separable because the magnitude and sign of a tax on one form of energy depends in part on the relative emissions of the other energy sources. We extend the analysis by determining the effect on the input mix when the integrated tax subsidy framework is used to incentivize use of a relatively cleaner input (cellulosic fuel) to produce blended fuel rather than a more polluting source (crude oil). Also, unlike Galinato and Yoder (2010), we solve the integrated tax-subsidy schedule using a general equilibrium framework as opposed to a partial equilibrium model to capture any potential spillover effects from other sectors in the production chain.

The integrated tax-subsidy framework has some similarities to the tax mechanism outlined in the double dividend literature that imposes pollution taxes on dirty goods and uses its corresponding revenues to reduce the rate of a pre-existing distortionary tax such as income tax (Parry 1998). There are two key structural differences with this tax mechanism and the one we solve in our model. First, the double dividend literature usually uses labor as a revenue source and a destination for subsidies but in our case, labor only plays an indirect role because the tax and subsidized inputs are all in one sector of the economy. Second, the double dividend literature does not solve any optimal subsidy level for the pre-existing distortionary tax since the market is usually assumed to not have any externalities related to it. In our case, not only do we solve for the optimal tax on the polluting input, but we also solve for the optimal subsidy of a cleaner input because it may be possible that the cleaner input yields pollution albeit at a lower level than the dirtier input.

The renewable fuel mandate set by the EPA is an input pollution standard. The input pollution standard is second only to output standards in curbing total production of a dirty firm (Helfand 1991). The standard is imposed as an input ratio mandate, in other words, the required amount of cellulosic biofuel to be used in production is equal to a percentage of the nonrenewable fuel used in production. In 2014 this percentage was set at approximately 0.02%, rising to 0.128% by 2016 (EPA 2016).[1] When cellulosic production is insufficient, fuel producers can buy waiver credits to satisfy their cellulosic RFS obligation (GPO 2011). Purchasing one waiver credit is equivalent to using a gallon of cellulosic biofuel, and is priced at the greater of $.25 and $3.00 minus the wholesale price of gasoline (GPO 2011). These two instruments together have led to low cellulosic production even when the input-ratio requirement is raised because firms have the option to purchase waivers instead (Skolrud et al. 2014). Skolrud and Galinato (2015) integrate a revenue-neutral tax into a general equilibrium framework where crude oil use is taxed and the revenues are used to reduce a sales tax in Washington and an income tax in Oregon. However, they do not consider incentivizing adoption of alternative inputs in fuel blending such as subsidizing cellulosic ethanol production. We are not aware of any study that considers the welfare effects of an integrated tax subsidy framework in the presence of the RFS policies.

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[1] These percentages have been adjusted downwards by the EPA to account for limited cellulosic biofuel production (EPA 2016). In 2016, the percentage standard specified by the RFS legislation was set at approximately 2.6%, rising to over 9% by 2022. A 9% standard at current fuel consumption is equivalent to approximately 16 billion gallons of cellulosic biofuel (GPO 2011).

We modify the general equilibrium model developed by Skolrud et al. (2014) to solve for the optimal tax-subsidy mechanism in the presence of the RFS policy. We build on their model by integrating a general equilibrium framework, imperfect competition and an input ratio mandate. When a constraint on tax revenues are implemented, the marginal welfare from the targeted tax is introduced in the optimal conditions creating a smaller tax rate for crude oil and a subsidy for cellulosic fuel.

We turn to numerical simulations to determine the general equilibrium effects of the tax-subsidy mechanism. Results indicate that the imposition of such a mechanism would be welfare improving in Washington. In the unconstrained case, we find that the tax on crude oil ranges between $0.35/gallon and $0.74/gallon, while the optimal tax on cellulosic biofuel ranges from $0.12/gallon to $0.51/gallon. The optimal unconstrained tax rates are larger than the Pigouvian level to account for additional distortions due to imperfect competition and the existence of waiver credits. When a targeted net tax revenue of zero is imposed, the crude oil tax shrinks significantly, ranging from $0.00006/gallon to $0.0005/gallon, while the tax on cellulosic biofuel turns to a subsidy, which ranges from $0.41/gallon to $1.28/gallon. The disparity in magnitude and sign between the taxes is due to the lower emission coefficient of cellulosic biofuel compared to crude oil and the low input ratio between cellulosic biofuel and crude oil. If such an integrated tax-subsidy policy is implemented, cellulosic biofuel usage increases by 28% to 238% but overall social welfare increases by less than 1%.

The rest of this article is organized as follows. Section 2 presents the model. Section 3 derives and analyzes the Pigouvian and the integrated tax-subsidy scheme. Section 4 outlines the parameters and functional forms used in the simulation, describes the data, and discusses the simulation procedure. Section 5 summarizes the simulation results and Section 6 concludes the study.

2. Model

Our general equilibrium model has six sectors which include two feedstock sectors, a cellulosic refining sector, a blended fuel sector, a composite good sector, and a consumer sector. The output from the two feedstock sectors, the agricultural and forest sectors, can either be used as inputs for the production of cellulosic biofuel in the cellulosic refining sector or used by the composite good sector to produce a final good. While cellulosic feedstock can be refined into different types of biofuel, refiners have focused on cellulosic ethanol in particular, a focus which is reflected in our theoretical and numerical analysis. The blended fuel sector, in turn, purchases the cellulosic ethanol along with crude oil to produce blended fuel while facing the input ratio mandate and waiver credit policies in the RFS. Finally, consumers purchase fuel and a composite consumption good. Production of blended fuel emits pollution which is harmful to the consumer. The government corrects this externality using a revenue-neutral, integrated tax-subsidy that taxes the dirty input and subsidizes the clean input. Figure 1 summarizes the relationship between sectors in the model and highlights the various interdependencies between the sectors of the model.

2.1 Sectors in the Economy

We model the behavior of each agent in the six sectors in the economy.

2.1.1 Consumption sector

The representative consumer derives utility from blended fuel, B, and composite good, X. Emissions from blended fuel production, E, create disutility for the consumer. Utility is,

$$U(B,X,E)=u(B,X)-\delta E, \tag{1}$$

where $u(\bullet)$ is an increasing and concave sub-utility function and δ is the marginal disutility of pollution. Total emissions from blended fuel production depends on aggregate emission intensities from the use of crude oil, Y_i^o, and cellulosic ethanol, Y_i^c, by all firms in the blended fuel sector, $E = e^c \sum_{i=1}^{n} Y_i^c + e^o \sum_{i=1}^{n} Y_i^o$, where the emissions coefficient for crude oil is higher than for cellulosic ethanol, $e^o < e^c$ (Galinato and Yoder 2010).

Consumers own all resources in the economy. Thus, the consumer's budget constraint is,

$$(2) \qquad p^b B + X = rK + wL + mR + \pi^x,$$

where p^b is the price of blended fuel, r is the rental rate of capital, K is the consumer's capital endowment, w is the wage rate, L is fixed labor supply, m is the rental rate of land, R is the consumer's land endowment, and π^x are the profits from blended fuel production. We normalize the price of the composite good to 1.

The conditions that maximize (1) subject to (2) are the budget constraint in (2) along with the condition stating that the marginal rate of substitution equals relative prices,

$$(3) \qquad \frac{u_B}{u_X} = p^b.$$

Solving equation (3) simultaneously with the budget constraint leads to the demand functions $B^*(p^b, I)$ and $X^*(p^b, I)$, where $I = rK + wL + mR + \pi^x$.

2.1.2 Blended fuel sector

Firm i in the blended fuel sector chooses labor, L_i^b, capital, K_i^b, crude oil, Y_i^o, and cellulosic ethanol, Y_i^c, to produce blended fuel, Y_i^b, using the production function $Y_i^b = Y_i^b(K_i^b, L_i^b, Y_i^c, Y_i^o)$.[2] Blended fuel output is increasing and concave in all the arguments. Also, we assume that crude oil is produced exogenously outside the economy. We model each of the n firms as competing in a

[2] Using i subscript notation for the blended fuel sector is the only deviation from our practice of using subscripts as notation for partial derivatives. In referring to the partial derivative of an i-subscripted variable, we use explicit notation, e.g. $\partial \pi_i / \partial Y_i^c$ to express the partial derivative of the profit of firm i with respect to its use of cellulosic ethanol.

Cournot oligopoly.[3] Each firm takes input prices as given and solves the following profit maximization problem:

$$\max_{\{K_i^b, L_i^b, Y_i^c, Y_i^o, W_i\}} \pi_i = p^b \left(\sum_{i=1}^n Y_i^b \left(K_i^b, L_i^b, Y_i^c, Y_i^o\right)\right) Y_i^b \left(K_i^b, L_i^b, Y_i^c, Y_i^o\right) - rK_i^b - wL_i^b - (p^c + \tau^c)Y_i^c - (p^o + \tau^o)Y_i^o - W_i, \quad (4)$$

where $p^b(\bullet)$ is the inverse demand curve for blended fuel, p^c and p^o are the respective prices of cellulosic ethanol and crude oil, τ^c and τ^o are the respective taxes and/or subsidies for cellulosic ethanol and crude oil, and W_i is the firm's expenditure on waiver credits.

Maximization of (4) is subject to the Renewable Fuel Standard (RFS) constraint that a percentage of cellulosic ethanol must be purchased depending on the total amount of crude oil used in production. Each firm has two ways of satisfying this constraint: they can (1) use enough cellulosic ethanol (Y_i^c) in the production process, or (2), spend enough on waiver credits (W_i / g) (GPO 2011). The constraint can be represented as,

$$Z^c Y_i^o = Y_i^c + \frac{W_i}{g}, \quad (5)$$

where Z^c is the RFS percentage standard for cellulosic ethanol, and g is the waiver credit price.

The first-order conditions for an interior solution to the firm's profit maximization problem in (4) after substituting in the RFS constraint in (5) are given by,

[3] We model the blended fuel sector as an oligopoly to be appropriate for the case of Washington State. The Pacific Northwest is largely served by just five blended fuel producers (oil refineries). While collusive behavior has not been formally identified, the sector was investigated in 2008 by the Washington State Attorney General on suspicion of collusion (Washington State Office of the Attorney General 2016).

(6)

$$
\begin{aligned}
\frac{\partial \pi_i^x}{\partial K_i^b} &= p^b \frac{\partial Y^b}{\partial K_i^b}\left(\frac{1}{n\varepsilon^b}+1\right) - r = 0,\\
\frac{\partial \pi_i^x}{\partial L_i^b} &= p^b \frac{\partial Y^b}{\partial L_i^b}\left(\frac{1}{n\varepsilon^b}+1\right) - w = 0,\\
\frac{\partial \pi_i^x}{\partial Y_i^c} &= p^b \frac{\partial Y^b}{\partial Y_i^c}\left(\frac{1}{n\varepsilon^b}+1\right) - (p^c + \tau^c - g) = 0,\\
\frac{\partial \pi_i^x}{\partial Y_i^o} &= p^b \frac{\partial Y^b}{\partial Y_i^o}\left(\frac{1}{n\varepsilon^b}+1\right) - (p^o + \tau^o + gZ^c) = 0,
\end{aligned}
$$

where $\varepsilon^b \equiv (dB / dp^b)(p^b / B)$ is the price elasticity of demand for blended fuel. Other firms in the sector have similar first order conditions. Simultaneously solving all the first order conditions from the *i* firms will yield the best response functions.

Each equation shows the marginal revenue of each input equals its marginal cost. The marginal cost of crude oil includes the input ratio requirement and the tax level. For cellulosic ethanol, input use entails an addition in marginal revenue in the form of the waiver price. Note the complementary impact that the taxes and RFS policy variables have in the first-order conditions for cellulosic ethanol and crude oil. An increase in τ^o leads to the same effect as an increase in g or Z^c by an equivalent magnitude. On the other hand, an increase in τ^c yields the exact same effect as a decrease in g of the same magnitude. The RFS input ratio and waiver credit system can be perfectly replicated through the appropriate selection of τ^c and τ^o. To see this, set τ^c equal to the negative of the waiver price g, and then set τ^o equal to the waiver price multiplied by the percentage standard, gZ^c, in the equations in (6). This implies that the optimal tax policy for each input can be adjusted to fully internalize any remaining externality that the RFS policy fails to correct.

2.1.3 Cellulosic refining sector

A representative firm in the perfectly competitive cellulosic refining sector chooses capital, K^c, labor L^c, cellulosic feedstock from the agricultural and forestry sectors, Y^a and Y^f, to produce cellulosic ethanol, Y^c, in accordance with the production function $Y^c = Y^c(K^c, L^c, Y^a, Y^f)$. Output is increasing and concave in all arguments. First-order conditions for the representative firm's maximization problem are given by:

$$
\begin{aligned}
&p^c Y^c_{K^c}(K^c, L^c, Y^a, Y^f) - r = 0, \\
&p^c Y^c_{L^c}(K^c, L^c, Y^a, Y^f) - w = 0, \\
&p^c Y^c_{Y^a}(K^c, L^c, Y^a, Y^f) - p^a = 0, \\
&p^c Y^c_{Y^f}(K^c, L^c, Y^a, Y^f) - p^f = 0,
\end{aligned} \tag{7}
$$

where p^a and p^f are the prices of cellulosic feedstock from the agriculture and forestry sectors respectively. The value of marginal product of each input equals its input price.

2.1.4 Cellulosic feedstock sectors and the composite good sector

Production of cellulosic feedstock occurs in both the agricultural and forestry sectors, both of which utilize capital, labor, and land as inputs. Similarly, production of the other final good, which represents a composite good of all remaining goods in the model economy, utilizes capital, labor, and land. Production in each perfectly competitive sector is characterized by the production function $Y^s = Y^s(K^s, L^s, R^s), \forall s = a, f$,x. First-order conditions from profit maximization are,

$$
\begin{aligned}
&p^s Y^s_{K^s}(K^s, L^s, R^s) - r = 0, \\
&p^s Y^s_{L^s}(K^s, L^s, R^s) - w = 0, \\
&p^s Y^s_{R^s}(K^s, L^s, R^s) - m = 0,
\end{aligned} \tag{8}
$$

for all $s = a, f$, x. Equilibrium entails the value of marginal product equals its input price.

2.2 Equilibrium

The equilibrium condition that solves the model consists of the first-order conditions from each sector, represented by equations (2) and (3), the four equations in (6), the four equations in (7), the nine equations in (8), and the following eight market clearing conditions, one of which is redundant by Walras' Law:

$$
\begin{aligned}
&\sum_{i=1}^{n} Y_i^b = B,\\
&Y^x(K^x, L^x, R^x) = X,\\
&\sum_{i=1}^{n} Y_i^c = Y^c(K^c, L^c, Y^a, Y^f),\\
(9)\qquad &Y^s = Y^s(K^s, L^s, R^s),\ \forall s = a, f,\\
&\sum_{i=1}^{n} K_i^b + K^x + K^c + K^a + K^f = K,\\
&\sum_{i=1}^{n} L_i^b + L^x + L^c + L^a + L^f = L,\\
&R^a + R^f + R^x = R.
\end{aligned}
$$

The equilibrium definition admits a set of 27 equations in 27 unknowns, a system which will be solved simultaneously in our numerical simulations.

3. Optimal taxes

To mitigate the pollution externality, the government maximizes social welfare by choosing the optimal tax levels for each polluting input. We consider two tax scenarios. The first uses unconstrained tax revenue while the second scenario constrains the tax revenue to an exogenous target. The latter case allows us to analyze the effect of a revenue-neutral tax system.

3.1 Environmental tax with unconstrained revenues

Social welfare is the sum of consumer surplus, profits from fuel blending, tax revenues including waiver expenditures, less the disutility from pollution. The government's objective is to maximize social welfare by choosing taxes,

$$(10)\qquad \max_{\{\tau^c, \tau^o\}} \Omega = A + \pi^b + \tau^c Y^c + \tau^o Y^o + W - \delta E,$$

where $A = u(B^*(p^b, I), X^*(p^b, I)) - p^b B - X$ is the consumer surplus, $\pi^b = \sum_{i=1}^{n} \pi_i^b$ is aggregate profits in the blended sector, $Y^c = \sum_{i=1}^{n} Y_i^c$ is aggregate output in cellulosic ethanol, $Y^o = \sum_{i=1}^{n} Y_i^o$ is aggregate crude oil use, and $W = \sum_{i=1}^{n} W_i$ is aggregate waivers purchased. Profit in the composite good sector is zero because we assume constant returns to scale and perfect competition. The first-order conditions are given by:

$$(11) \qquad \Omega_{\tau^k} = A_{\tau^k} + \pi_{\tau^k}^b + Y^k + \tau^k Y_{\tau^k}^k + \tau^l Y_{\tau^k}^l + W_{\tau^k} - \delta(e^k Y_{\tau^k}^k + e^l Y_{\tau^k}^l) = 0, \text{ for } k = c, o \text{ s.t. } k \neq l,$$

where subscripts on Y^k indicate partial derivatives of the *aggregate* quantity Y^k with respect to the subscripted argument. From the envelope theorem, $\partial \pi^b / \partial \tau^k = -Y^k$ for $k = c, o$ s.t. $k \neq l.$ The unconstrained tax will deviate from the Pigouvian expression[4] due to the impact of the tax rate on consumer surplus, A_{τ^k}, through its impact on the oligopolistic blended fuel price and through the impact of the tax rate on waiver expenditures, W_{τ^k}. Simultaneously solving the first-order conditions yields the optimal unconstrained tax rates, $\tilde{\tau}^k$:[5]

$$(12) \qquad \tilde{\tau}^k = \delta e^k + \underbrace{\frac{Y_{\tau^k}^l}{Y_{\tau^k}^k Y_{\tau^l}^l - Y_{\tau^k}^l Y_{\tau^l}^k}}_{(+)} \left(W_{\tau^l} + A_{\tau^l}\right) - \underbrace{\frac{Y_{\tau^l}^l}{Y_{\tau^k}^k Y_{\tau^l}^l - Y_{\tau^k}^l Y_{\tau^l}^k}}_{(-)} \left(W_{\tau^k} + A_{\tau^k}\right), \text{ for } k = c, o \text{ s.t. } k \neq l.$$

The tax can be partitioned in two parts, the typical Pigouvian expression, δe^k, and expressions that captures the effect of changes in both tax rates on waiver expenditures and consumer surplus. The latter terms are difficult to sign, but we can draw inference from its components that allows us to understand the sensitivity of waiver expenditures and consumer surplus to pollution taxes and the RFS policy variables.

[4] If the effect of the taxes on consumer surplus and the impact on waiver expenditures are both zero, i.e. $(A_{\tau^k} = 0)$ and $(W_{\tau^k} = 0)$, we can solve the first-order conditions in (11) to yield the typical Pigouvian tax expression, $\tau^k = \delta e^k$ for $k = c, o$, which equates the optimal tax rate to the marginal environmental damage to consumers.

[5] See Appendix, Section A.1 for full derivation.

The second term in equation (12) expresses the effect of the other polluting good tax, τ^l, on waiver expenditures and consumer surplus $(W_{\tau^l} + A_{\tau^l})$, while the third term captures the impact of the own-good tax, τ^k, on waiver expenditures and consumer surplus $(W_{\tau^k} + A_{\tau^k})$. Each of these effects is multiplied by a factor composed of marginal effects of the two taxes on cellulosic ethanol and crude oil inputs, i.e. $Y^l_{\tau^k} / (Y^k_{\tau^k} Y^l_{\tau^l} - Y^l_{\tau^k} Y^k_{\tau^l})$ and $Y^l_{\tau^l} / (Y^k_{\tau^k} Y^l_{\tau^l} - Y^l_{\tau^k} Y^k_{\tau^l})$. If the cross-tax effects, τ^l_k, for $k = c, o$ s.t. $k \neq l$ are positive and the absolute value of the product of own-tax effects outweighs the absolute value of the cross-tax effects, $Y^k_{\tau^k} Y^l_{\tau^l} - Y^l_{\tau^k} Y^k_{\tau^l} > 0$, then increases in the sensitivity of waiver expenditures and consumer surplus to the pollution taxes lead to a larger deviation in the optimal revenue-unconstrained tax from the typical Pigouvian expression. The last two terms of equation (12) correct for the market power in blended fuel sector and the subsidizing effect of the waiver credits in using fossil fuel. When both distortions are large, the tax will be higher relative to the Pigouvian level to account for the added distortions in the market.

Further, we expect an increase in the optimal crude oil tax to have a negative impact on waiver expenditures and an increase in the optimal cellulosic ethanol tax to have a positive impact. This can be seen by analyzing W_{τ^o} and W_{τ^c}:

(13)
$$W_{\tau^o} = g(Z^c \underset{(-)}{Y^o_{\tau^o}} - \underset{(+)}{Y^c_{\tau^o}}) < 0,$$
$$W_{\tau^c} = g(Z^c \underset{(+)}{Y^o_{\tau^c}} - \underset{(-)}{Y^c_{\tau^c}}) > 0.$$

This is an intuitive result: as the crude oil tax increases, less crude oil is used as an input in blended fuel production, which decreases the RFS requirement for cellulosic ethanol usage, Z^c, subsequently requiring the purchase of fewer waivers. Similarly, an increase in the cellulosic ethanol tax increases waiver expenditures because as the tax increases, cellulosic ethanol use declines, requiring more waiver purchases to meet the RFS mandate.

The direct effect of the RFS policy variables on the optimal tax rates operate through their impact on the sensitivity of waiver expenditures to the tax rates. From equation (13), we observe that the direct effect of increases in the waiver price, g, or the percentage standard, Z^c, on W_{τ^o} is negative, and the effect on W_{τ^c} is positive. Thus, the direct impact from either policy variable on the optimal tax rate is ambiguous.

The impact of the tax on consumer surplus, A_{τ^k}, is given by $-B(\partial p^b / \partial \tau^k)$.[6] The sign depends critically on the impact of the tax on the price of blended fuel. Since the price of blended fuel is determined by an oligopoly and an increase in the tax rate results in an increase in each firm's marginal cost, we expect that an increase in either the crude oil or cellulosic ethanol tax will result in a reduction of output and an increase in the blended fuel price, so $A_{\tau^k} < 0$, for $k = c, o$.

Given the individual effects we have outlined, we can finally make an inference about the overall sign of equation (12). While it is clear that $W_{\tau^o} + A_{\tau^o} < 0$, the sign of $W_{\tau^c} + A_{\tau^c}$ is less certain. If $|W_{\tau^c}| < |A_{\tau^c}|$, then the net effect of the second and third term in equation (12) is negative. In this case, the combined effect of the oligopoly market power and the waiver credit reduces output closer to the socially optimal level compared to the case with a perfectly competitive market and no waiver credits. Thus, the optimal tax rate required to reach the socially optimal level of production of blended fuel is lower. However, if $|W_{\tau^c}| \geq |A_{\tau^c}|$, the sign of the summation of the two terms in equation (12) is ambiguous. Thus, the deviation in the optimal revenue-unconstrained tax increases as consumer surplus and waiver expenditures become more sensitive to the tax rates. However, the direction of the deviation is ambiguous and depends on the magnitude of the change in waiver expenditures and consumer surplus with respect to changes in cellulosic ethanol tax.

[6] See Appendix, Section A.3 for derivation.

3.2 Revenue-neutral environmental tax

When a revenue-neutral constraint is imposed, the government's objective function remains the same, but now an additional constraint is added to the maximization problem. So we have:

$$
(14)\qquad \begin{aligned} &\max_{\{\tau^c,\tau^o\}} \Omega = A + \pi^b + \tau^c Y^c + \tau^o Y^o + W - \delta E, \\ &\text{s.t. } T = \tau^c Y^c + \tau^o Y^o, \end{aligned}
$$

where *T* is an exogenous tax target. If a revenue-neutral tax target is preferred by the government, then $T = 0$. The first order conditions that solve the problem include the constraint along with the conditions,

$$
(15)\qquad \begin{aligned} \mathrm{L}_{\tau^k} &= A_{\tau^k} + \pi^b_{\tau^k} + Y^k + \tau^k Y^k_{\tau^k} + \tau^l Y^l_{\tau^k} + W_{\tau^k} - \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k}) \\ &\quad - \lambda(\tau^k Y^k_{\tau^k} + Y^k + \tau^l Y^l_{\tau^k}) = 0, \text{ for } k = c, o \text{ s.t. } k \neq l, \end{aligned}
$$

where λ is the Lagrangian multiplier that measures the marginal social welfare of relaxing the tax-revenue target *T*.

Following similar algebraic steps as in the derivation of the unconstrained tax, we can write the optimal revenue-constrained tax, denoted by $\hat{\tau}^k$, as:

$$
(16)\qquad \begin{aligned} &\hat{\tau}^k = \frac{\delta}{1-\lambda^*(T)} e^k + \frac{1}{Y^k_{\tau^k} Y^l_{\tau^l} - Y^k_{\tau^l} Y^l_{\tau^k}} \left(Y^l_{\tau^k} \frac{W_{\tau^l} + A_{\tau^l} - \lambda^* Y^l}{1-\lambda^*(T)} - Y^l_{\tau^l} \frac{W_{\tau^k} + A_{\tau^k} - \lambda^* Y^k}{1-\lambda^*(T)} \right), \\ &\text{for } k = c, o \text{ s.t. } k \neq l, \end{aligned}
$$

where $\lambda^*(T)$ represents the optimal λ (which is a function of T) that solves the system of first-order conditions.[7] Similar to Galinato and Yoder (2010), each tax rate is increasing in *T* as long as $T < T^*$ where T^* is aggregate tax revenue from the unconstrained tax case. In fact, if $T = 0$, one

[7] Refer to Appendix A.2 for complete derivation and the full expression of $\lambda^*(T)$.

input is taxed while the other is subsidized. As the tax target increases, the positive tax rate increases while the subsidy decreases.

Unlike Galinato and Yoder (2010) who consider an output tax and perfectly competitive markets, we find two other effects when considering an input tax in an imperfect market. First, since the tax rate also accounts for the distortions from market power and the waiver credit, it may be the case that the more pollution intensive input, crude oil, is subsidized while the less pollution intensive input, cellulosic ethanol, is taxed. This would occur if the reduction in waiver expenditure from the use of crude oil is large and the government considers waiver credits a significant source of revenues. Second, since we impose an input tax instead of an output tax, the output price's role is only confined to its impact on consumer surplus changes due to the tax rate. If the price is not sensitive to tax changes, consumer surplus will not be affected even when T increases which implies that the change in the integrated tax-subsidy rates are not as large. In our numerical simulations, we focus our analysis on the revenue-neutral case where $T = 0$.

4. Numerical simulation

We describe the data and functional form assumptions used in the simulation and calibration techniques for Washington State, Idaho and Oregon.

4.1 Functional forms and parameters

A constant elasticity of substitution (CES) functional form is used in each of the six sectors: agricultural, forestry, refining, blended fuel, composite good and consumer. CES production functions are chosen over the Cobb-Douglas to capture differences in input substitutability between the productive sectors. The CES form also has a sufficient number of parameters for the model calibration based on optimality and market clearing conditions to be exactly identified. In the composite, agricultural, and forestry sectors, this implies that

(17) $$Y^s = A^s \left(\sum_{j=\{K,L,R\}} d_j^s (j^s)^{\rho^s} \right)^{1/\rho^s}$$

for $s = \{a, f, x\}$, where A^s is a calibrated scaling/technology parameter, and d_j^s, $j = \{K, L, R\}$, are calibrated share parameters such that $\Sigma_{j=\{K,L,R\}} d_j^s = 1$ for $s = \{a, f, x\}$. The elasticity of substitution is defined by $\sigma^s \equiv 1/(1-\rho^s)$.

In the cellulosic feedstock refining and blended fuel sectors we employ nested CES functions, which allows us to capture different elasticities of substitution between pairs of inputs. The functional form specification for the cellulosic feedstock refining sector is as follows:

(18) $$Y^c = A^c \left((\alpha^c) \left(\sum_{j=\{K^c, L^c\}} d_j^c (j)^{\rho^c_{K^cL^c}} \right)^{\rho^c/\rho^c_{K^cL^c}} + (1-\alpha^c) \left(\sum_{j=\{Y^a, Y^f\}} d_j^c (j)^{\rho^c_{Y^aY^f}} \right)^{\rho^c/\rho^c_{Y^aY^f}} \right)^{1/\rho^c},$$

which allows for separate elasticities of substitution for capital and labor, $\sigma^c_{K^cL^c}$, cellulosic feedstock from agricultural and forestry sectors, $\sigma^c_{Y^aY^f}$, and between each pair of inputs, σ^c. The functional form for the blended fuel sector follows a similar pattern:

(19) $$Y_i^b = A^b \left((\alpha^b) \left(\sum_{j=\{K_i^b, L_i^b\}} d_j^b (j)^{\rho^b_{K^bL^b}} \right)^{\rho^b/\rho^b_{K^bL^b}} + (1-\alpha^b) \left(\sum_{j=\{Y_i^c, Y_i^o\}} d_j^b (j)^{\rho^b_{Y^cY^o}} \right)^{\rho^b/\rho^b_{Y^cY^o}} \right)^{1/\rho^b},$$

allowing for separate elasticities of substitution for capital and labor, $\sigma^b_{K^bL^b}$, crude oil and cellulosic ethanol from the refining sector, $\sigma^b_{Y^cY^o}$, and between each pair of inputs, σ^b. Elasticities of substitution used in the calibration are reported in Table 1.

The data used in the calibration and simulations are derived from different sources. We obtain quantity and price data for Washington, Oregon, and Idaho for various sectors and summarize their values and sources in Table 2. Differences in state-level quantities demonstrate Washington State's emphasis on agriculture over forestry, whereas Oregon is the opposite. Both Idaho's forestry and agricultural sectors are smaller than Washington or Oregon. Washington State employs more labor and capital in agriculture and less labor and capital in forestry than Oregon. Washington State has a higher wage rate and land rental rate than Oregon or Idaho. The remainder of the prices in the model do not vary by state.

In 2014, the EPA reported national production of cellulosic ethanol equal to 33 million gallons (RFSP 2015). As state-level production is not provided, we assume that Washington State, Oregon, and Idaho accounted for a share of national cellulosic ethanol production equal to their respective shares of national petroleum consumption. In 2012, Washington's share of national petroleum consumption was 2% (EIA 2013d), Oregon's share was 0.9% (EIA 2013b), and Idaho's share was 0.04% (EIA 2013a), accounting for cellulosic ethanol production of 660,000 gallons, 297,000 gallons, and 132,000 gallons respectively.

In our model, we disaggregate the production of cellulosic feedstock into two sources, agriculture and forestry. Without information specifying production from each sector, we assume that half the feedstock is produced by the agricultural sector (in the form of switchgrass) and half from the forestry sector. Using yield data from Sims et al. (2010), we calculate the amount of forest residues and switchgrass required to produce the postulated amount of cellulosic ethanol per state.[8] To calculate the forestry land requirement, we multiply forest residues (dry tons) by the ratio of state-level forestry land to state-level residue production (Gale et al. 2012; Smith 2012). The agricultural land requirement is based on an estimated yield of 6 dry tons of switchgrass per acre (University of Kentucky 2013). We assume capital/land and labor/land ratios are the same as in state-level agriculture and forestry production.

Finally, the utility function is CES as well, such that $U(B,X)=(d_B B^{\rho}+d_X X^{\rho})^{1/\rho}-\delta E.$ We

[8] Sims et al. (2010) indicate a range of 110 to 270 liters per ton (l/t) for conversion from agricultural material (switchgrass) to ethanol, and a range of 125 to 300 l/t for forestry residues. We use the midpoints of each range for our conversion factor.

obtain a value for δ from the literature, utilizing Galinato and Yoder (2010), which equates the disutility of pollution to \$25/ton of CO_2. We use an emissions coefficient for blended fuel equal to 0.0089 tons of CO_2/gallon (EIA 2016), and an emissions coefficient for cellulosic ethanol equal to 0.0012 tons of CO_2/gallon (Wang, Wu and Huo 2007).

4.2 Simulation and calibration procedure

To calibrate the individual share parameters of the production functions, we use the method outlined by Howitt (1995), wherein each system of first-order conditions is solved simultaneously for the unknown share and scaling parameters as a function of baseline data. As an example, consider the following calibration of the forestry sector. After applying the CES functional form to the forestry production function, we can write the ratio of any two first-order conditions as:

(20) $$\frac{d_i^f}{d_j^f} = \frac{(j^f)^{\rho^f - 1} p_i}{(i^f)^{\rho^f - 1} p_j},$$ for $i, j = K, L, R$ where p_i is the price for input i, $i = K, L, R$.

Combining two of the ratio conditions and the condition that $d_K^f + d_L^f + d_R^f = 1$ uniquely identifies the share parameters. The scaling parameter A^f is recovered from the production function:

(21) $$A^f = \frac{Y^f}{\left(d_K^f (K^f)^{\rho^f} + d_L^f (L^f)^{\rho^f} + d_R^f (R^f)^{\rho^f}\right)^{1/\rho^f}}.$$

To calibrate d_i^f, $i = K, L, R$ and A^f, we require data for the elasticity of substitution, $\sigma^f = 1/(1-\rho^f)$, input quantities, K^f, L^f, and R^f, and the output quantity, Y^f, which can be found in Table 1 and Table 2. Calibration of the remaining sectors is conducted in a similar manner.

After our calibration, we conduct a numerical simulation to determine the optimal taxes and subsidies in both the revenue-unconstrained (Pigouvian) case and the revenue-constrained case under the model. Deriving the optimal taxes and subsidies allows us to analyze changes in social welfare, blended fuel consumption and cellulosic ethanol production.

Without an analytical expression, we have to utilize numerical optimization to solve for the optimal tax rates. Specifically, we form a system of 27 equations in 27 unknowns, consisting of the first-order conditions from each sector (equations (2) (3), (6), (7), (8)) and the equilibrium conditions in (9). We then specify a grid for the optimal revenue-unconstrained (Pigouvian) tax, ranging from -1 to +1 in increments of 0.05, for both crude oil and cellulosic ethanol taxes. At each point in the two dimensional grid (of which there are 41^2=1,681 distinct points), the entire system of 27 equations is re-solved, and the corresponding social welfare value is calculated at each point. Thus, we define the locally optimal tax as the point that is associated with the highest social welfare. Cellulosic ethanol and blended fuel production are calculated at this point as well.

The numerical simulation for the revenue-constrained $(T=0)$ case proceeds in a similar fashion, with the exception of the grid specification. In this case, we specify a grid for cellulosic fuel ranging from -2 to +2, and we specify a crude oil tax based on the value of the cellulosic fuel tax derived from the revenue-neutrality expression which is:

(22) $$\tau^c Y^c + \tau^o Y^o = 0 \Rightarrow \tau^o = -\tau^c (Y^c / Y^o) .$$

The entire set of 27 model equations is re-solved at every iteration, and the revenue-neutral tax combination associated with the highest social welfare calculation is chosen as the local optimum.

5. Simulation results

Table 3 summarizes the simulation results that calculate the optimal taxes, fuel production and social welfare changes. The revenue-unconstrained taxes for crude oil vary by state, ranging from a low of \$0.35/gallon in Idaho to a high of \$0.92/gallon in Oregon. All taxes are higher than the typical Pigouvian rate, suggesting a positive addition to the tax rate to account for market power distortions and the waiver credit. Note that the marginal damage, δ, and the emissions coefficients

e^c and e^o do not vary across states. The differences in simulated tax rates are mainly due to the marginal impact of taxes on endogenous variables, which vary by state due to differences in calibrated parameters and baseline data.

Revenue-unconstrained taxes for cellulosic ethanol are lower than crude-oil taxes, reflecting their lower emissions coefficient. They vary by state as well, from \$0.12/gallon in Idaho to \$0.51/gallon in Washington. Interestingly, the ordering of taxes across states is not consistent between crude oil and cellulosic ethanol taxes where the highest tax for crude oil is in Oregon while the highest tax for cellulosic ethanol is Washington. The differences can be attributed to the sensitivity of the blended fuel prices and waiver revenues to taxes in each state. Again, taxes are higher than the typical Pigouvian expressions, suggesting a positive addition to the tax rate when accounting for market power and the waiver revenue effect. Our estimates are comparable to the results simulated by Galinato and Yoder (2010) where they derive an output tax of \$0.198 for cellulosic ethanol for the entire United States.

Revenue-constrained taxes, with revenues set to zero, are smaller for both crude oil and cellulosic ethanol. Crude oil taxes are small, ranging from \$0.00006/gallon to \$0.0005/gallon. The revenue-constrained taxes for cellulosic ethanol are actually subsidies. In Washington, the subsidy is \$0.41/gallon, and in Idaho, the subsidy is \$1.28/gallon. The large difference in magnitude between crude oil and cellulosic ethanol taxes/subsidies is due to the low input ratio between cellulosic ethanol and crude oil. Only a small amount of tax on crude oil is needed to subsidize cellulosic ethanol production. Aggregated to the state-level, this equates to a total tax bill between 0.3402 million dollars for Washington and 0.565 million dollars for Idaho collected from crude oil and used to subsidize cellulosic ethanol. The reason why revenues are not as large is because cellulosic ethanol itself has a positive emission coefficient which is 14% of the crude oil coefficient (Wang, Wu and Huo 2007).

Blended fuel and cellulosic ethanol production are affected when the taxes are imposed. In the revenue-unconstrained case, blended fuel and cellulosic ethanol both decrease from about 7% to 15% and from 1% to 15%, respectively, depending on the state. In the revenue-constrained case, crude oil use drops a negligible amount, but cellulosic ethanol increases significantly, ranging from 28.5% to 238.4%.

In either tax scenario, total changes to welfare are minor. The maximum welfare change in the revenue-unconstrained case is just 0.49%, while the change in the revenue-constrained case is practically zero. Constraining tax revenues have an impact on welfare, but that impact is negligible. The results are similar to those derived by Galinato and Yoder (2010) where they show that imposing a revenue-neutral tax only increases welfare by 1% of the total increase in welfare relative to the revenue unconstrained case.

The RFS policy variables perfectly substitute for the taxes as shown in equations (6). In this case, an increase in the cellulosic ethanol subsidy has the same effect as an increase in the cellulosic waiver credit price, and an increase in the crude oil tax has a similar effect to increasing the waiver price multiplied by the cellulosic percentage standard. Therefore, as the input ratio requirement increases based on the RFS schedule, the optimal crude oil tax would decline. If the tax revenue target is fixed at zero, the optimal cellulosic ethanol subsidy will also decrease accordingly. On the other hand, if the waiver price increases, the optimal cellulosic ethanol subsidy will fall, as will the crude oil tax to ensure revenue neutrality. In this case, the rising waiver price acts exactly like a tax on crude oil.

Unfortunately, we lack elasticities of substitution for several sectors. In general, we set elasticities such that to allow for either near perfect substitutability or near perfect complementarity depending on the case. Model results are very robust to the pairs of inputs for which we have designated near perfect substitutability (crude oil and cellulosic ethanol, cellulosic material from forestry and agricultural sectors). Table 4 displays the results of a robustness check on the input pairs assumed to have an elasticity of 0.05 (near perfect complementarity). We re-run the simulation assuming elasticities of 0.01 (approaching Leontief) and 0.99 (approaching Cobb-Douglas) for each sector/input pair. In general, we find very little change to the optimal tax rates and associated welfare measures. The average change in optimal taxes across all sectors is less than two percent.

6. Conclusion

This paper derives the optimal integrated tax-subsidy policy that reduces GHG emissions given the existing policies under the RFS to measure welfare effects and cellulosic fuel production. We develop a general equilibrium model that incorporates six sectors which includes two feedstock sectors (agriculture and forestry), a cellulosic refining sector, a blended fuel sector, a composite good producing sector and a consumption sector of final goods. A welfare maximizing government selects taxes on the use of crude oil and cellulosic ethanol.

We find that if a revenue-unconstrained tax is imposed, the crude oil and cellulosic ethanol taxes are higher than the marginal damages based on the emissions coefficients of both inputs. A premium is added to the pollution tax rate to internalize the added distortion created by market power in the blended fuel market and the existence of the waiver credit.

A revenue-neutral tax subsidy scheme would lead to a positive tax rate for crude oil with a very small magnitude ranging from \$0.00006/gallon to \$0.0005/gallon while cellulosic ethanol is subsidized at a rate of \$0.41/gallon to \$1.28/gallon. The large difference in magnitude between crude oil and cellulosic ethanol taxes/subsidies is due to the input ratio between cellulosic ethanol and crude oil which implies only a small amount of tax on crude oil is needed to subsidize cellulosic ethanol production.

If chosen correctly, the tax/subsidy scheme can substitute perfectly for the two jointly-implemented RFS policies, the cellulosic percentage standard and the waiver credit policy. This relationship implies that individual states could augment the impact of the RFS policy through an appropriately chosen integrated tax/subsidy. As the cellulosic percentage standard increases over time in accordance with the RFS legislation, both the optimal cellulosic ethanol subsidy and crude oil tax will decline.

The welfare effects of a revenue-neutral tax-subsidy scheme are small compared to a revenue-neutral pollution tax that reduces an existing distortionary tax such as a sales tax or income tax. Skolrud and Galinato (2015) show that increasing a tax on blended fuel and reducing a sales tax in Washington or income tax in Oregon increases social welfare by 19% to 20% while the integrated tax-subsidy scheme yields less than a 1% increase in welfare. However, cellulosic fuel production only increases by about 1% in a revenue-neutral tax while the integrated tax subsidy increases cellulosic fuel production by 28% to 238%. The results make intuitive sense since the integrated tax-subsidy framework only affects the energy sector while a revenue-neutral pollution tax would affect a more significant share of the economy. Thus, a policymaker who is more concerned about a growing cellulosic fuel industry would opt to impose an integrated tax-subsidy policy within the energy industry as opposed to a revenue-neutral tax affecting multiple sectors in the economy.

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Tables and figures

Table 1—Elasticities of Substitution

Sector	Elasticity	Source
Agricultural sector[a]	0.21	Yi et al. (2014)
Forestry sector[b]	0.46	Daniels (2010)
Cellulosic refining sector		
Total	0.50	Assumption
Labor/capital	0.50	Assumption
Agricultural cellulose/forestry cellulose	$\to\infty$	Assumption
Blended fuel sector		
Total	0.50	Assumption
Labor/capital	0.50	Assumption
Crude oil/cellulosic ethanol	$\to\infty$	Assumption
Composite good sector	0.50	Assumption
Consumer's utility function	0.1068	Banks et al. (1997)

[a]We use estimates from switchgrass production for the agricultural sector.
[b]The elasticity is an average of three different estimated elasticities between capital and labor, labor and logs, and capital and logs.

Table 2—Parameter Values

Parameters	State			Units	Source
	WA	OR	ID		
Inputs:					
Agricultural labor[a]	1.16	0.34	0.10	Full-time laborers[g]	BLS (2013a; 2013b; 2013c)
Agricultural capital[b]	3.79	1.56	0.80	Tractors/equipment	NASS (2013b)
Agricultural resources	1,096	493.10	219.16	Acres	NASS (2013c)
Forestry labor[c]	3.17	1.87	0.72	Full-time laborers	BLS (2013a; 2013b; 2013c)
Forestry capital[d]	52.82	29.67	50.91	Capital units[h]	Smith (2012), Simmons et al. (2014), Gale et al. (2012)
Forestry resources	17,257	11,840	14,095	Acres	Smith (2012), Simmons et al. (2014), Gale et al. (2012)
Cellulosic refining labor	22.60	10.17	4.52	Full-time laborers	BLS (2013a; 2013b; 2013c)
Cellulosic refining capital	342.64	154.19	68.53	Capital units	WRC (2012)
Fuel blending labor[e]	1130	508	226	Full-time laborers	BLS (2013a; 2013b; 2013c)
Fuel blending capital[f]	17,132	7,709	3,426	Capital units	WRC (2012)
Crude oil	5.67	2.55	1.13	Gallons (bil.)	EIA (2013d; 2013b; 2013a)
Composite good labor	15,035	12,098	4,839	Full-time laborers	BLS (2013a; 2013b; 2013c)
Composite good capital	174,157	159,495	130,830	Capital units	NASS (2013b), Smith (2012), Simmons et al. (2014), Gale et al. (2012)
Composite good resources	27.65	36.57	25.87	Acres (mil.)	NASS (2013c), Smith (2012), Simmons et al. (2014), Gale et al. (2012)
Outputs:					
Cellulosic feedstock, agriculture[i]	6,575	2,959	1,314	Tons	Sims et al. (2010), EIA (2013d; 2013b; 2013a)
Cellulosic feedstock, forestry[i]	5,879	2,645	1,175	Tons	Sims et al. (2010), EIA (2013d; 2013b; 2013a)
Cellulosic ethanol[j]	660	297	132	Gallons (th.)	RFSP (2015), EIA (2013d; 2013b; 2013a)
Blended fuel	2.60	1.17	0.52	Gallons (bil.)	EIA (2013d; 2013b; 2013a)
Composite good[k]	11.98	8.34	4.97	$ (bil.)	NASS (2013d), Smith (2012), Simmons et al. (2014), Gale et al. (2012)
Prices:					
Wage rate	36,296	33,596	32,907	$/year	BLS (2013a; 2013b; 2013c)
Rental rate of capital[l]	8,680	8,680	8,680	$/year	ERS (2014)
Land resource price	215	130	143	$/acre	NASS (2013a)
Cellulosic feedstock, agriculture	65	65	65	$/dry ton	U. Kentucky (2013)
Cellulosic feedstock, forestry	52.27	52.27	52.27	$/dry ton	Gale et al. (2012)
Cellulosic ethanol	2.35	2.35	2.35	$/gallon	GBC (2011)
Crude oil	2.24	2.24	2.24	$/gallon	EIA (2013c)
Final blended fuel[m]	3.76	3.76	3.76	$/gallon	EIA (2013e)

[a]Consists of agricultural inspectors, graders and sorters of agricultural products, agricultural equipment operators, and general farmworkers.

[b]Agricultural capital is computed as an average of the amount of different types of agricultural equipment (tractors) used in Washington State in 2012.

[c]Labor input in the forestry sector consists of forest and conservation workers, fallers, logging equipment operators, and log graders and scalers.

[d]Annual operating cost for sawmills multiplied by the number of sawmills in each state, expressed in capital units.[h]

[e]Labor for the blended fuel sector includes categories for petroleum pump system operators, refinery operators and gaugers.

[f]Total 2012 non-labor capital expenditures, expressed in capital units.[h]

[g]Full-time laborers are those that are employed 40/hrs/wk. for one year.

[h]Capital units are expressed in terms of sector-level input expenditure divided by the capital price, e.g. forestry capital is expressed in units of annual sawmill operating expenditure divided by the capital price.

[i]We model half the cellulosic ethanol production as derived from agricultural cellulosic feedstock (switchgrass) and half from forestry cellulosic feedstock (mill residues). These values represent the necessary amount of feedstock required to produce those levels in accordance with the conversion factors in Sims et al. (2010).
[j]Equal to the 2014 RFS mandated level of cellulosic ethanol multiplied by each state's share of national petroleum consumption.
[k]The sum of total value from agriculture and forestry sectors by state.
[l]Annual tractor rental rate.
[m]The final blended fuel price is the 2012 average retail gasoline price for the Western United States less California.

Table 3—Optimal Taxes, Changes in Fuel Production and Welfare

	State		
	WA	OR	ID
Optimal taxes ($/gallon)			
Revenue unconstrained			
Crude oil	$0.74	$0.92	$0.35
Cellulosic ethanol	$0.51	$0.23	$0.12
Revenue-neutral $(T = 0)$			
Crude oil	$0.00006	$0.00012	$0.00050
Cellulosic ethanol	-$0.41	-$0.68	-$1.28
Fuel production (% change)			
Revenue unconstrained			
Blended fuel	-12.5%	-15.1%	-6.9%
Cellulosic ethanol	-15.4%	-14.2%	-0.8%
Revenue-neutral $(T = 0)$			
Crude oil	-0.0007%	-0.0017%	-0.0087%
Cellulosic ethanol	28.5%	59.8%	238.4%
Welfare (% change)			
Revenue unconstrained	0.29%	0.49%	0.13%
Revenue-neutral (T = 0)	0.00006 %	0.00020 %	0.0010%

Table 4—Elasticity of Substitution Robustness

Sector	$\sigma = 0.01$				$\sigma = 0.99$			
	Revenue unconstrained		Revenue constrained ($T = 0$)		Revenue unconstrained		Revenue constrained ($T = 0$)	
	$\tilde{\tau}^o$	$\tilde{\tau}^c$	$\hat{\tau}^o$	$\hat{\tau}^c$	$\tilde{\tau}^o$	$\tilde{\tau}^c$	$\hat{\tau}^o$	$\hat{\tau}^c$
Cellulosic refining sector								
Total	0.7401	0.5105	0.0000639	-0.4103	0.7402	0.5100	0.0000639	-0.4102
	(0.0001)	(0.0005)	(0.0000039)	(-0.0003)	(0.0002)	(0.0000)	(0.0000039)	(-0.0002)
Labor/capital	0.7405	0.5104	0.0000569	-0.4101	0.7403	0.5102	0.0000644	-0.4100
	(0.0005)	(0.0003)	(-0.0000031)	(-0.0001)	(0.0003)	(0.0002)	(0.0000044)	(0.0000)
Blended fuel sector								
Total	0.7395	0.5104	0.0000643	-0.4103	0.7398	0.5102	0.0000641	-0.4104
	(-0.0005)	(0.0004)	(0.0000043)	(-0.0003)	(-0.0002)	(0.0002)	(0.0000041)	(-0.0004)
Labor/capital	0.7405	0.5096	0.0000551	-0.4104	0.7397	0.5102	0.0000637	-0.4103
	(0.0005)	(-0.0004)	(-0.000004)	(-0.0004)	(-0.0003)	(0.0001)	(0.0000037)	(-0.0003)
Composite good sector	0.7404	0.5104	0.0000585	-0.4102	0.7397	0.5098	0.0000610	-0.4096
	(0.0004)	(0.0004)	(-0.0000015)	(-0.0002)	(-0.0003)	-(0.0002)	(0.0000010)	(0.0004)

Notes: Values represent optimal crude oil and cellulosic ethanol taxes/subsidies, for two different elasticity of substitution assumptions and for both revenue constrained $T = 0$ and unconstrained cases. Values in parentheses represent the change from the optimal tax/subsidy for each case. All values are expressed in $/gallon. When the elasticity of substitution in each sector is altered, the remaining sectors retain their default assumption of 0.05.

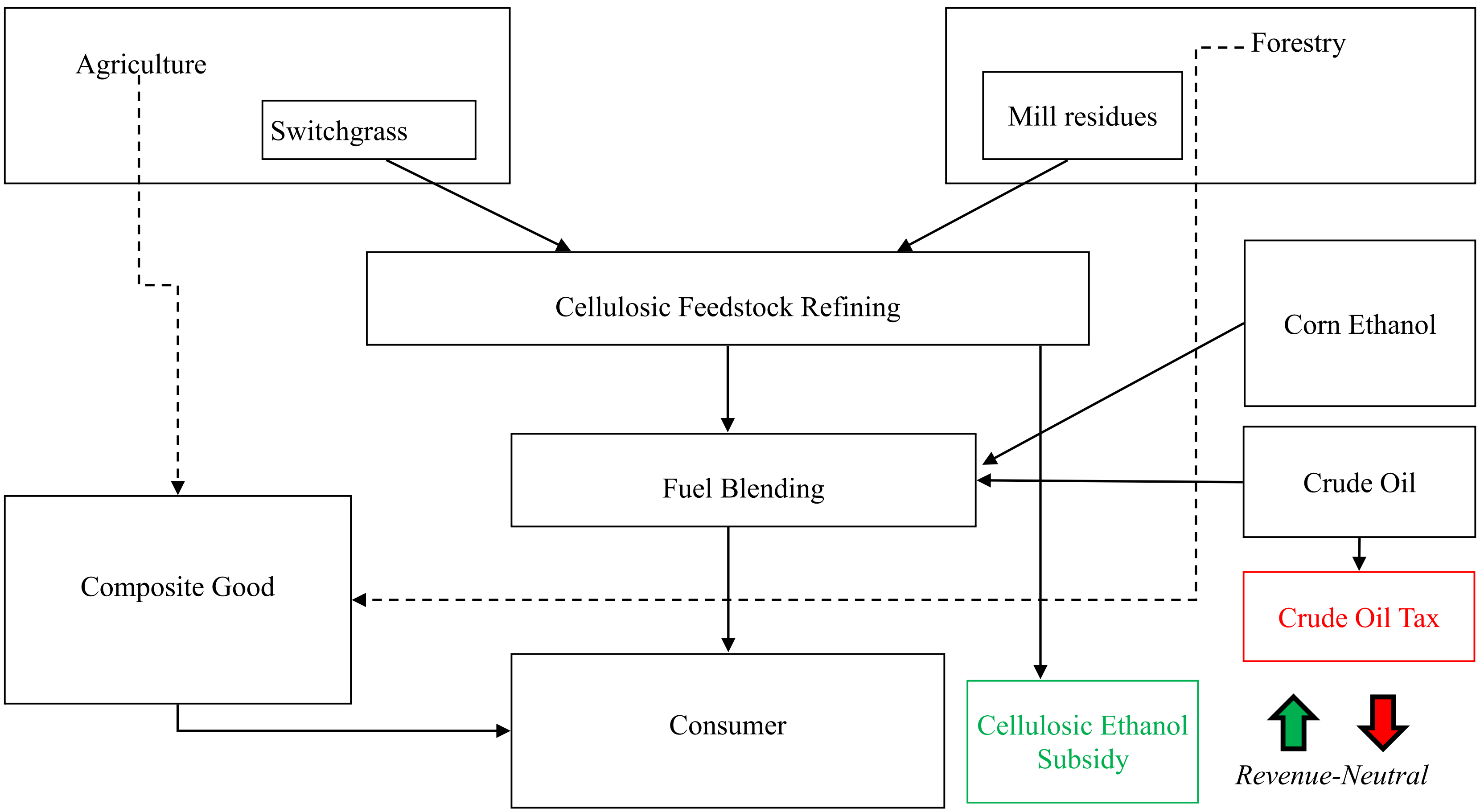

Figure 1. Sectoral Connections in the Production and Consumption of Cellulosic Ethanol

Appendix

A.1 Derivation of the optimal revenue-unconstrained tax

In the revenue-unconstrained case, the social planner's optimization problem is given by:

(1) $$\max_{\{\tau^c,\tau^o\}} \Omega = A + \pi^b + \tau^c Y^c + \tau^o Y^o + W - \delta E,$$

and the associated first-order conditions are given by:

(2) $$\Omega_{\tau^k} = A_{\tau^k} + \pi^b_{\tau^k} + Y^k + \tau^k Y^k_{\tau^k} + \tau^l Y^l_{\tau^k} + W_{\tau^k} - \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k}) = 0, \text{ for } k = c, o \text{ s.t. } k \neq l.$$

From the envelope theorem, we have that $\partial \pi^b / \partial \tau^k = -Y^k$ for $k = c, o$ s.t. $k \neq l$. Solving for τ^k yields:

(3) $$\tau^k = \frac{1}{Y^k_{\tau^k}}\left(-\tau^l Y^l_{\tau^k} - W_{\tau^k} - A_{\tau^k} + \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k})\right), \text{ for } k = c, o \text{ s.t. } k \neq l.$$

Simultaneously solving the system of two equations:

(4) $$\begin{aligned}
\tau^k &= \frac{1}{Y^k_{\tau^k}}\left\{-Y^l_{\tau^k}\left[\frac{1}{Y^l_{\tau^l}}\left(-\tau^k Y^k_{\tau^l} - W_{\tau^l} - A_{\tau^l} + \delta(e^l Y^l_{\tau^l} + e^k Y^k_{\tau^l})\right)\right]\right.\\
&\qquad \left. - W_{\tau^k} - A_{\tau^k} + \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k})\right\} \Rightarrow\\
\tau^k\left(1 - \frac{Y^l_{\tau^k} Y^k_{\tau^l}}{Y^k_{\tau^k} Y^l_{\tau^l}}\right) &= -\frac{Y^l_{\tau^k}}{Y^k_{\tau^k} Y^l_{\tau^l}}\left(-W_{\tau^l} - A_{\tau^l} + \delta(e^l Y^l_{\tau^l} + e^k Y^k_{\tau^l})\right)\\
&\qquad + \frac{1}{Y^k_{\tau^k}}\left(-W_{\tau^k} - A_{\tau^k} + \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k})\right), \text{ for } k = c, o \text{ s.t. } k \neq l.
\end{aligned}$$

Further simplification yields:

$$\tau^k = -\left(\frac{Y^k_{\tau^k}Y^l_{\tau^l}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\right)\frac{Y^l_{\tau^k}}{Y^k_{\tau^k}Y^l_{\tau^l}}\left(-W_{\tau^l} - A_{\tau^l} + \delta(e^l Y^l_{\tau^l} + e^k Y^k_{\tau^l})\right)$$

$$+\left(\frac{Y^k_{\tau^k}Y^l_{\tau^l}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\right)\frac{1}{Y^k_{\tau^k}}\left(-W_{\tau^k} - A_{\tau^k} + \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k})\right) \Rightarrow$$

$$\tau^k = -\frac{Y^l_{\tau^k}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\left(-W_{\tau^l} - A_{\tau^l} + \delta(e^l Y^l_{\tau^l} + e^k Y^k_{\tau^l})\right)$$

$$+\left(\frac{Y^l_{\tau^l}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\right)\left(-W_{\tau^k} - A_{\tau^k} + \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k})\right) \Rightarrow$$

$$\tau^k = \delta e^k\left(-\frac{Y^l_{\tau^k}Y^k_{\tau^l}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}} + \frac{Y^l_{\tau^l}Y^k_{\tau^k}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\right)$$

$$+\delta e^l\left(-\frac{Y^l_{\tau^k}Y^l_{\tau^l}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}} + \frac{Y^l_{\tau^l}Y^l_{\tau^k}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\right)$$

(5)
$$-\frac{Y^l_{\tau^k}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\left(-W_{\tau^l} - A_{\tau^l}\right) + \left(\frac{Y^l_{\tau^l}}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\right)\left(-W_{\tau^k} - A_{\tau^k}\right), \text{ for } k = c,o \text{ s.t. } k \neq l.$$

We can simplify the last expression to write τ^k as:

(6)
$$\tau^k = \delta e^k + \frac{1}{Y^k_{\tau^k}Y^l_{\tau^l} - Y^l_{\tau^k}Y^k_{\tau^l}}\left(Y^l_{\tau^k}\left(W_{\tau^l} + A_{\tau^l}\right) - Y^l_{\tau^l}\left(W_{\tau^k} + A_{\tau^k}\right)\right), \text{ for } k = c,o \text{ s.t. } k \neq l.$$

The reader can verify that if consumer surplus and waiver expenditures were determined exogenously, i.e. $W_{\tau^k} = 0$ and $A_{\tau^k} = 0$, the expression for τ^k would reduce to the Pigouvian expression, $\tau^k = \delta e^k$.

A.2 Derivation of the optimal revenue-neutral tax

In the revenue-neutral case, the objective function is given by:

(7)
$$\max_{\{\tau^c,\tau^o\}} \Omega = A + \pi^b + \tau^c Y^c + \tau^o Y^o + W - \delta E,$$
$$\text{s.t. } T = \tau^c Y^c + \tau^o Y^o,$$

with corresponding Lagrangian:

(8) $$\mathrm{L} = A + \pi^b + \tau^c Y^c + \tau^o Y^o + W - \delta E + \lambda(T - \tau^c Y^c - \tau^o Y^o).$$

The first-order conditions are:

(9) $$\begin{aligned} \mathrm{L}_{\tau^k} &= A_{\tau^k} + \pi^b_{\tau^k} + Y^k + \tau^k Y^k_{\tau^k} + \tau^l Y^l_{\tau^k} + W_{\tau^k} - \delta(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k}) \\ &\quad - \lambda(\tau^k Y^k_{\tau^k} + Y^k + \tau^l Y^l_{\tau^k}) = 0, \text{ for } k = c, o \text{ s.t. } k \neq l, \\ \mathrm{L}_\lambda &= T - \tau^c Y^c - \tau^o Y^o. \end{aligned}$$

Solving for τ^k as a function of λ gives us:

(10) $$\tau^k = \frac{1}{(1-\lambda) Y^k_{\tau^k}} \left(-\tau^l Y^l_{\tau^k}(1-\lambda) - W_{\tau^k} - A_{\tau^k} - \lambda Y^k + \delta\left(e^k Y^k_{\tau^k} + e^l Y^l_{\tau^k} \right) \right),$$
for $k = c, o$ s.t. $k \neq l$.

Similar to the previous derivation, we simultaneously solve the system in (10) to obtain:

(11) $$\tau^k = \frac{\delta}{1-\lambda} e^k + \frac{1}{Y^k_{\tau^k} Y^l_{\tau^l} - Y^k_{\tau^l} Y^l_{\tau^k}} \left(Y^l_{\tau^k} \frac{W_{\tau^l} + A_{\tau^l} - \lambda Y^l}{1-\lambda} - Y^l_{\tau^l} \frac{W_{\tau^k} + A_{\tau^k} - \lambda Y^k}{1-\lambda} \right),$$
for $k = c, o$ s.t. $k \neq l$.

To derive the optimal value of λ, we substitute the previous equation into the revenue constraint and solve for λ:

(12) $$\begin{aligned} T(1-\lambda) &= Y^o \left(\delta e^o + \frac{1}{Y^o_{\tau^o} Y^c_{\tau^c} - Y^o_{\tau^c} Y^c_{\tau^o}} \left(Y^c_{\tau^o} \left(W_{\tau^c} + A_{\tau^c} - \lambda Y^c \right) - Y^c_{\tau^c} \left(W_{\tau^o} + A_{\tau^o} - \lambda Y^o \right) \right) \right) \\ &\quad + Y^c \left(\delta e^c + \frac{1}{Y^c_{\tau^c} Y^o_{\tau^o} - Y^c_{\tau^o} Y^o_{\tau^c}} \left(Y^o_{\tau^c} \left(W_{\tau^o} + A_{\tau^o} - \lambda Y^o \right) - Y^o_{\tau^o} \left(W_{\tau^c} + A_{\tau^c} - \lambda Y^c \right) \right) \right). \end{aligned}$$

Solving for λ:

$$T(1-\lambda)=\frac{\lambda}{Y^o_{\tau^o}Y^c_{\tau^c}-Y^o_{\tau^c}Y^c_{\tau^o}}\left(Y^o\left(Y^c_{\tau^c}Y^o-Y^cY^c_{\tau^o}\right)+Y^c\left(Y^o_{\tau^o}Y^c-Y^oY^o_{\tau^c}\right)\right)$$

(13)

$$+Y^o\left(\delta e^o+\frac{1}{Y^o_{\tau^o}Y^c_{\tau^c}-Y^o_{\tau^c}Y^c_{\tau^o}}\left(Y^c_{\tau^o}\left(W_{\tau^c}+A_{\tau^c}\right)-Y^c_{\tau^c}\left(W_{\tau^o}+A_{\tau^o}\right)\right)\right)$$

$$+Y^c\left(\delta e^c+\frac{1}{Y^c_{\tau^c}Y^o_{\tau^o}-Y^c_{\tau^o}Y^o_{\tau^c}}\left(Y^o_{\tau^c}\left(W_{\tau^o}+A_{\tau^o}\right)-Y^o_{\tau^o}\left(W_{\tau^c}+A_{\tau^c}\right)\right)\right).$$

Simplifying the previous expression and isolating λ:

(14)

$$\lambda^*(T)=\frac{T-\left(Y^o\delta e^o+Y^c\delta e^c\right)-\dfrac{\left(W_{\tau^c}+A_{\tau^c}\right)\left(Y^oY^c_{\tau^o}-Y^o_{\tau^o}Y^c\right)+\left(W_{\tau^o}+A_{\tau^o}\right)\left(Y^cY^o_{\tau^c}-Y^c_{\tau^c}Y^o\right)}{Y^o_{\tau^o}Y^c_{\tau^c}-Y^o_{\tau^c}Y^c_{\tau^o}}}{T+\dfrac{Y^o\left(Y^c_{\tau^c}Y^o-Y^cY^c_{\tau^o}\right)+Y^c\left(Y^o_{\tau^o}Y^c-Y^oY^o_{\tau^c}\right)}{Y^o_{\tau^o}Y^c_{\tau^c}-Y^o_{\tau^c}Y^c_{\tau^o}}}.$$

A.3 Derivative of consumer surplus with respect to τ^k

We can write the derivative of consumer surplus with respect to τ^k in the following way:

(15)

$$\begin{aligned}
\frac{\partial A}{\partial\tau^k}&=\frac{\partial}{\partial\tau^k}\left(v(p^b(\tau^k,\tau^l),I)-p^b(\tau^k,\tau^l)B(\tau^k,\tau^l)-X(\tau^k,\tau^l)\right)\\
&=\frac{\partial}{\partial\tau^k}\left(u\left(B(\tau^k),X(\tau^k)\right)-p^b(\tau^k)B(\tau^k)-X(\tau^k)\right)\\
&=u_B\frac{\partial B}{\partial\tau^k}+u_X\frac{\partial X}{\partial\tau^k}-p^b\frac{\partial B}{\partial\tau^k}-\frac{\partial p^b}{\partial\tau^k}B-\frac{\partial X}{\partial\tau^k}\\
&=\left(u_B-p^b\right)\frac{\partial B}{\partial\tau^k}+\left(u_X-1\right)\frac{\partial X}{\partial\tau^k}-B\frac{\partial p^b}{\partial\tau^k}\\
&=-B\frac{\partial p^b}{\partial\tau^k},\ \text{for } k=c,o.
\end{aligned}$$