



The Impact of Feedstock Supply and Petroleum Price Variability on Domestic Biofuel and Feedstock Markets – The Case of the United States

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Summary

The promotion of biofuel use in preference to traditional petroleum-based transportation fuel has linked agricultural commodity markets and energy markets more closely together. Biofuel policies can involve multiple policy instruments, but studies examining their effects on biofuel feedstock and energy markets are scarce. In addition, the impact of alternative policy approaches in the context of variability in petroleum prices and the supply of biofuel feedstock has received limited attention.

Focusing on the current situation in the United States, in which prohibitively high duties prevent imports of ethanol, this paper examines how variability in the price of petroleum and corn supply affects domestic market variability under three types of domestic policies, inclusive of their combinations, for promoting the use of ethanol: 1) the provision of a fixed subsidy (tax credit) for blending ethanol with gasoline; 2) the use of a blending mandate; and 3) the use of a consumption mandate. Varying relative variability in petroleum price and corn supply, we analyze numerically the implications of changes in domestic biofuel policy for variability (measured by the coefficient of variation) in ethanol use and corn prices. We also provide some brief insights into the design of market stabilization policies.

Results obtained from Monte Carlo simulations show that in the absence of mandates the quantity of ethanol used under a subsidy policy is highly susceptible to fluctuations in oil prices and corn supply, providing that there are no constraints to adjustment in ethanol demand. The impact of oil price fluctuations on the price of corn is large, but corn supply fluctuations have no or a small impact on the equilibrium corn price, depending on the flexibility of the use of corn in ethanol refining. This is because variations in ethanol volume absorb shocks caused by corn supply fluctuations. Consequently, high fluctuations in the price of petroleum are expected to result in high variability in the corn price in the absence of mandates.

With a mandate (with or without a subsidy), as the likelihood that the mandate becomes binding increases, variability in ethanol use declines, the impact of variations in petroleum price on corn prices is reduced, and the impact of variations in corn supply on prices is accentuated. Therefore, if the mandate is likely to be binding, high fluctuations in corn supply are expected to result in high variability in the corn price. If the likelihood that ethanol use exceeds the mandated level is high, the effects are similar to those in the absence of a mandate. The effects of changes in biofuel policy, such as a reduction in the level of tax credit under a mandate and an increase in its level, on the price of corn depend on the relative magnitudes of world oil price and domestic corn supply fluctuations.

Keywords: Biofuels, subsidies, mandates, variability

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1. Introduction

Many countries that currently rely on imports of petroleum for liquid fuels have increased their focus on biofuels in order to pursue a range of goals, including a reduction in greenhouse gas emissions, enhancement of energy security, improvement in local air quality, and rural development. Governments have generally intervened in the domestic market to promote the consumption and production of biofuels because in most cases the biofuel industry would not have developed without support (Tyner & Taheripour, 2008). Among the alternatives, a subsidy (tax exemption or tax credit) for the production or consumption of biofuels and blending or consumption mandates are the most prominent instruments (de Gorter & Just, 2007; Jull *et al.*, 2007; Kojima *et al.*, 2007; Rothkopf, 2007). Although some countries do not use subsidies or mandates, most major economies, such as Brazil, EU, the United States, and China, have implemented both. Consequently, it is important to investigate how such policy instruments (particularly in combination) affect biofuel, feedstock and gasoline markets (Jank *et al.*, 2007; Steenblik, 2007a, 2007b). Examining the implications of the linkage between feedstock and energy markets is essential because the increasing use of agricultural resources in energy production links these markets more closely together (Tyner & Taheripour, 2008). There has been considerable debate about biofuel policy design and its impact on agricultural markets and the environment².

Although domestic biofuel policies typically involve multiple policy instruments, the literature on their implications for feedstock and energy markets is scarce. Through a series of papers, de Gorter and Just (2007, 2009a) analyze multiple policy instruments (tax exemption or tax credits and blending or consumption mandates) simultaneously using a partial equilibrium model. They assess the economic effects of a blending or consumption mandate and an excise-tax credit, and their interaction effects in the context of the U.S. fuel market. FAPRI (2009) provides a numerical analysis of the implications of hypothetical changes in U.S. ethanol policies, inclusive of an ethanol mandate, tax credits, and import tariffs.

In addition to the scarcity of literature examining combinations of policy instruments, the implications of alternative policy approaches in the context of fluctuations in petroleum prices and the supply of feedstock has received limited attention. Most existing studies

² A host of studies have assessed the impact of biofuel programs on agricultural and fuel markets and on social welfare, using either partial or general equilibrium analysis (Lundgren *et al.*, 2008). Several studies have concluded that biofuel policies can have unintended economic consequences (Vedenov & Wetzstein, 2008; Khanna *et al.*, 2008). Despite such criticisms it seems inevitable that for political reasons biofuels will play an important role in future energy policies in many countries.

assume that the relevant economic functions are known with certainty and are stable. In reality, however, key factors such as the position of the feedstock supply curve and the level of world oil prices are likely to be variable. McPhail and Babcock (2008) use a stochastic partial equilibrium model to examine the effect of U.S. ethanol expansion and mandates on price risk for corn. Using output from a partially stochastic simulation Thompson *et al.* (2009) examine how variations in corn yield and the petroleum price affect corn price, ethanol price and ethanol use with and without a mandate in the United States. Despite these contributions, the impact of alternative biofuel policy instruments on variability in biofuel and feedstock markets has not been comprehensively evaluated.

Focusing on the current situation in the United States, in which prohibitively high duties prevent imports of ethanol, this article examines how fluctuations in the price of petroleum and domestic corn supply affect U.S. market variability under three types of domestic policies, inclusive of their combinations, for promoting the use of ethanol: 1) the provision of a fixed subsidy (tax credit) for blending ethanol with gasoline; 2) the use of a blending mandate; and 3) the use of a consumption mandate. By varying relative variability in petroleum price and corn supply we analyze numerically the implications of changes to domestic biofuel policy for variability (measured by the coefficient of variation) in ethanol use and corn prices³. We also provide some brief insights into the design of market stabilization policies.

Five key domestic variables are likely to be affected by these policies: the quantity of ethanol used, the price of corn, the price of blended fuel (the ethanol supply price), blended fuel use, and gasoline use. We focus on two of these variables: the corn price and ethanol use. Variability in corn prices is likely to have significant domestic implications through negative impacts on the agriculture industry or even the whole economy (Newbery & Stiglitz, 1981; Grega, 2002). Additionally, increased variability in corn prices in a large country like the U.S. could have important international implications (Elobeid & Hart, 2007; Muhammad & Kebede, 2009). High variability in biofuel use may have a negative impact on the biofuel industry by creating periods of boom and bust, causing episodes of bankruptcy and reduced capital investment, such as observed in the U.S. in 2007-2008 (Hochman *et al.*, 2008).

³ We do not consider storage policies for petroleum or feedstock (corn). We also assume that corn for ethanol has alternative uses, such as for food or livestock feed. Moreover, we exclude extreme cases where subsidies and/or mandates are not needed to achieve biofuel goals, i.e., a persistently high gasoline price relative to the marginal cost of biofuel production, or a persistently low marginal cost of biofuel production relative to the gasoline price.

Our results show that as the probability that the biofuel mandate becomes binding increases (the probability of binding mandates is zero in the absence of mandate), variability in ethanol use declines, the impact of fluctuations in petroleum price on corn prices is reduced, and the impact of fluctuations in corn supply on corn prices is accentuated. Thus, the effects of changes in U.S. domestic biofuel policy, such as a reduction in the level of tax credit under mandates and an increase in the level (the imposition) of mandate, on the price of corn rely on the relative magnitudes of fluctuations in world oil prices and domestic corn supply.

The paper is organized as follows. The next section defines the linkage between corn and energy markets, and considers how variability can be introduced into these. In section 3 we present analytical models to show how variations in the world oil price and domestic corn supply affect energy and corn markets under different policy alternatives, and discuss a theoretical comparison of policies in terms of ethanol use and corn price variability. Monte Carlo simulation results are discussed in section 4. On the basis of our findings we provide some brief insights into the design of market stabilization policies in section 5. The final section provides some concluding remarks.

2. Basic Framework

To investigate the impact of variability in the petroleum price and domestic corn supply on corn and energy markets in the United States, we first need to define the linkage between these and how variability can be introduced into the markets. Throughout this paper we assume that prohibitively high import duties prevent trade in ethanol, and that all domestic consumption is sourced from domestic production⁴. We begin with the static model presented by de Gorter and Just (2008a) employing nonlinear supply and demand curves. We then introduce variability into this model. The impact of biofuel policies is investigated in the following section.

2.1 *The Linkage between Corn and Energy Markets*

Consider a competitive market with an aggregate supply curve for corn S_C and an aggregate non-ethanol demand for corn D_{NE} (including domestic food and livestock feed demand, and foreign demand for corn). Any market returns to ethanol by-products (e.g.,

⁴ This parallels the current situation in the United States.

distillers' grains) are assumed to be reflected in the demand curve. Assuming constant returns to scale, the supply of ethanol S_E is derived from the horizontal difference (excess supply) between S_C and D_{NE} . Therefore, their intersection represents the equilibrium corn price without ethanol production, p_{NE} , and this defines the intercept of the ethanol supply curve (see figure 1)⁵.

Following de Gorter and Just we assume an exogenous petroleum price⁶ and perfect substitutability between ethanol and fossil fuel⁷. Suppose the energy market is also competitive. Let S_G denote the supply curve for gasoline (perfectly elastic) and p_G the gasoline price, which is the sum of the petroleum price and an excise fuel tax. The demand for liquid transportation (mixed) fuel is denoted by D_{MF} . Total fuel consumption Q_{MF} is determined at the intersection of S_G and D_{MF} (if there is no ethanol production, gasoline accounts for all liquid fuel usage). The intercept of the ethanol supply curve is assumed to be higher than the price of oil (the gasoline price minus the tax) in line with the historical pattern of oil prices relative to the cost of corn in the United States. Thus, if there are no biofuel policy measures the quantity of ethanol produced and consumed is zero.

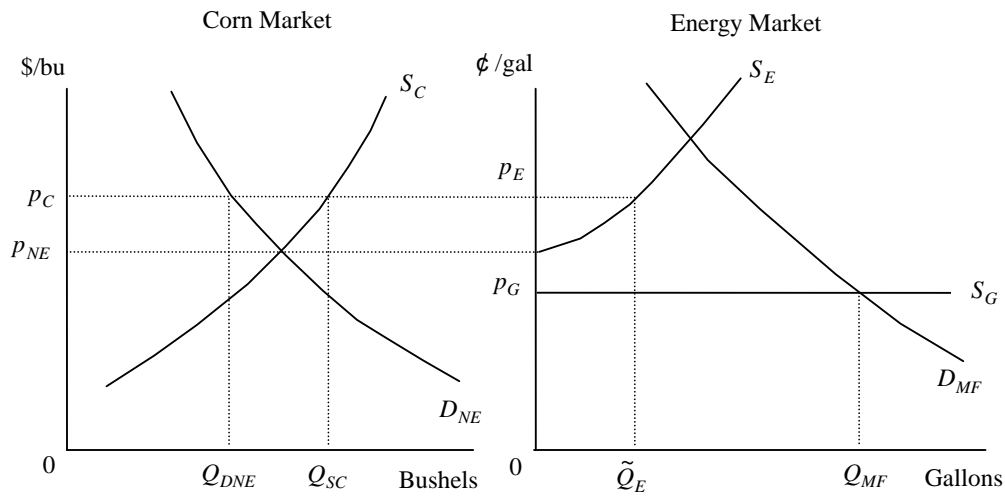


Figure 1: The linkage between corn and energy markets

⁵ Note that ethanol processing costs are ignored in figure 1.

⁶ Since the current share of ethanol in total fuel use is small, the assumption of an exogenous petroleum price is reasonable. Even if the world oil price is endogenous, our principal conclusions are expected to be robust.

⁷ It is unlikely that consumers can choose the blend ratio flexibly. Of course, changes in the vehicle fleet to "flex fuel" vehicles will make such choice possible in the future in the United States, as is currently the case in Brazil. But even if ethanol and gasoline are imperfect substitutes, variation in ethanol use is strongly related to variation in the price of gasoline, so relaxing this assumption will not affect our results.

Suppose the actual quantity of ethanol use is \tilde{Q}_E , the market (supply) price for ethanol, p_E , is determined by the supply curve for ethanol. The corn price is determined at p_C which is directly linked to p_E . Since any market returns to ethanol by-products are reflected in the demand curve, $Q_{SC} - Q_{DNE}$ represents the net removal of corn for ethanol production. The relationship between the corn price and the ethanol price is:

$$p_C = \left(\frac{k}{1-\tau} \right) p_E - c. \quad (1)$$

where k represents gallons of ethanol produced from one bushel of corn, τ is the proportion of the value of corn returned to the market in the form of by-products, and c is processing costs. According to de Gorter and Just (2008a, 2009b), the estimate of $k/(1-\tau)$ for corn in the United States is 4.06, which means that the corn price is very sensitive to a change in the price of ethanol.

2.2 Variability in the Petroleum Price and Domestic Corn Supply

Because we assume that the petroleum price is exogenous, the inverse supply curve for oil is perfectly elastic. The stochastic oil price is expressed as: $p_o = \bar{p}_o + \lambda$, where \bar{p}_o is the expected petroleum price and λ is a random variable with mean zero and variance σ_λ^2 . Thus, the inverse supply curve for oil (gasoline) shifts up or down according to the value of the stochastic component.

Introducing variability into corn supply is far more complicated because we need to take account of how such variability (assuming non-ethanol corn demand is fixed) affects the equilibrium price of corn in the absence of ethanol production, and consequently derive the inverse supply curve for ethanol. For simplicity, we use constant elasticity supply and demand functions for corn, and assume that output is log-normally distributed (Newbery & Stiglitz, 1981). If aggregate supply and demand elasticities are known, we can obtain the coefficient of variation of the intercept of the inverse ethanol supply curve. We assume that the annual inverse supply curve for ethanol has a constant coefficient of variation with respect to the ethanol supply price p_E whatever the level of ethanol production. In other words, multiplicative shifts in supply are assumed. Additionally, we assume that there is no technological change and that non-ethanol corn demand is fixed in the short-run.

Let the constant elasticity (non-ethanol) corn demand function be:

$$Q_{DC} = Ap^\varepsilon, \varepsilon < 0, \quad (2)$$

and let the constant elasticity of corn supply be:

$$Q_{SC} = Bp^\eta, \eta > 0, \quad (3)$$

where p is corn price. Suppose that the sole source of variation is on the supply side, and that output is log-normally distributed. The inverse corn supply function can be written as:

$$p = (Q_{SC} / B)^{1/\eta}, Q_{SC} = \bar{Q}_{SC}\theta, E\theta = 1, \text{Var}\theta \cong \sigma_\theta^2, CV_{Q_{SC}} \cong \sigma_\theta. \quad (4)$$

By solving $Q_{DC} = \bar{Q}_{SC}$ we have:

$$p_{NE} = (A/B)^{\frac{1}{\eta-\varepsilon}} \theta^{\frac{1}{\eta-\varepsilon}}. \quad (5)$$

Therefore, variation in the annual equilibrium price of corn in the absence of ethanol production depends on the demand and supply elasticities (ε and η). In that case the coefficient of variation of corn price without ethanol production can be written as⁸:

$$CV_{p_{NE}} \cong \frac{\sigma_\theta}{\eta - \varepsilon}. \quad (6)$$

As the demand curve (and/or supply curve) becomes more inelastic, the coefficient of variation of the corn price in the absence of ethanol production increases. For example, the dotted demand curve D'_{NE} in figure 2 is more inelastic than that in the initial state, and variation in the corn price becomes higher given variation in corn supply.

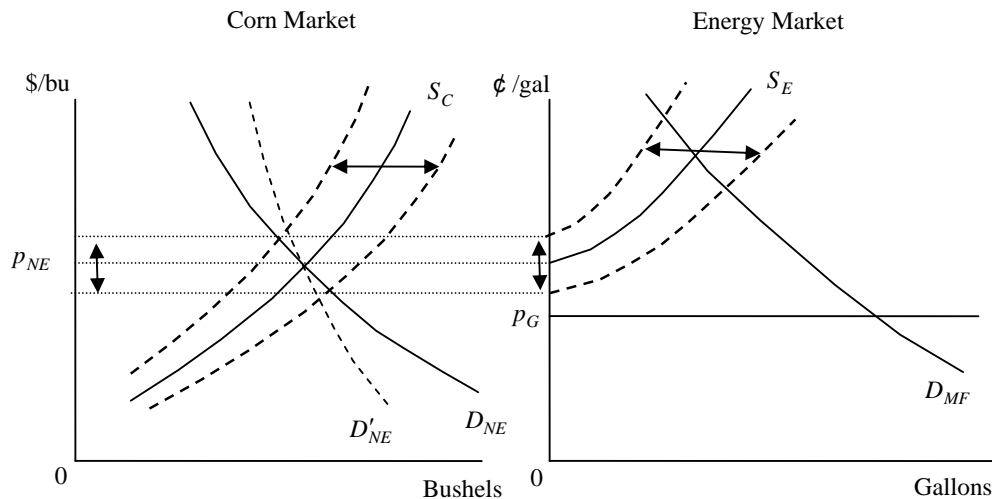


Figure 2: Corn supply variability and shifts in ethanol supply

⁸ For a proof of equation (6), see appendix A.

To find the coefficient of variation of p_E given the quantity of ethanol used, we use the relationship in equation (1)⁹:

$$CV_{p_E} = \frac{\sigma_\theta}{\eta - \varepsilon} \frac{(Ep_E - (1 - \tau)c/k)}{Ep_E}. \quad (7)$$

In the subsequent numerical simulations we specify the variance of a random variable associated with corn supply using (7). How variability in corn supply affects the ethanol supply curve under our assumptions is shown in figure 2.

3. Biofuel Policies and Impacts of Variability

On the basis of the model presented in the previous section we can examine the impact of the three types of biofuel policies on U.S. market variability. First, we examine the case in which a fixed tax credit per gallon is granted to blenders. Second, we consider the use of such a subsidy in combination with a blending mandate which requires a minimum share of ethanol be used in all fuel sold. Finally, we consider the combination of a tax credit and a consumption mandate which requires a minimum amount of ethanol be used. We assume that blenders meet the required level of ethanol use under binding mandates by adjusting the mixed fuel price¹⁰. For convenience in the remainder of the paper, we refer to the three policy alternatives as: 1) BS for the fixed biofuel subsidy (tax credit); 2) BMS for the blending mandate plus subsidy; and 3) CMS for the consumption mandate plus subsidy. The use of a mandate without a subsidy is considered as a special case.

3.1 The Biofuel Subsidy (BS)

In this case a subsidy (tax credit) to blenders is the sole biofuel policy instrument. Let us first consider the implications in the absence of variability. We assume that a given per gallon excise tax t is imposed on motor fuel. A tax credit per gallon s is provided for ethanol. Hence, the inverse supply curve, inclusive of the tax, shifts downwards by the amount s and biofuel producers bid up the price of ethanol (demand price) to the gasoline price in order to maximize their benefit (de Gorter & Just, 2008a). The quantity of ethanol used Q_E^{BS} is determined where the inverse supply curve, including the tax credit, S'_E , intersects the

⁹ For a proof of equation (7), see appendix B.

¹⁰ We assume that the mandate is fully enforced. Penalties for violation are assumed to be prohibitively high. For a detailed discussion of U.S. biofuel mandates, see Thompson *et al.* (2008).

gasoline price p_G (including the excise tax, i.e., $p_G = p_O + t$). The market price of ethanol (supply price) p_E is determined by the initial ethanol supply curve and equals the price of oil (without tax) plus the tax credit. The market price for mixed fuels is equal to the gasoline price. Total fuel consumption, Q_{MF} , does not change and gasoline is replaced by ethanol by the amount Q_E^{BS} . In this case only blenders gain from the subsidy. It is apparent that as the level of the tax credit increases, ethanol use increases and gasoline use decreases. The market equilibrium with the tax credit is illustrated in figure 3 (for a more detailed discussion see de Gorter & Just, 2008a).

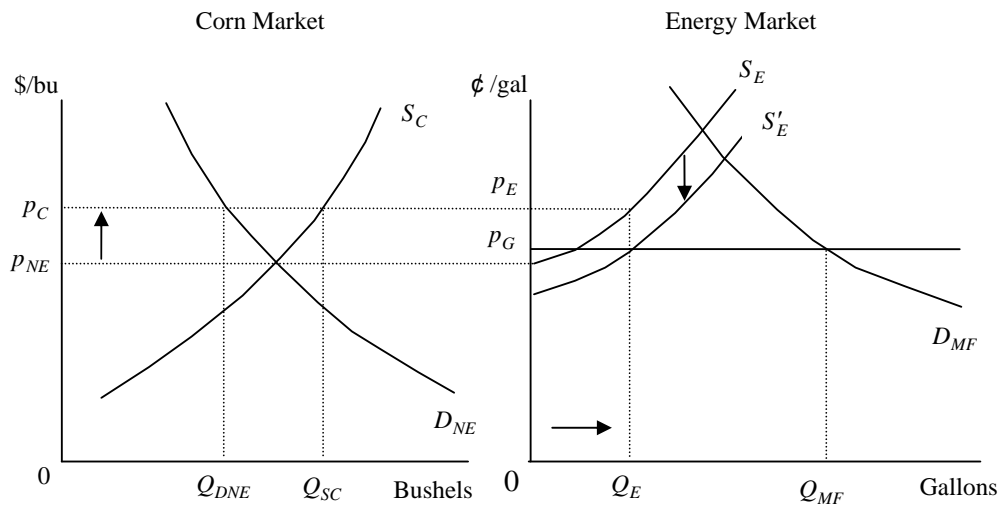


Figure 3: Tax credit

Now consider the effect of fluctuations in the world oil price and domestic corn supply. Both of these affect equilibrium ethanol use, which is positive only if the intercept of the ethanol supply curve, including the tax credit, is greater than the gasoline price. A sufficiently low oil price and/or low corn supply will result in no ethanol production/use. Variability in ethanol use also depends on the elasticity of the inverse supply curve for ethanol. The market price of ethanol (corn price) is influenced by oil price fluctuations, but there is no additional impact from the ethanol market. This is because p_E is always equal to the oil price plus the tax credit. If the oil price increases (decreases), p_E also increases (decreases). If the oil price is unchanged, p_E is also unchanged regardless of the position of the ethanol supply curve. If there are no constraints to adjustment in ethanol demand, variations in ethanol volume absorb corn supply shocks under a competitive market. If changes in ethanol use are less flexible

(e.g., through limited flexibility in the use of corn in ethanol refining), the impact of fluctuations in corn supply on the short-run equilibrium corn price is increased and the impact of oil fluctuations is reduced.

3.2 Blending Mandate with a Subsidy (BMS)

Again let us first consider the static case¹¹. An ethanol blending mandate requires that a minimum share of ethanol $\tilde{\alpha}$ is used in all fuel sold ($0 < \tilde{\alpha} < 1$). The consumer has to pay the weighted average price of ethanol and gasoline (the price of mixed fuel):

$$p_{MF} = \alpha p_E + (1 - \alpha) p_G. \quad (8)$$

Thus, the inverse supply curve for mixed (blended) fuel lies between the ethanol supply curve and the perfectly elastic gasoline supply curve, as shown in figure 4. The equilibrium price and quantity for mixed fuels are determined at the intersection of the mixed fuel supply and demand curves. Given the tax credit and the minimum blend ratio $\tilde{\alpha}$, if $p_{MF}^{BMS}(\tilde{\alpha}, s) \geq p_G$ the mandate is binding, which requires:

$$\tilde{\alpha} S_{MF}(p_{MF}) = S_E(p_E) \text{ and } (1 - \tilde{\alpha}) S_{MF}(p_{MF}) = S_G. \quad (9)$$

A binding mandate imposes ethanol consumption equal to $\tilde{\alpha} D_{MF}(p_{MF})$ for any p_{MF} . Therefore, the quantity of ethanol is $Q_E^{BMS} = \tilde{\alpha} Q_{MF}^{BMS}$. However, if $p_{MF}^{BMS}(\tilde{\alpha}, s) < p_G$, the marginal cost of ethanol production at the required minimum usage is lower than the gasoline price. The mandate is no longer binding because blenders will voluntarily increase the blend ratio beyond the required minimum level and ethanol use will increase up to the point at which its marginal cost equals the gasoline price (note that the quantity of ethanol used in this case equals the equilibrium quantity under BS). Blenders have no incentive to reduce the mixed fuel price below the gasoline price because their benefits from the subsidy are reduced (only oil suppliers would benefit from an increase in gasoline use). Consequently, ethanol use can be written as:

$$Q_E^{BMS} = \begin{cases} Q_E^{BS} & \text{if } p_{MF}^{BMS}(\tilde{\alpha}, s) < p_G \\ \tilde{\alpha} Q_{MF}^{BMS} & \text{if } p_{MF}^{BMS}(\tilde{\alpha}, s) \geq p_G \end{cases}. \quad (10)$$

The market price of ethanol is given by:

$$p_E^{BMS} = \begin{cases} S_E^{-1}(Q_E^{BS}) & \text{if } p_{MF}^{BMS}(\tilde{\alpha}, s) < p_G \\ S_E^{-1}(\tilde{\alpha} Q_{MF}^{BMS}) & \text{if } p_{MF}^{BMS}(\tilde{\alpha}, s) \geq p_G \end{cases}. \quad (11)$$

¹¹ See de Gorter and Just (2009a) for a detailed discussion on the economics of a blending mandate in a static context.

Figures 4 and 5 illustrate the binding mandate and the mandate-exceeded cases, respectively. Given $\tilde{\alpha}$, an increase in the tax credit leads to a downward shift in the mixed fuel supply curve and the mixed fuel price falls (due to competition). This means that as the tax credit increases, the likelihood that the mandate will be exceeded (usage of ethanol will be in excess of the mandated proportion) rises.

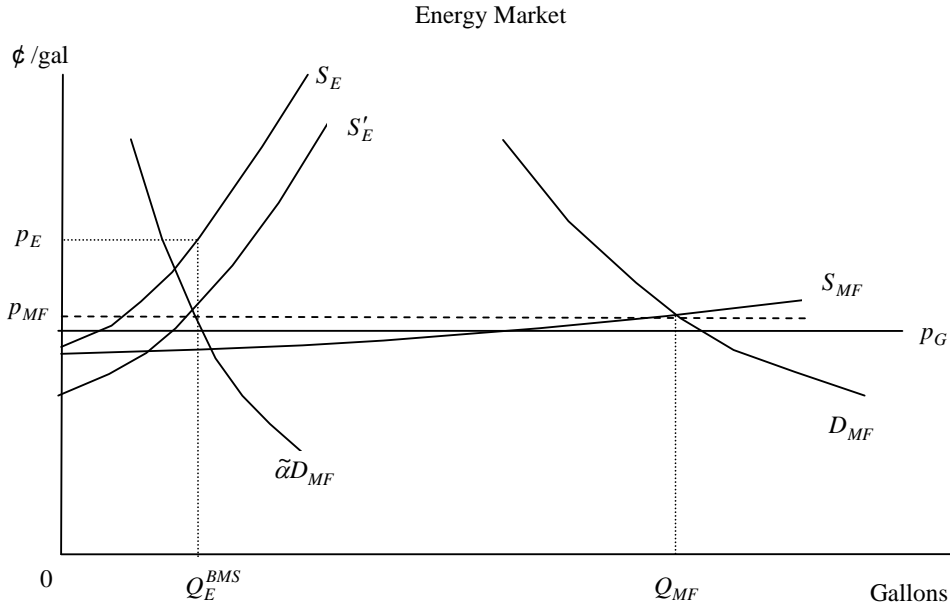


Figure 4: A blending mandate with a tax credit – the binding case

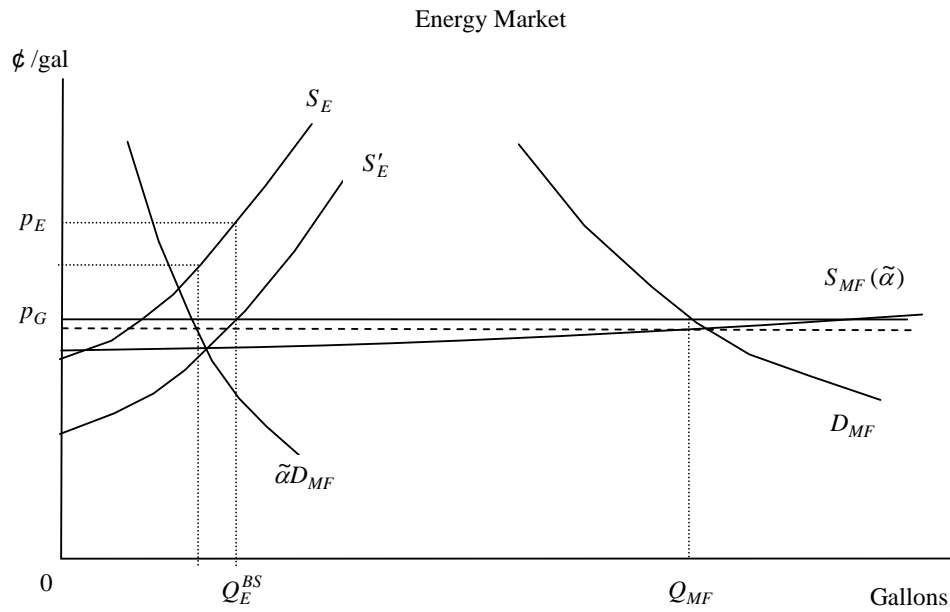


Figure 5: A blending mandate with a tax credit – the mandate is exceeded

Variability in the oil price and corn supply also influence the equilibrium mixed fuel price, and consequently the likelihood that the mandate is binding. If the oil price increases significantly, the mixed fuel price (at the minimum blend ratio) may be lower than the gasoline price and the mandate will be exceeded. The impact of variability in the petroleum price and corn supply on markets depends on whether the mandate is actually binding. To examine this, we consider the binding and non-binding cases separately.

As discussed above, if the mandate is exceeded, the quantity of ethanol used and its price are determined by the intersection of the ethanol supply curve and the gasoline supply curve. Therefore, if the mandate is exceeded, ethanol use absorbs shocks in the oil price and corn supply. The level of the oil price affects the market price of ethanol and hence the corn price.

If the mandate is binding, the quantity of ethanol used is determined by the demand curve for ethanol and the mixed fuel price. Variations in ethanol use depend on the elasticity of demand. Gasoline demand is likely to be inelastic in short-run (see Hughes *et al.* 2008) and ethanol demand is more inelastic than gasoline demand. Therefore, it is to be expected that when the blending mandate is binding, the ethanol demand curve will be highly inelastic. This means that ethanol use is insensitive to changes in the equilibrium mixed fuel price. If that case, changes in the petroleum price and corn supply will result in small variations in ethanol use and the market price of ethanol will absorb most of the variability, in particular, that created by fluctuations in corn supply. If ethanol supply is unchanged and demand is very inelastic, small variations in ethanol use due to changes in the oil price result in small variations in the market price of ethanol. However, if the oil price is unchanged, small variations in ethanol use caused by changes in corn supply lead to large variations in the market price of ethanol because of shifts in the inverse ethanol supply curve. In summary, if the blending mandate is binding and demand is very inelastic, ethanol use has low variability but the variability in corn price is high if fluctuations in corn supply are high.

3.3 Consumption Mandate with a Subsidy (CMS)

A consumption mandate¹² requires a minimum amount of ethanol \hat{Q}_E be used by fuel consumers. In this case, the inverse supply curve for mixed fuels can be written as:

$$p_{MF} = \frac{\hat{Q}_E}{Q_{MF}}(\hat{p}_E + t - s) + \left(1 - \frac{\hat{Q}_E}{Q_{MF}}\right)p_G = \frac{(\hat{p}_E + t - s)\hat{Q}_E + p_G(Q_{MF} - \hat{Q}_E)}{Q_{MF}}, \quad (12)$$

¹² de Gorter and Just (2007) discuss the static case of a consumption mandate.

where $\hat{p}_E = S_E^{-1}(\hat{Q}_E)$. Differentiating equation (12) with respect to Q_{MF} we have:

$$\frac{dp_{MF}}{dQ_{MF}} = -\frac{(\hat{p}_E + t - s - p_G)\hat{Q}_E}{(Q_{MF})^2}. \quad (13)$$

If $\hat{p}_E + t - s > p_G$, the first derivative is negative and the second derivative is positive. Therefore, the supply curve is flat at $\hat{p}_E + t - s$ until \hat{Q}_E is satisfied; it is convex-decreasing in total fuel consumption beyond \hat{Q}_E and asymptotic to the perfectly elastic gasoline supply curve. The mixed fuel price is determined by the intersection of the inverse supply and demand curves for mixed fuels, and is higher than the gasoline price. A consumption mandate is binding if $\hat{p}_E + t - s \geq p_G$ (i.e., the marginal cost of biofuel production with the tax credit at the required minimum level of ethanol use is higher than or equal to the gasoline price including the excise tax). In contrast, if $\hat{p}_E + t - s < p_G$, the mandate will be exceeded because blenders will voluntarily increase ethanol use up to the point at which the inverse ethanol supply with the tax credit intersects the gasoline price (this is the same situation as under BS). The mixed fuel price equals the gasoline price in this case. Ethanol use can be written as:

$$Q_E^{CMS} = \begin{cases} Q_E^{BS} & \text{if } \hat{p}_E + t - s < p_G \\ \hat{Q}_E & \text{if } \hat{p}_E + t - s \geq p_G \end{cases}. \quad (14)$$

The market price of ethanol is given by:

$$p_E^{CMS} = \begin{cases} S_E^{-1}(Q_E^{BS}) & \text{if } \hat{p}_E + t - s < p_G \\ \hat{p}_E & \text{if } \hat{p}_E + t - s \geq p_G \end{cases}. \quad (15)$$

The binding mandate and mandate-exceeded cases are shown in figures 6 and 7. Note that an increase in the tax credit again results in a downward shift in the mixed fuel supply curve and a fall in the mixed fuel price (due to competition). Therefore, as the tax credit increases, the likelihood that the mandate will be exceeded rises.

Again, variability in the oil price and corn supply influence whether the consumption mandate is binding. Consider an initial situation in which the mandate is binding. If the oil price increases significantly, the mandate may cease to be binding (as explained in the previous subsection). Like the BMS case, if the mandate is exceeded, ethanol use absorbs market shocks due to changes in the oil price and corn supply and the level of oil price affects the market price of ethanol (corn price).

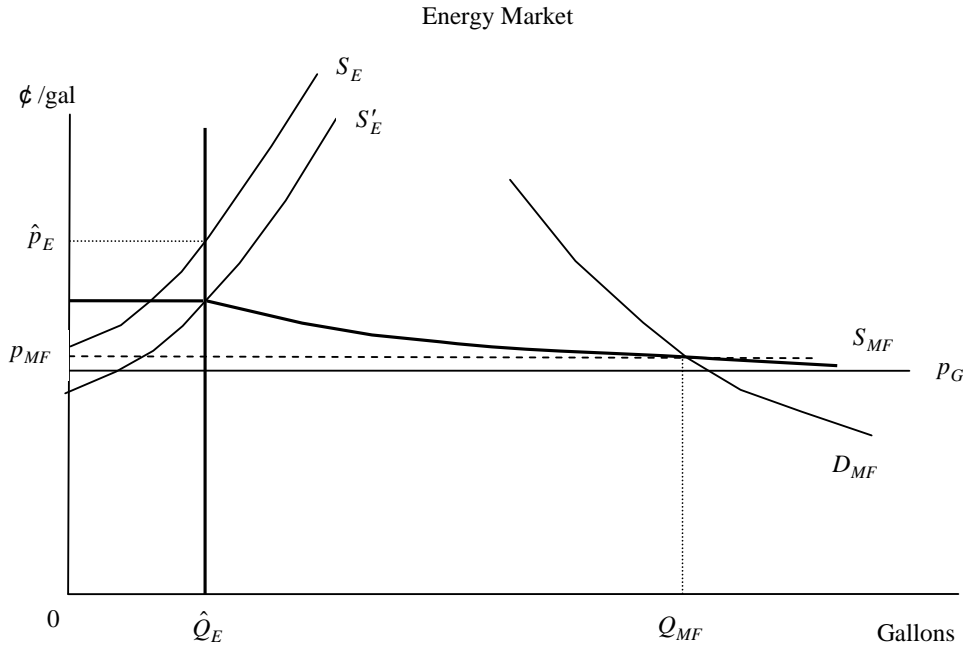


Figure 6: A consumption mandate with a tax credit – the binding case

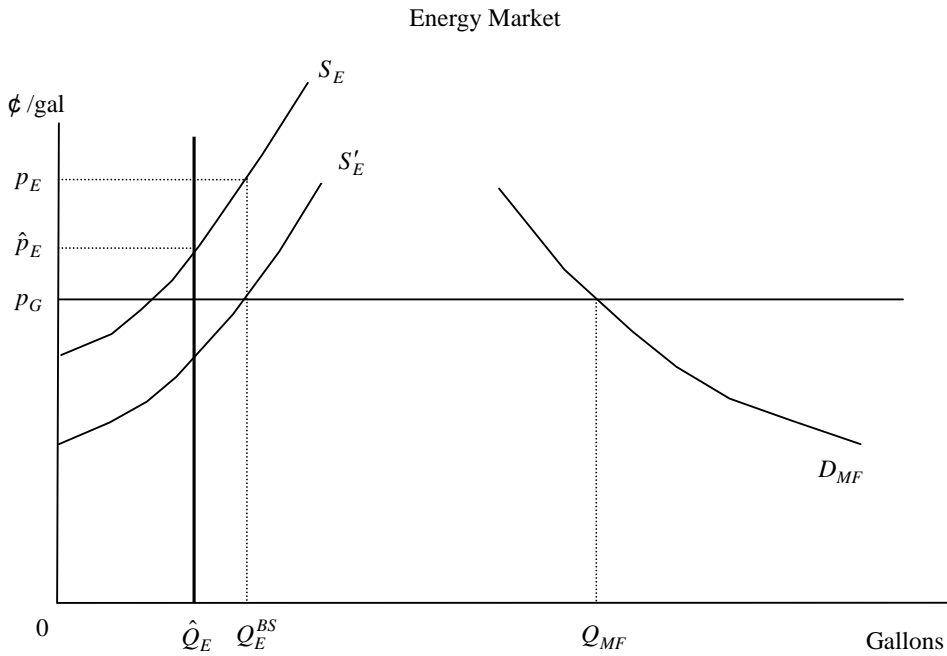


Figure 7: A consumption mandate with a tax credit– the mandate is exceeded

If the consumption mandate is always binding, the oil price does not affect the market price of ethanol. However, variations in corn supply are directly linked to variations in the market price of ethanol (corn price) because ethanol demand is perfectly inelastic and ethanol

supply fluctuates. Therefore, if the likelihood that the mandate is binding is increased (decreased), the impact of variability in corn supply on corn price would be larger (smaller) and the impact of variability in oil price would be smaller (larger).

3.4 Theoretical Derivations of Variability in Ethanol Use and Corn Price

To compare the effects of variability in the petroleum price and corn supply across policy alternatives we need to derive the coefficient of variation in ethanol use and corn price. The theoretical model developed above is helpful in understanding the factors that influence variability under each case. However, it is quite challenging to compare the relative impact of variations in ethanol use and corn price across alternative policies using a theoretical model, even if we assume linear supply and demand functions. This is because there is a possibility that the two variables involve a mixture of discrete and continuous distributions. We have to derive the probability that the mandate is binding (and the mandate is exceeded) to find their mean and variance under BMS and CMS. For example, if the joint probability density of random variables is given by $\varphi(\lambda, \theta)$, from equation (14) the expected ethanol use under CMS can be expressed as:

$$E(Q_E^{CMS}) = \Pr(Q_E = \hat{Q}_E) \times E(Q_E | Q_E = \hat{Q}_E) + \Pr(Q_E > \hat{Q}_E) \times E(Q_E | Q_E > \hat{Q}_E), \quad (16)$$

where

$$\Pr(Q_E = \hat{Q}_E) = \int_{-\infty}^{\infty} \int_{-\infty}^{\Theta} \varphi(\lambda, \theta) d\lambda d\theta, \quad \Pr(Q_E > \hat{Q}_E) = \int_{-\infty}^{\infty} \int_{-\infty}^{\Theta} \varphi(\lambda, \theta) d\lambda d\theta, \quad \text{and} \quad (17)$$

$$\Theta = \hat{p}_E(\theta) - s - p_O.$$

By the theorem of the decomposition of variance, its variance is:

$$\begin{aligned} \text{var}(Q_E^{CMS}) = & [\Pr(Q_E = \hat{Q}_E) \times \text{var}(Q_E | Q_E = \hat{Q}_E) + \Pr(Q_E > \hat{Q}_E) \times \text{var}(Q_E | Q_E > \hat{Q}_E)] \quad (18) \\ & + [\Pr(Q_E = \hat{Q}_E) \times (E(Q_E | Q_E = \hat{Q}_E) - E(Q_E^{CMS}))^2 \\ & + \Pr(Q_E > \hat{Q}_E) \times (E(Q_E | Q_E > \hat{Q}_E) - E(Q_E^{CMS}))^2]. \end{aligned}$$

The first term is the expected variance around the conditional mean, and the second term is the variance of the conditional mean. Similarly, the expected corn price can be written as:

$$E(p_C^{CMS}) = \Pr(Q_E = \hat{Q}_E) \times E(p_C | Q_E = \hat{Q}_E) + \Pr(Q_E > \hat{Q}_E) \times E(p_C | Q_E > \hat{Q}_E). \quad (19)$$

Its variance is given by:

$$\begin{aligned} \text{var}(p_C^{CMS}) = & [\Pr(Q_E = \hat{Q}_E) \times \text{var}(p_C | Q_E = \hat{Q}_E) + \Pr(Q_E > \hat{Q}_E) \times \text{var}(p_C | Q_E > \hat{Q}_E)] \quad (20) \\ & + [\Pr(Q_E = \hat{Q}_E) \times (E(p_C | Q_E = \hat{Q}_E) - E(p_C^{CMS}))^2 \\ & + \Pr(Q_E > \hat{Q}_E) \times (E(p_C | Q_E > \hat{Q}_E) - E(p_C^{CMS}))^2]. \end{aligned}$$

$$+ \Pr(Q_E > \hat{Q}_E) \times (E(p_C | Q_E > \hat{Q}_E) - E(p_C^{CMS}))^2].$$

Since σ_θ^2 is included only in $\text{var}(p_C | Q_E = \hat{Q}_E)$, σ_λ^2 is included only in $\text{var}(p_C | Q_E > \hat{Q}_E)$, $\partial \Pr(Q_E = \hat{Q}_E) / \partial s < 0$, and $\partial \Pr(Q_E > \hat{Q}_E) / \partial s > 0$, we find that as the level of tax credit increases, the impact of variation in corn supply on the corn price is reduced and the impact of variation in the petroleum price is increased. Nevertheless, it is difficult to compare the coefficient of variation among policies theoretically, especially when using nonlinear supply and demand functions. It is necessary to use numerical methods to evaluate the effects of policy alternatives on variability.

4. Numerical Examples

We perform Monte Carlo simulations to demonstrate how variability in the petroleum price and corn supply affects year-to-year variability in ethanol use and the corn price under several situations. In the following sections we present the scenarios examined, basic data used, functional forms, methods, and the results obtained.

4.1 Scenarios and Basic Data for the Analysis

Our primary objectives are to provide insight into the following four questions:

- 1) How do changes in relative variability in the petroleum price and corn supply influence market outcomes under each biofuel policy?
- 2) How do changes in the level of a tax credit affect ethanol use and corn price variability under mandates?
- 3) How does an increase in the level of mandates (the blend ratio) – other conditions unchanged – affect markets?
- 4) How do changes in the elasticity of ethanol supply and the minimum supply-inducing price affect the results?

To answer these questions, we use data drawn from de Gorter and Just (2007) for the U.S. corn-ethanol market to examine four scenarios with changes in relative variability in key variables. The market data (in 2006 or 2006-07) and assumed (or calculated) parameter values for the baseline in our simulations are summarized in table 1.

Table 1: Baseline data and parameter values for Monte Carlo simulations

Corn market (in 2006)	
Total corn production (2006-07)	10,745 million bushels
Domestic non-ethanol demand (2006-07)	6,401 million bushels
Export demand (2006-07)	2,200 million bushels
Corn used as an input to ethanol production (2006-07)	2,144 million bushels
Price elasticity of corn supply	0.2
Price elasticity of non-ethanol domestic demand for corn	- 0.2
Price elasticity of export demand for corn	- 1.0
Price elasticity of the aggregate demand for corn ^a	- 0.4
Price of corn	\$ 3.03 per bushel
Energy market (US ethanol and gasoline in 2006)	
Expected ethanol use	6,673 billion gallons
Total fuel consumption	142,400 billion gallons
Blend ratio	0.04686 (4.7%)
Expected price of ethanol	\$ 2.32 per gallon
Expected gasoline price including taxes	\$ 2.22 per gallon
Price elasticity of ethanol supply ^b	2.63
Price elasticity of fuel demand	- 0.2
Minimum ethanol supply inducing price ^c	\$ 2.0136
Fuel excise tax	\$ 0.41 per gallon
Tax credit (biofuel subsidy)	\$ 0.51 per gallon

^a Calculated using the elasticities of supply, non-ethanol domestic demand, and export demand for corn

^b Calculated using the elasticities of supply and aggregate demand for corn

^c The expected gasoline price net of tax plus \$ 0.2036 per gallon from de Gorter and Just (2007)

The four scenarios are as follows:

Scenario A

A tax credit of \$0.51 per gallon without any mandate¹³

Scenario B

A tax credit \$0.51 per gallon with a blending or consumption mandate in which the required level of ethanol use is equal to expected ethanol use under Scenario A (i.e., with a blend ratio of 4.7%)

¹³ There are also state tax credits. According to de Gorter and Just (2008b), the overall tax credit was 56.93 cents per gallon in 2006. In addition, the current US federal tax credit is 46 cents per gallon having recently been reduced from 51 cents. It is assumed that the current overall tax credit is roughly 51 cents per gallon.

Scenario C

No tax credit under mandates (blend ratio = 4.7%)

Scenario D

Mandates higher than expected ethanol use with the tax credit of \$0.51 (specifically a doubling of the blend ratio to 9.4%) – other conditions unchanged.

For the high mandate case (Scenario D), we double the baseline blend ratio (9.4%), and calculate the expected ethanol price (\$4.27) and expected ethanol use under BS (13,346 billion gallons).

To introduce variability into our analysis, we first computed the annual coefficient of variation (CV) of the gasoline price (including taxes) using monthly data on all types of gasoline, U.S. city average retail price: nominal cents per gallon including taxes from the Energy Information Administration, Department of Energy, and that for corn supply using corn production annual data from the National Agricultural Statistics Service (NASS) for 2000-2008 USDA (1970-2008). The computed average annual CV for the gasoline price was 10.6% and the average CV for corn production was 16.6%. We also examined the variation in corn yields for 1990 to 1999 and for 2000 to 2008 and found that this had declined from 14.4% to 12.2%. In order to be conservative in our analysis we chose to employ 10% as the baseline coefficient of variation for both gasoline price and corn supply. For a relatively high CV in corn supply (gasoline price) we use 15% (5%) for corn supply and 5% (15%) for gasoline price. Since a 1988-style drought could happen again and this would add considerably to market variability we use 20% as an extreme case CV for corn supply (5% for gasoline price). In summary, the following four cases are considered:

- 1) Baseline variation: 10% CV for both gasoline price and corn supply
- 2) Relatively high variation in corn supply: 15% CV for corn supply and 5% CV for gasoline price
- 3) Relatively high variation in gasoline price: 5% CV for corn supply and 15% CV for gasoline price
- 4) Very high variation in corn supply: 20% CV for corn supply and 5% CV for gasoline price.

4.2 Functional Forms and Methods

To conduct the simulations we calibrate a supply-demand model using the data summarized in table 1.

The inverse supply function for ethanol is:

$$S_E^{-1}: p_E = \left((1/\gamma)^\phi Q_E^{\frac{1}{\phi}} + \delta \right) \omega, \quad E(\omega) = 1, \quad \text{var}(\omega) = \sigma_\omega^2, \quad (21)$$

where γ and ϕ are parameters and ω is a random variable which is log-normally distributed.

We calculate its variance as:

$$\sigma_\omega^2 = \left(\frac{\sigma_\theta}{\eta - \varepsilon} \frac{(Ep_E - (1 - \tau)c/k)}{Ep_E} \right)^2. \quad (22)$$

This function does not have a constant elasticity but it does have a constant coefficient of variation, $CV_\omega = \sigma_\omega$. According to de Gorter and Just (2007), ethanol production would be zero with a tax credit of 20.36 cents per gallon. Since we assume an exogenous oil price, the intercept of the ethanol supply curve (the minimum supply-inducing price) is determined by the expected price of petroleum plus \$0.2036. The functional form for the inverse demand for liquid transportation fuel (mixed fuel) is specified as:

$$D_{MF}^{-1}: p_{MF} = (1/\kappa)^\zeta Q_{MF}^{\frac{1}{\zeta}}. \quad (23)$$

where κ is a parameter and $\zeta < 0$ is the elasticity of fuel demand. This function has a constant elasticity.

To determine the parameters of these functions, we use reasonable assumptions on elasticity values for ethanol supply and fuel demand. The short-run elasticity of fuel demand is assumed to be -0.2 . The elasticity of ethanol supply is calculated using the elasticities of aggregate (non-ethanol) demand and the supply of corn¹⁴. Since the supply curve for ethanol is defined as the horizontal difference between the supply curve for corn and the non-ethanol demand curve for corn, the elasticity of ethanol supply is given by:

$$\eta_{ES} = \eta \times \frac{Q_{CS}}{Q_{CE}} - \varepsilon \times \frac{Q_{ADC}}{Q_{CE}}, \quad (24)$$

where Q_{CS} is corn production, Q_{CE} is corn used for ethanol production, and Q_{ADC} represents the aggregate demand for corn (non-ethanol domestic demand Q_{NED} plus export demand Q_{ED}).

¹⁴ Luchansky and Monks (2009) estimate an inelastic price elasticity of ethanol supply (0.237), but their estimate is too inelastic to use in our numerical example. Rather, we derive the elasticity of ethanol supply using de Gorter and Just's method.

The elasticities assumed in the corn market are as follows: 0.2, -0.2, and -1.0 for supply, non-ethanol domestic demand, and export demand, respectively (de Gorter & Just, 2009a). The price elasticity of the aggregate demand for corn ε is calculated as:

$$\varepsilon = \frac{\partial Q_{ADC}}{\partial p_C} \cdot \frac{p_C}{Q_{ADC}} = \left(\frac{\partial Q_{NBE}}{\partial p_C} + \frac{\partial Q_{ED}}{\partial p_C} \right) \frac{p_C}{Q_{ADC}} = a_{NED} \frac{\partial Q_{NED}}{\partial p_C} \frac{p_C}{Q_{NED}} + a_{ED} \frac{\partial Q_{ED}}{\partial p_C} \frac{p_C}{Q_{ED}}. \quad (25)$$

where a_{NED} (a_{ED}) is the proportion of non-ethanol domestic demand (export demand) in total demand. The calculated elasticities of ethanol supply and the aggregate demand for corn (based on the U.S. corn-ethanol market in 2006-07) are given in table 1.

Using the econometric software package TSP 5.0 (Hall & Cummins, 2005) we generated 5,000 random values for the random variable associated with the oil price from a normal distribution and for the random variable associated with corn supply from a log-normal distribution. For simplicity, the two random variables are assumed to be independent.

4.3 Results

The results of Monte Carlo simulations for the baseline data and parameters are reported in table 2. It is apparent that the variation in ethanol use under Scenario A is the highest of the scenarios. This means that ethanol use is sensitive to fluctuations in gasoline price and corn supply if no mandate is imposed. The variation in corn price under this scenario increases as the variation in gasoline price increases relative to that in corn supply. Thus, large fluctuations in the gasoline price will lead to large fluctuations in the corn price in the absence of a mandate.

When blending or consumption mandates are imposed¹⁵ (with the level of tax credit unchanged), the variation in ethanol use is reduced in all the cases examined, but it is not completely eliminated because there is a finite probability that the mandate will be exceeded. Variability in corn price is lower under the baseline and with high variation in the gasoline price, but is increased with high variation in the corn supply. This is because the imposition of a mandate reduces the impact of gasoline price fluctuations on corn price but increases the impact of corn supply fluctuations. Elimination of the tax credit under this condition results in lower variation in the quantity of ethanol used, reduces variation in corn price for relatively high variation in gasoline price, and increases variation in corn price given relatively high variation in corn supply. Since removing the tax credit increases the likelihood of a binding

¹⁵ In table 2 we provide only the results of imposing blending mandates because we obtain similar outcomes when imposing consumption mandates.

mandate, the impact of gasoline price on corn price becomes smaller and the impact of corn supply becomes larger as the likelihood increases that the mandate is binding. An increase in the minimum level of required ethanol use, other factors held constant, has a similar impact (to the elimination of subsidy) on variability in ethanol use and corn price because the likelihood of binding mandates is increased. It is clear that eliminating the tax credit and increasing the blend ratio simultaneously will mutually reinforce the impact.

Table 2: The coefficient of variation (%) in the quantity of ethanol (QE) and the price of corn (PC)

Scenarios	Baseline variations		High variation in gasoline price		High variation in corn supply		Very high variation in corn supply	
	QE	PC	QE	PC	QE	PC	QE	PC
A. Tax credit \$0.51 only	43	25	56	35	36	14	45	15
B. Tax credit \$0.51 and blending mandate (4.7 % blending requirement)	11	16	13	21	11	16	13	20
C. Mandate only (4.7 % blending requirement)	2	16	5	10	1	25	3	33
D. Tax credit \$0.51 and mandate (9.4 % blending requirement)	2	14	2	7	1	22	1	29

Baseline variations: 10% CV for both gasoline price and corn supply

High variation in gasoline price: 15% CV for gasoline price and 5% CV for corn supply

High variation in corn supply: 5% CV for gasoline price and 15% CV for corn supply

Very high variation in corn supply: 5% CV for gasoline price and 20% CV for corn supply

We obtain similar qualitative results by changing the elasticity of ethanol supply. Although a more elastic ethanol supply reduces the impact of corn supply variability on the markets and results in more unstable ethanol use with no or non-binding mandates, our principal findings are robust. In addition, changing the level of the minimum supply-inducing price (the intercept of the ethanol supply curve) has no effect on our main conclusions.

5. Policy Implications

High variability in the price of feedstock for biofuels could be problematic. For example, an increase in the demand for U.S. corn used in ethanol production is likely to have an impact not only on domestic markets but also globally. As a major exporter of corn, an increase in the price of corn in the United States will have a spillover effect on the world market and this could translate into higher prices for other grains, as well as livestock products. Countries that have poor, rural, food insecure, and undernourished populations that tend to spend a larger proportion of their income on food, are particularly vulnerable to rising and volatile food prices (Elobeid & Hart, 2007). In addition, high variation in ethanol use may make the biofuel industry riskier, which in turn may lead to reduced capital investment.

If policy makers want to reduce market variability (under the assumption that less variability is preferable) the results from our simulations imply that the preferred policy depends on the policy objective and market situation. Some insights into possible market stabilization policies are outlined briefly.

With a fixed biofuel subsidy that generates biofuel production, measures to stabilize feedstock prices by damping fluctuations in feedstock supply (through the use of stocks) will not be effective when there is no biofuel mandate or a low probability that a mandate will be binding. In that case fluctuations in the petroleum price will be the major factor affecting feedstock prices. Hence, it would be appropriate to focus on reducing short-term variations in the gasoline price, for example by using a countercyclical variable excise-tax on gasoline, or by using a countercyclical biofuel subsidy to stabilize the market¹⁶. Of course, the costs and benefits of such stabilization policies would need to be investigated to determine their desirability.

When there is a fixed subsidy and the likelihood that a mandate becomes binding is expected to be high, stabilizing domestic feedstock supply by using public stocks could be appropriate, in particular if potential variations in the biofuel price (feedstock price) increase as biofuel production increases. The use of a variable biofuel subsidy in this case will affect only the consumption of petroleum-based transportation fuel.

If policy makers would like to reduce variations in biofuel use and feedstock price simultaneously under a fixed biofuel subsidy, imposing a mandate and reducing feedstock supply variations could both be important. But if the level of the mandate is too high, the mixed fuel price will be increased significantly. A variable subsidy can be used to achieve a

¹⁶ Tyner and Quear (2006) examine the difference between a fixed and variable subsidy for corn-based ethanol.

targeted (or mandated) volume of biofuel use or to stabilize the feedstock price and biofuel use without increasing the mixed fuel price (above the gasoline price). However, budget limitations or other political reasons may make it difficult for a government to vary the level of the subsidy at will.

It is apparent that further research is needed regarding the choice, design, and net benefit of stabilization instruments under potential variability in agricultural markets created by the integration of the biofuel sector. In particular, the design of biofuel subsidy policy could be important in helping to stabilize markets.

6. Concluding Remarks

The development of the biofuel industry will dramatically alter the linkage between agricultural and energy markets. Researchers and policy makers have argued in favor of promoting biofuel production and consumption on the grounds of reducing greenhouse gas emissions, improving energy security, increasing farm incomes, and job creation. The net contribution of biofuels in these areas may be less than proposed, but the current trend towards the promotion of biofuel production and use is expected to continue.

A host of studies have investigated various aspects of the impact of biofuels, but limited attention has been devoted to analyzing the impact of multiple policy instruments designed to increase biofuel use in the presence of variability in energy and agricultural markets. Focusing on the current situation in the United States where there is no significant trade in biofuels, this paper examines the impact of variability in the price of petroleum price and biofuel feedstock supply (corn supply) on market variability under various policy alternatives involving the use of a biofuel subsidy (tax credit) and blending or consumption mandates. Our focus is on how short-term (year-to-year) variability in ethanol use and corn price is affected by these policy alternatives with changes in the relative variability of the petroleum price and corn supply. We also examine the impact of eliminating (or increasing) the tax credit and increasing minimum ethanol use requirements on market variability under changes in relative variability.

Our results indicate that if a tax credit granted to blenders is the only biofuel policy instrument (there is no blending or consumption mandate), the quantity of ethanol used is sensitive to fluctuations in the petroleum price and/or domestic corn supply. The corn price is affected by petroleum price fluctuations but there is no additional impact from the ethanol market because the amount of ethanol produced/used responds to changes in the corn market.

When mandates are imposed, the variation in ethanol use declines, the impact of variation in corn supply on corn price is increased, and the impact of oil price fluctuations is decreased. The effects are larger as the likelihood increases that a mandate becomes binding. Therefore, the effect of changes in biofuel policy on the price of corn depends on the relative magnitude of fluctuations in world oil prices and domestic corn supply. When gasoline price fluctuations are relatively high in comparison to corn supply, imposing mandates and/or a reduction in the tax credit could result in reduced variability in corn price. In contrast, when variation in corn supply is relatively high, increased variability in the corn price could result¹⁷. Variability in the corn price will be unchanged if a reduction in the effect of gasoline price fluctuations on corn price variations is offset by an increase in the effect of corn supply variations. Moreover, a more elastic ethanol supply results in a reduction in the impact of corn supply fluctuations on corn price, and higher variation in ethanol use. Our principal results are robust to changes in the elasticity of ethanol supply and the minimum ethanol supply-inducing price.

Our findings can contribute to the ongoing debate on the design of domestic biofuel policy in that they clarify important implications of policy alternatives for stability in both the biofuel and feedstock markets. Further analysis is needed of options for stabilization policy. In addition, it would be useful to extend the model to the open economy case to consider the impact of trade in biofuels and trade policies on the stability of domestic and international markets.

¹⁷ As the difference between CV of gasoline price and CV of corn supply increases, the impact of imposing mandates and/or reducing a tax credit increases. This means that as the difference between CVs increases, (percentage) changes in the CV of the corn price increase.

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Appendix A: Proof of equation 6

Let the constant elasticity (non-ethanol) corn demand function be:

$$Q_{DC} = Ap^\varepsilon, \quad \varepsilon < 0. \quad (\text{A.1})$$

Also let the constant elasticity corn supply be:

$$Q_{SC} = Bp^\eta, \quad \eta > 0. \quad (\text{A.2})$$

Suppose that the source of risk lies on the supply side, and that output is log-normally distributed (θ is log-normally distributed). The inverse corn supply function can be written as:

$$p = (Q_{SC} / B)^{1/\eta}, \quad Q_{SC} = \bar{Q}_{SC}\theta, \quad E\theta = 1, \quad \text{Var}\theta \cong \sigma^2, \quad \text{CV}_{Q_{SC}} \cong \sigma. \quad (\text{A.3})$$

Let $\theta = e^Z$ and $Z \sim N(\mu, \sigma^2)$, then $E\theta = Ee^Z = e^{\mu + \sigma^2/2}$. Since we assume $E\theta = 1$, $\mu = -\sigma^2/2$. The variance of θ is:

$$\text{Var}(\theta) = (e^{\sigma^2} - 1)e^{2\mu + \sigma^2} = e^{\sigma^2} - 1. \quad (\text{A.4})$$

Since $e^x \cong 1 + x$, $\text{Var}\theta = \sigma_\theta^2 \cong \sigma^2$. By solving $Q_{DC} = \bar{Q}_{SC}$ we have:

$$p_{NE} = (A/B)^{\frac{1}{\eta - \varepsilon}} \theta^{\frac{1}{\eta - \varepsilon}}. \quad (\text{A.5})$$

Therefore, variation in equilibrium corn price without ethanol production depends on the demand and supply elasticities (ε and η). Let $1/(\eta - \varepsilon) = \beta$. Then, the expected value of the corn price without ethanol production can be derived as:

$$Ep_{NE} = (A/B)^\beta E\theta^\beta = (A/B)^\beta \exp\left(\frac{1}{2}\beta(\beta - 1)\sigma^2\right), \quad (\text{A.6})$$

where $E\theta^\beta = \exp\left(\beta\mu + \frac{1}{2}\beta^2\sigma^2\right) = \exp\left(-\frac{1}{2}\beta\sigma^2 + \frac{1}{2}\beta^2\sigma^2\right) = \exp\left(\frac{1}{2}\beta(\beta - 1)\sigma^2\right)$.

The variance of corn price without ethanol production is given by:

$$\begin{aligned} \text{Var}(p_{NE}) &= E\left\{\left((A/B)^\beta \theta^\beta - Ep_{NE}\right)^2\right\} = (A/B)^{2\beta} E\theta^{2\beta} - (A/B)^{2\beta} (E\theta^\beta)^2 \\ &= (A/B)^{2\beta} \left\{\exp(\beta(2\beta - 1)\sigma^2) - \exp(\beta(\beta - 1)\sigma^2)\right\} \\ &= (A/B)^{2\beta} \exp(\beta(\beta - 1)\sigma^2) \left\{\exp(\beta^2\sigma^2) - 1\right\}. \end{aligned} \quad (\text{A.7})$$

Its coefficient of variation is given by:

$$\text{CV}_{p_{NE}} = \frac{\sqrt{(A/B)^{2\beta} \exp(\beta(\beta - 1)\sigma^2) \left\{\exp(\beta^2\sigma^2) - 1\right\}}}{(A/B)^\beta \exp\left(\frac{1}{2}\beta(\beta - 1)\sigma^2\right)} = \sqrt{\left\{\exp(\beta^2\sigma^2) - 1\right\}}. \quad (\text{A.8})$$

By Maclaurin series approximations this expression can be rewritten as:

$$CV_{PNE} \cong \sqrt{\beta^2 \sigma^2} \cong \beta \sigma_\theta = \frac{\sigma_\theta}{\eta - \varepsilon}. \quad (\text{A.9})$$

Note that this result relies on the accuracy of the approximation $e^x \cong 1 + x$. Mathematically $x > -1$ because $x \cong \log(1+x)$ or $e^x > 0$. When x is close to 0, the difference is very small, but if x is greater than 0.42, the difference is greater than 0.1, which is large. If x is large, for example 5, this approximation would not be accurate. We find that it is accurate in our simulations because σ_θ^2 and $\beta^2 \sigma^2$ are close to zero.

Appendix B: Proof of equation 7

The relationship between the corn price and the ethanol price is given in equation (1) in the body text:

$$p_C = \frac{k}{1-\tau} p_E - c. \quad (\text{B.1})$$

Its expectation and variance are:

$$Ep_C = \frac{k}{1-\tau} Ep_E - c \text{ and } \text{Var}(p_C) = \left(\frac{k}{1-\tau}\right)^2 \text{Var}(p_E). \quad (\text{B.2})$$

Its CV is:

$$CV(p_C) = \frac{\left(\frac{k}{1-\tau}\right) \sqrt{\text{Var}(p_E)}}{\left(\frac{k}{1-\tau}\right) Ep_E - c} = \frac{\sigma_{p_E}}{Ep_E - \left(\frac{(1-\tau)c}{k}\right)} \quad (\text{B.3})$$

and

$$CV(p_C)(Ep_E - (1-\tau)c/k) = \sigma_{p_E}. \quad (\text{B.4})$$

Dividing both sides by Ep_E :

$$CV(p_C) \left(\frac{Ep_E - (1-\tau)c/k}{Ep_E} \right) = \frac{\sigma_{p_E}}{Ep_E} = CV(p_E). \quad (\text{B.5})$$

Since we assume that the inverse ethanol supply has a constant CV, and it is reasonable to use this relationship at the “expected ethanol price”, the CV of the market ethanol price can be expressed as equation (7) in the body text.

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