Investment in Cellulosic Biofuel Refineries:
Do Renewable Identification Numbers Matter?

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September 20, 2010

Abstract

A floor and trade policy in Renewable Identification Numbers (RINs) is the market mechanism by which U.S. biofuel consumption mandates are met. A conceptual model is developed to study the impact of RINs on stimulating investment in cellulosic biofuel refineries. In a two-period framework, we compare the first-period investment level (FIL) in three scenarios: (1) *laissez-faire*, (2) RINs under a non-waivable mandate (NWM) policy, and (3) RINs under a waivable mandate (WM) policy. Results show that when firm-level marginal costs are constants, then RINs under WM policy do not stimulate FIL but they do increase the expected profit of more efficient investors. When firm-level marginal costs are not constants, however, RINs under WM policy stimulate FIL. RINs under NWM policy may or may not stimulate FIL, depending on the distribution of second-period cellulosic biofuel prices and on firm-level marginal costs.

Key words: cellulosic biofuels, investment, Renewable Identification Numbers, waivable mandate

JEL classification: D24, L52, Q48

1

The U.S. Energy Independence and Security Act of 2007 (EISA) that was passed into law in December 2007 mandates U.S. consumption of 21 billion gallons of advanced biofuels by 2022. Of this, 16 billion gallons are to come from cellulosic feedstocks. Mandates for cellulosic biofuels begin at 0.1 billion gallons in 2010, increasing to 16 billion gallons in 2022. However, it is not yet clear as of 2010 which technology platform will prove to be the most efficient at producing cellulosic biofuels, and it is unclear when, if ever, the market value of cellulosic biofuels will cover production costs. Furthermore, cellulosic biofuel costs are currently not competitive with corn ethanol costs (Bryant et al. 2010; Bullis 2007; Leber 2010; Vasudevan, Gagnon, and Briggs 2009). As a result of technology uncertainty and poor financial competitiveness, no commercial-scale cellulosic biofuel refinery has been built as of May 2010 (Renewable Fuels Association, 2010). EISA's Renewable Fuel Standard (RFS), along with biofuel tax credits, aims to support investment in biofuel refineries.

The RFS mandates a floor on the amount of biofuels being consumed in every calendar year. Trade in Renewable Identification Numbers (RINs) is the market mechanism by which the mandates are to be met. Each batch, or gallon, of biofuel is assigned a RIN after it is produced or imported. As long as biofuels are blended with gasoline and made ready for consumption, the RIN attached to the biofuels can be separated and can then be bought or sold on the RIN market. Obligated parties (i.e., producers or importers of motor fuel) must give the Environmental Protection Agency (EPA) enough RINs to meet their RFS mandate every year. They can obtain RINs either through the purchase of biofuels or by entering the RIN market and buying RINs. Since the price of RINs will be reflected in the price of biofuels, the RFS would seem to lower the risk of investing in cellulosic biofuels refineries. This is because when cellulosic biofuel production is lower than the mandate, the RIN price will rise to reflect the scarcity of biofuels.

However, EISA allows for waivers of mandates, as specified in Section 202 of EISA:

> "(D) Cellulosic Biofuel. – (i) For any calendar year for which the projected volume of cellulosic biofuel production is less than the minimum applicable volume established under paragraph (2)(B), $\cdots$, the Administrator shall reduce the applicable volume of cellulosic biofuel required under paragraph (2)(B) to the projected volume available during that calendar year."

For example, a waiver was given for cellulosic biofuel in 2010. In March 2010 the EPA waived the 2010 cellulosic biofuel mandate from 100 million gallons, as listed in EISA, to 5 million gallons (or 6.5 million ethanol equivalent gallons) (EPA 2010).

The purpose of this study is to determine the impact of RIN trade on the incentive to invest in a cellulosic biofuel refinery when the mandate is waivable. The literature on the effects of biofuel mandates has not yet addressed this question. McPhail and Babcock (2008a, 2008b) studied the production and welfare effects of expanded corn ethanol mandates. Althoff, Ehmke, and Gray (2003) and de Gorter and Just (2009) analyzed the mandate as an upward shift of the fuel supply curve because, they argued, the price per gallon of fuel would be increased by mandating that biofuel be blended with gasoline. Gardner (2003) modeled the mandate by adding the mandate quantity directly to the corn demand. Taheripour and Tyner (2007) studied the impacts of the mandate on the distribution of ethanol subsidies by assuming that the mandate and the limited ethanol production capacity made the supply curve for ethanol vertical. FAPRI (2007) studied the impact of a 15 billion gallon biofuel mandate on the supply and demand of ethanol and agricultural commodities. Lapan and Moschini (2009) modeled mandates as a floor on biofuel consumption. Roberts and Schlenker (2010) studied the effects of U.S. biofuel mandates on world food prices. All of these studies implicitly assumed that the mandate will be met and did not consider the possibility that a mandate could be waived.

To explore the implications of RINs under mandates we construct a two-period model in which an investor can either invest in the current period or wait and decide whether to invest in the future. We compare first-period investment levels in three scenarios: (1) *laissez-faire*, (2) RINs under a non-waivable mandate (NWM) policy, and (3) RINs under a waivable mandate (WM) policy. We find that the investment impact of RINs, whether they are under NWM or WM, depends on the distribution of the cellulosic biofuel's price in the second period and also on the investors' marginal costs. When the price distribution is such that almost surely every realization is sufficiently high, and when the marginal costs are constants, then neither RINs under NWM policy nor RINs under WM policy affect the first-period investment level. This is because under these two conditions the expected net profit of investors who are break-even in the laissez-faire scenario is not affected by RINs. If that condition on the price distribution does not hold and if marginal costs are constants, then RINs under WM policy has no effect on the investment level. But it still can increase, at least weakly, the expected profit of more efficient investors. However, when marginal costs are increasing, then RINs in both scenarios (2) and (3) can stimulate the investment level in the first period because they increase the marginal profit of break-even investors.

The contribution of this article is threefold. First, it emphasizes the waivability aspect of the mandates and studies this aspect's investment effects. Second, it shows that WM policy has the effect of rewarding more efficient investors or refineries. Third, policy implications are derived from the results of this article. In what follows, we first develop a conceptual model of a potential investor's decision problem. Then we apply this model to study the three scenarios previously described. Specifically, we study first-year investment levels under the *laissez-faire* scenario in which any mandate is absent. We also investigate the investment effects of NWM policy. Then, we consider the effects of WM

policy on first-period investment levels and on investors' expected profit. The last section provides concluding remarks.

Model

In a two-period world, there is a unit mass continuum of potential risk-neutral investors in the cellulosic biofuel industry. Each chooses whether to invest in period one. We denote the action set in period one as $\{I_1, NI_1\}$. Here I_1 and NI_1 mean investing and not investing in period one, respectively. "To invest" means to build a biofuel production refinery. Once the refinery is built, the cost of doing so, f, is sunk. We normalize each refinery's capacity to one unit. Even though the refineries have the same capacity and fixed cost, their production technologies may differ. This heterogeneity is captured by allowing each refinery's constant marginal cost c to vary, $c \in [0, \infty)$.[1] Let $G(c)$ denote the distribution function of c.

Since there is a continuum of investors, each investor's production capacity has no effect on total capacity. Therefore an investor will be a price taker after she enters the cellulosic biofuel industry.[2] If an investor invests and produces in period one, she will receive revenue p_1 in that period because capacity is normalized to one unit. Here p_1 is the price of cellulosic biofuel in period one, which is exogenously determined.[3] We assume that investment and production happen simultaneously. If an investor does not invest in the first period, she receives nothing but still has the opportunity to invest in the second period. The price of cellulosic biofuel in period two, p_2, is uncertain. Its distribution is $J(p_2)$ with support $[0, \infty)$. At the beginning of period two, p_2 and hence p^{RIN} are realized and investors can make their decisions accordingly, where p^{RIN} is the RIN price in period two. In period two, investors who invested in period one may stay

open or shut down, while investors who did not invest in period one may invest or not.

Figure 1 presents the timeline of an investor's decision problem. At the very beginning of period one, p_1 is given. After observing p_1 and forming an expectation of profit received in period two, every investor chooses an action from the period-one action set $\{I_1, NI_1\}$. Based on the choices made by investors, the period-one aggregate capacity, X_1, is built up. At the beginning of period two, p_2 is realized. Let M denote the mandate level in period two. Then p^{RIN} is determined as a function of X_1, p_2, and M. Upon knowing p_2 and p^{RIN}, investors will make period-two decisions accordingly.

Solving an investor's problem requires backward induction. In period two, after observing p_2 and p^{RIN}, the investor makes a decision that maximizes her profit in the period. If she has invested in period one, then she will shut down her plant whenever $p_2 + p^{RIN} - c < 0$. So her maximized profit in period two is $\max\{p_2 + p^{RIN} - c, 0\}$. If she has not invested in period one, then she will invest whenever $p_2 + p^{RIN} - c - f > 0$. Then her maximized profit in period two is $\max\{p_2 + p^{RIN} - c - f, 0\}$. In period one, she will choose I_1 or NI_1 to maximize her expected total profit from both period one and period two. Figure 2 depicts the decision tree for an investor's problem. Specifically, the discounted expected profit from investing in period one (I_1) is

$$(1) \qquad B(I_1) = p_1 - c - f + \beta \int_0^\infty \max[p_2 + p^{RIN} - c, 0] dJ(p_2),$$

where $\beta \in [0, 1]$ is the discount factor. The discounted expected profit from not investing in period one (NI_1) is

$$(2) \qquad B(NI_1) = \beta \int_0^\infty \max[p_2 + p^{RIN} - c - f, 0] dJ(p_2).$$

We define the marginal benefit to a potential investor with marginal cost c in period

one as

(3) $\Delta(c) \equiv B(I_1) - B(NI_1)$

$= p_1 - c - f$

$+ \beta \int_0^\infty \{\max[p_2 + p^{RIN} - c, 0] - \max[p_2 + p^{RIN} - c - f, 0]\} dJ(p_2)$

$= p_1 - c - f + \beta \int_0^\infty \min\{\max[p_2 + p^{RIN} - c, 0], f\} dJ(p_2).$

An investor with marginal cost c will invest in the first period if $\Delta(c) > 0$. Investors with c such that $\Delta(c) = 0$ are indifferent between I_1 and NI_1. We refer to such investors as "break-even investors" from now on and assume break-even investors invest in period one. Let $z \equiv \min\{\max[p_2 + p^{RIN} - c, 0], f\}$, so that $z \in [0, f]$. Figure 3 shows the value of z as a function of $p_2 + p^{RIN}$, where the latter is the total value of one unit of cellulosic biofuel. Hence for a fixed c, the value of $\Delta(c)$ ranges from $p_1 - c - f$ to $p_1 - c - (1-\beta)f$ according to the magnitude of z. Therefore we have that $\Delta(p_1 - (1-\beta)f) \leq 0$. Together with the observation that $\Delta(c)$ is strictly decreasing in c, $\Delta(p_1 - (1-\beta)f) \leq 0$ implies investors with marginal cost greater than $p_1 - (1-\beta)f$ will never invest in period one. We define

(4) $$\bar{c} \equiv p_1 - (1-\beta)f,$$

which can be seen as the upper bound of the marginal cost of investors who may invest in period one.

We can view $p_1 - c - f$ as the period-one profit difference between the two choices in period one: I_1 and NI_1. Term $\beta \int_0^\infty z dJ(p_2)$ can be seen as the discounted expected period-two profit difference between these two choices. If the sum of these profit differences in

two periods is greater than 0, then investing in period one is financially worthwhile. We have just shown that investors with $c > \bar{c}$ cannot have a positive value of this sum. Or more intuitively, since cost f cannot be recovered once it is invested, the choice NI_1 keeps the option not to invest in period two open. That is, when the situation does not favor cellulosic biofuel in period two, an investor will have the option to not invest in period two if she chooses NI_1 in period one. But if she chooses I_1 in period one, she does not have this option because the investment cost is sunk. Therefore, the gain from deferring investment in period one is

$$(5) \quad \beta \int_0^\infty \max[p_2 + p^{RIN} - c - f, 0] dJ(p_2) - [\beta \int_0^\infty \max[p_2 + p^{RIN} - c, 0] dJ(p_2) - f]$$
$$= f - \beta \int_0^\infty z dJ(p_2).$$

The opportunity cost for this gain is $p_1 - c$, the benefit from producing cellulosic biofuels in period one. We can see that the opportunity cost is decreasing but the gain is increasing with the marginal cost c. Therefore, the higher is an investor's marginal cost, the larger is the incentive for investors to defer the investment. Hence, if $(p_1 - c) - [f - \beta \int_0^\infty z dJ(p_2)] \geq 0$, then investors will choose I_1 in period one. Since $z \in [0, f]$, then $(1 - \beta)f \leq f - \beta \int_0^\infty z dJ(p_2) \leq f$. Therefore, if $p_1 - c < (1 - \beta)f$, then $p_1 - c < f - \beta \int_0^\infty z dJ(p_2)$, which means investors with $c > \bar{c}$ will never invest in period one. The reason is that for such investors the cost of deferring investment is always less than the gain from doing so.

Moreover, we know from evaluating equation (3) that $\Delta(0) \leq \bar{c}$. If $\bar{c} \leq 0$, then no potential investor will invest in period one. This could be an appropriate approximation to the advanced biofuel industry in early 2010 when a waiver was granted: low prices and high investment costs make commercial-scale cellulosic biofuel refineries unviable. We

summarize the above analysis as Result 1.

Result 1. *Investors with marginal cost greater than $\bar{c}$ will never invest in period one. If $\bar{c} < 0$, then no investor will invest in period one.*

In light of Result 1, in the rest of the article we focus on the situation in which $\bar{c} \geq 0$. We compare the investment level in the first period under three scenarios: (1) *laissez-faire*; (2) NWM policy, and (3) WM policy.

Baseline Scenario: *Laissez-faire*

In this scenario the government does not impose a mandate. Therefore, a RIN market does not exist. The decision problem is an investment decision absent any policy intervention. Consequently, in this scenario we set $p^{RIN} = 0$. From equation (3) and an integration by parts we have

$$
\begin{aligned}
(6) \qquad \Delta^{lf}(c) & \equiv p_1 - c - f + \beta \int_0^\infty z \, dJ(p_2) \\
& = p_1 - c - (1-\beta)f - \beta \int_c^{c+f} J(p_2) \, dp_2.
\end{aligned}
$$

Here $\Delta^{lf}(\cdot)$ is used to denote the $\Delta(\cdot)$ function in the *laissez-faire* scenario. Expression $\int_c^{c+f} J(p_2) \, dp_2$ can be viewed as f minus the expected period-two profit difference between actions I_1 and NI_1. If $\int_c^{c+f} J(p_2) \, dp_2 = 0$, then we can conclude that the expected period-two profit difference between actions I_1 and NI_1 is f. We define c^{lf} throughout as the marginal cost such that $\Delta^{lf}(c^{lf}) = 0$. Then for any $c \leq c^{lf}$ (or $c > c^{lf}$), we have $\Delta^{lf}(c) \geq 0$ (or $\Delta^{lf}(c) < 0$) since $\partial \Delta^{lf}(c)/\partial c = -1 - \beta[J(c+f) - J(c)] < 0$. Hence, the realized capacity in period one is $X_1^{lf} = G(c^{lf})$.

From equation (6) we can see that if $J(p_1 + \beta f) = 0$, then $\Delta^{lf}(\bar{c}) = 0$ and hence $c^{lf} =$

9

$\bar{c}$. This conclusion can be shown using figure 3 as well.[4] It means that if almost surely each realization of p_2 is sufficiently high (i.e., higher than $p_1 + \beta f$), then any investor with marginal cost lower than $\bar{c}$ will invest in period one. This is because when the realizations of p_2 are sufficiently high, then investment will occur anyway for these investors in period two. However, the gain from deferring investment reaches its minimum possible value of $(1 - \beta)f$, and even investors with marginal cost $c = \bar{c}$ are indifferent between I_1 and NI_1. Therefore, investors with marginal cost $c < \bar{c}$ strictly prefer I_1.

A more intuitive explanation is as follows. The value of deferring investment is that the investor will have the option to not invest, so that the fixed cost f can be saved whenever a low p_2 is realized. But $J(p_1 + \beta f) = 0$ ensures that the situation is so "good" (i.e., the realization of p_2 will be almost surely higher than $p_1 + \beta f$) that investors with marginal cost $\bar{c}$ will invest in period two whenever they have not already invested in period one. Then the gain of deferring investment is just to save one period of interest of the fixed cost f, which is $(1 - \beta)f$. If this gain is less than the benefit forgone by deferring the investment (i.e., benefit from producing cellulosic biofuel in period one, $p_1 - c$), then investors will invest in period one.

From equation (6) we see that $\Delta^{lf}(0) = \bar{c} - \beta \int_0^f J(p_2)dp_2$. If $\Delta^{lf}(0) \geq 0$, then there is a unique $c^{lf} \geq 0$ such that $\Delta^{lf}(c^{lf}) = 0$. If $\Delta^{lf}(0) < 0$, however, no investor will invest in period one. Here we assume this case away. Figure 4 provides a visual representation of $\Delta^{lf}(c)$ and c^{lf} in the baseline scenario.[5]

From equation (6) we can also see that c^{lf} is implicitly determined by

(7) $$p_1 - c^{lf} - (1 - \beta)f - \beta \int_{c^{lf}}^{c^{lf}+f} J(p_2)dp_2 = 0.$$

By the implicit function theorem we have $\partial c^{lf}/\partial p_1 > 0$, $\partial c^{lf}/\partial f < 0$, and $\partial c^{lf}/\partial \beta > 0$. These inequalities allow for several intuitive conclusions. When p_1 is larger, even in-

vestors with high marginal cost may find it profitable to invest in the first period. There-fore, the total investment in the first period will be larger. Clearly a higher fixed cost f will discourage investment. Moreover, when the profit in the future has lower present value, investment will be reduced.

We summarize the above analysis as follows.

Result 2. *In the laissez-faire scenario, assume $\Delta^{lf}(0) > 0$. If the realizations of p_2 are sufficiently high (i.e., $J(p_1 + \beta f) = 0$), then $c^{lf} = \bar{c}$. Otherwise $c^{lf} \leq \bar{c}$. The investment level $G(c^{lf})$ in period one is positively affected by increasing the first-period price and the discount factor but negatively affected by increasing the fixed cost.*

This baseline model provides a benchmark for our analysis of WM policy. To better understand the effects of this policy, it is helpful to first study the effects of NWM policy.[6]

The Effects of NWM Policy

Under either NWM policy or WM policy, if M, the mandate level in period two, is less than or equal to $G(c^{lf})$, then the mandate will never bind. If $M > 1$, however, the mandate will never be met because the full potential of cellulosic biofuel production is normal-ized to 1. Therefore, we assume $M \in (G(c^{lf}), 1]$. The RIN price in period two depends on the realization of p_2, the mandate level M, and the available capacity at the begin-ning of period two, i.e., the capacity built in period one, X_1. Since in this section RIN prices differ between the situation in which $M \in (G(\bar{c}), 1]$ and the situation in which $M \in (G(c^{lf}), G(\bar{c})]$, we analyze these two cases separately. However, if $c^{lf} = \bar{c}$, then $(G(c^{lf}), G(\bar{c})]$ is an empty set and hence only the first case is relevant. The second case exists only when $c^{lf} < \bar{c}$, which requires $J(p_1 + \beta f) > 0$ by Result 2. Therefore, during the analysis of the second case we assume that $c^{lf} < \bar{c}$ holds.

Case 1. $M \in (G(\bar{c}), 1]$

We define c^M such that $G(c^M) \equiv M$, i.e., c^M is the marginal cost of the break-even investor when the mandate is just met. Then we have $c^M > \bar{c}$ due to $M > G(\bar{c})$ in this case. From Result 1 we know that any investor with $c > \bar{c}$ will never invest in period one. Therefore, investors with marginal cost c^M would never invest in period one, and hence the first-period aggregate investment level must satisfy $X_1 \leq G(\bar{c}) < M$. In period two, if p_2 is not high enough to induce investment to meet mandate level M, then demand in the RIN market will require that $p_2 + p^{RIN} = c^M + f$. If p_2 is high enough to ensure that the mandate is met, then $p^{RIN} = 0$. Specifically,

$$(8) \qquad\qquad p^{RIN} \;=\; \max\{c^M + f - p_2, 0\}.$$

For investors with $c \leq \bar{c}$ (i.e., investors that may invest in period one), equations (3) and (8) imply

$$(9) \qquad\qquad \Delta^{nw}(c) = p_1 - c - (1 - \beta)f,$$

where $\Delta^{nw}(\cdot)$ denotes the $\Delta(\cdot)$ function in this NWM policy. The algebra to arrive at equation (9) is shown in the supplemental materials, Item A. Here we illustrate the intuition behind this equation. Since in period two $p_2 + p^{RIN} = \max\{c^M + f, p_2\}$, investors with $c \leq \bar{c}$ that had not already invested in period one will invest in period two anyway. Therefore, as we discussed in the baseline scenario, the benefit of deferring investment is just to save one period of interest on the fixed cost f, which is $(1 - \beta)f$. The opportunity cost of this benefit is $p_1 - c$. The difference between this cost and benefit is measured by

12

$\Delta^{nw}(c)$ in equation (9). Putting $\Delta^{nw}(c) = 0$ gives us

$$(10) \qquad\qquad\qquad\qquad c^{nw} = \bar{c},$$

where c^{nw} is the marginal cost of break-even investors under NWM policy. Since $\Delta^{nw}(c)$ is strictly decreasing with c, then any investors with $c \leq \bar{c}$ will always invest in period one. Therefore, the investment level in period one in this case is $X_1^{nw} = G(\bar{c})$.

One can also obtain equation (10) using a Nash equilibrium approach. The essence of our model is that an individual investor makes her first-period investment decision based on her expectation of all other investers' first-period investment decisions. That is, given all other investers' first-period investment strategies, which will determine the realized first-period aggregate investment level, X_1, then the investor chooses a strategy from $\{I_1, NI_1\}$ to maximize her expected profit. To find out the equilibrium strategies, we can practice the following mental experiment. Suppose we start from a strategy set S_0 containing each investor's first-period investment strategy. This strategy set S_0 determines an aggregate first-period investment level, X_1^0. By expecting X_1^0, each investor will adjust her first-period investment strategy to maximize the expected profit using equations (3) and (8). After each investor's adjustment, a new first-period investment strategy set, S_1, is formed, which correspondingly determines a new aggregate first-period investment level, X_1^1. We define the relationship between X_1^0 and X_1^1 such that $X_1^1 = r(X_1^0)$. Here $r(X_1)$ can be interpreted as a response function that summarizes all investors' responses to a conjectured period-one investment level, $X_1^0 \in \Omega \equiv [0, G(\bar{c})]$. Result 1 has shown that X_1^0 cannot be greater than $G(\bar{c})$. From equations (8) and (9) we know that in this case $r(X_1) = G(\bar{c})$ for any $X_1^0 \in \Omega$. In the Nash equilibrium we must have the realized period-one investment level, $r(X_1^0)$, equal to the conjectured period-one investment level, X_1^0. Since (i) Ω is nonempty, compact and convex; and (ii) $r(X_1)$ is a continuous function

from Ω into itself, then by the Brouwer Fixed-Point Theorem we know this equilibrium exists. Moreover, the equilibrium is unique because $r(X_1)$ in this case is a constant, $G(\bar{c})$. From figure 5 we can see the fixed point is at $X_1 = G(\bar{c})$. Therefore, the equilibrium period-one investment level is $X_1^{nw} = G(\bar{c})$.

One interesting observation in this case is that the investment level in period one is not affected by the mandate level M or the distribution of p_2. The reason is as follows. If the realization of p_2 is lower than $c^M + f$ (i.e., p_2 itself is not high enough to ensure the mandate is met), then the NWM will create demand for RINs so that p_2 plus p^{RIN} can make the mandate be met. That is, an NWM level $M > G(\bar{c})$ ensures that $p_2 + p^{RIN} = \max\{c^M + f, p_2\}$, which is high enough to induce investment in period two from investors with $c \leq \bar{c}$ because $c^M > \bar{c}$. Then we have $p_2 + p^{RIN} \geq c^M + f \geq \bar{c} + f \geq p_1 + \beta f$. Under this situation, investors with $c \leq \bar{c}$ will invest in period one since when $p_2 + p^{RIN} \geq p_1 + \beta f$, then for these investors the gain from deferring investment will be less than or equal to the cost of doing so. This is as we discussed in the baseline scenario. Moreover, from Result 1 we know that investors with $c > \bar{c}$ never invest in period one. Therefore, once the NWM level M is higher than $G(\bar{c})$, the realized investment level in period one will be $X_1^{nw} = G(\bar{c})$ so that the specific mandate level and the distribution of p_2 will not affect X_1^{nw}.

Comparing equations (6) and (9) we can find $\Delta^{lf}(c) - \Delta^{nw}(c) = -\beta \int_c^{c+f} J(p_2) dp_2 \leq 0$, which gives us $c^{lf} \leq c^{nw}$. Equality holds when the distribution of p_2 is such that $J(p_1 + \beta f) = 0$. Inequality $c^{lf} \leq c^{nw}$ shows that, when compared with the baseline scenario, the NWM policy has a positive effect on the period-one investment level. But if $J(p_1 + \beta f) = 0$, then the NWM policy has no effect on the first-period investment level. The intuition is as follows. The purpose of the RIN policy is to place a floor on the total value (i.e., $p_2 + p^{RIN}$) of cellulosic biofuel. This ensures that the mandate is met when the price

of cellulosic biofuels in the second period is low. In this case the floor is $c^M + f$. If the price is high enough under every state in period two, this purpose of the RIN policy for investors with $c < \bar{c}$ becomes latent because for them the value of p_2 is sufficiently high to induce investment in period one. Therefore, the NWM policy does not affect the investment level in the first period when $J(p_1 + \beta f) = 0$.

We summarize the above analysis in this case as Result 3.

Result 3. *Suppose the NWM level satisfies $M \in (G(\bar{c}), 1]$. Then (1) investors with $c \leq \bar{c}$ will invest in the first period; (2) the capacity built in period one is $X_1^M = G(\bar{c})$; (3) the magnitude of M and distribution of p_2 have no effect on X_1^M; (4) $c^{nw} \geq c^{lf}$, which indicates that NWM policy has a positive effect on investment levels in period one; and (5) $c^{nw} = c^{lf}$ when $J(p_1 + \beta f) = 0$.*

In Case 1, new investment is needed in period two to meet the mandate. Next, we study Case 2 where $M \in (G(c^{lf}), G(\bar{c})]$, in which new investment may or may not be needed to meet the mandate in period two.

Case 2. $M \in (G(c^{lf}), G(\bar{c})]$

To establish the equilibrium investment level in period one, X_1^{nw}, we apply backward induction by first solving an investor's problem in period two. At the beginning of period two, p_2 is realized, which together with X_1 and M determines the RIN price. If $X_1 \geq M$, then no new investment is needed to meet mandate level M in period two. So the purpose of the RIN market is only to keep enough refineries running to supply M units of biofuel. If p_2 is high enough to achieve this, then $p^{RIN} = 0$; otherwise $p^{RIN} = c^M - p_2$. Therefore, $p^{RIN} = \max\{c^M - p_2, 0\}$. If $X_1 < M$, as in Case 1 of this section, we have

$p^{RIN} = \max\{c^M + f - p_2, 0\}$. Specifically,

$$
(11) \qquad p^{RIN} = \begin{cases} \max\{c^M + f - p_2, 0\} & \text{if } X_1 < M, \\ \max\{c^M - p_2, 0\} & \text{if } X_1 \geq M. \end{cases}
$$

Plugging this RIN price into equation (3) we can obtain $\Delta^{nw}(c)$. Let c^{nw} satisfy $\Delta^{nw}(c^{nw}) = 0$. Then only investors with $c \leq c^{nw}$ will invest in period one. Again let $r(X_1)$ be interpreted as a response function that summarizes all investors' responses to an expected period-one investment level, X_1. Then an equilibrium investment level in period one, X_1^{nw}, if it exists, should be such that $X_1^{nw} = r(X_1^{nw})$. That is, the expected investment level, X_1^{nw}, must be equal to the realized investment level based on this expectation, $r(X_1^{nw})$.

If $X_1 < M$, then $p^{RIN} = \max\{c^M + f - p_2, 0\}$ according to equation (11). As we have shown in Case 1, investors with marginal cost satisfying $c \leq \bar{c}$ will invest in period one and the realized aggregate investment level in period one will be $r(X_1) = G(\bar{c})$, which implies $r(X_1) > X_1$ due to $X_1 < M$ and $M \leq G(\bar{c})$.

If $X_1 \geq M$, then $p^{RIN} = \max\{c^M - p_2, 0\}$. Plugging this RIN price into equation (3), we get

$$
\begin{aligned}
(12) \; \Delta^{nw}(c) \;=\;& p_1 - c - f + \beta \Big\{ \int_0^{c^M} \{\max[c^M - c, 0] - \max[c^M - c - f, 0]\} dJ(p_2) \\
&+ \int_{c^M}^{\infty} \{\max[p_2 - c, 0] - \max[p_2 - c - f, 0]\} dJ(p_2) \Big\} \\
=\;& p_1 - c - f + \beta \Big\{ \int_0^{c^M} \min\{\max[c^M - c, 0], f\} dJ(p_2) \\
&+ \int_{c^M}^{\infty} \min\{\max[p_2 - c, 0], f\} dJ(p_2) \Big\}.
\end{aligned}
$$

The algebra to arrive at equation (12) is provided in the supplemental materials, Item

B. We can show that $c^{lf} \leq c^{nw} < c^M$, which indicates $G(c^{lf}) \leq r(X_1) = G(c^{nw}) < M$. The algebra to demonstrate this is given in the supplemental materials, Item C.

Figure 6 shows the curve of the response function $r(X_1)$ when $X_1 \in [0, G(\bar{c})]$. The $r(X_1)$ curve lies above the 45° line when $X_1 < M$ but below the 45° line when $X_1 \geq M$. This discontinuity is created by the fall of the RIN price from $\max\{c^M + f - p_2, 0\}$ to $\max\{c^M - p_2, 0\}$ when X_1 changes from $M - \varepsilon$ to M, where ε is a small positive real number. This RIN price's fall is due to the existence of fixed cost f and a characteristic of the NWM. The characteristic is that when the available capacity is less than mandate level, then demand in the RIN market will rise so high that new investment can be induced. That is, the RIN price must be high enough so that $p_2 + p^{RIN}$ can cover the fixed cost and the variable cost, which is $f + c^M$. But if the first-period investment level is greater than or equal to the mandate level, the RIN price only needs to be high enough so that $p_2 + p^{RIN}$ can keep M plants running, i.e., $p_2 + p^{RIN} \geq c^M$. The discontinuous response function (or supply) due to the existence of fixed cost is illustrated in detail on page 145 of Mas-Colell, Whinston, and Green (1995). Clearly, were $f = 0$, then equation (11) shows that the RIN price function is continuous; hence the response function $r(\cdot)$ will be continuous as well.

From figure 6 we can see that the $r(X_1)$ curve does not cross the 45° line, which means an X_1^{nw} such that $X_1^{nw} = r(X_1^{nw})$, and hence a Pure Strategy Nash Equilibrium (PSNE) investment level does not exist. We leave the strict proof to the supplemental materials, Item D. In the following paragraph we briefly discuss why a mixed strategy equilibrium does not exist either. The same intuition for the non-existence of PSNE investment applies here. Since there are infinite players (i.e., investors) in our model, the existence theorem of a mixed-strategy equilibrium for finite strategic-form games (Fudenberg and Tirole 1991, p. 29) does not apply to it. For the existence of Nash equilibria in games with infinite players, we refer our readers to Salonen (2010), in which the sufficient conditions

for the existence of a mixed-strategy Nash equilibrium in a game with infinite players are studied.

Suppose there is a mixed-strategy equilibrium, in which investors with marginal cost c choose action I_1 with probability $\pi(c) \in [0,1]$ and action NI_1 with probability $1 - \pi(c)$. Then the realized expected investment level in period one is $X_1^* = \int_0^\infty \pi(c) dG(c)$. The key here is to show that by expecting X_1^*, investors' first-period investment strategy will be different from $\pi(c)$. If $X_1^* < M$ then, as we have shown in Case 1, action I_1 will strictly dominate action NI_1 for investors with $c < \bar{c}$; however, for investors with $c > \bar{c}$, NI_1 strictly dominates I_1. In addition in Case 2 we have $M \in (G(c^{lf}), G(\bar{c})]$; therefore, $r(X_1^*) = G(\bar{c}) > X_1^*$, which means the realized investment level based on expecting X_1^* is greater than X_1^*. This contradicts the assumption that X_1^* is the equilibrium investment level, which indicates that $\pi(c)$ is not a mixed-strategy equilibrium if $X_1^* < M$. If $X_1^* \geq M$ then, as we have shown in the supplemental materials, Item C, for investors with $c < c^{nw}$ action I_1 will strictly dominate action NI_1, and for investors with $c > c^{nw}$, NI_1 strictly dominates I_1. Because $c^{lf} \leq c^{nw} < c^M$ (see the supplemental materials, Item C) and $X_1^* \geq M$, we have $r(X_1^*) = G(c^{nw}) < X_1^*$. This also contradicts the assumption that X_1^* is the equilibrium investment level. In sum, a mixed strategy in Case 2 does not exist. We can summarize the above analysis as Result 4.

Result 4. *Suppose the NWM level M satisfies $M \in (G(c^{lf}), G(\bar{c})]$. Then the equilibrium investment level in period one does not exist because of the existence of fixed cost and non-waivability.*

The Effects of WM Policy

If the mandate allows for a waiver when the production capacity is not available, as was stated in Section 202 of EISA (2007), how will the policy affect investors' decisions in period one? Can the policy still stimulate investment in period one? In this section we show that it depends on the properties of investors' marginal cost functions. If the marginal cost for investors is constant, then WM policy has no effect on the investment decision in period one. This conclusion does not hold whenever the marginal cost is strictly increasing. Our analysis also points out a transfer issue of WM policy. That is, WM policy does increase the expected profit of more efficient investors, even in the situation in which investors' marginal costs are constants.

The Effect on Investment Level in Period One — Constant Marginal Costs

In this scenario, the price of RINs in the second period will still be jointly determined by p_2, X_1, and M. But now the mandate is waivable. For the same reason as in the last section, we continue to divide the analysis into two cases: $M \in (G(\bar{c}), 1]$ and $M \in (G(c^{lf}), G(\bar{c})]$. And as in the NWM policy scenario, we also assume $c^{lf} < \bar{c}$ during the analysis of the second case.

Case 1. $M \in (G(\bar{c}), 1]$

Suppose that at the beginning of period two, the realized capacity from period one is X_1. In this case we must have $X_1 < M$. The reason is the same as that given for Case 1 in the previous section. If p_2 is not high enough to induce investment in the second period to meet the mandate, then the mandate will be waived to a level that can be supported by p_2 and p^{RIN}. Specifically, if $p_2 < G^{-1}(X_1)$ (i.e., p_2 is not high enough to keep X_1 refineries running), the mandate will be waived to X_1. In this case, the RIN market will work so

19

that p^{RIN} and p_2 together can keep X_1 refineries running. That is, $p_2 + p^{RIN} = G^{-1}(X_1)$. If $p_2 \in [G^{-1}(X_1), G^{-1}(X_1) + f]$ (i.e., p_2 is high enough to keep X_1 plants running but not high enough to induce new investment in period two), then the mandate will be waived to X_1 as well. In this case p^{RIN} will be 0 since p_2 is high enough to keep the available plants running. If $p_2 > G^{-1}(X_1) + f$, then investors with $c \in (G^{-1}(X_1), p_2 - f]$ will invest in period two since $p_2 - f - c \geq 0$. In this case the mandate will be waived to $G(p_2 - f)$ whenever $G(p_2 - f) < M$. If $G(p_2 - f) \geq M$, however, then the mandate level M will be met. Since p_2 is high enough to keep $G(p_2 - f)$ plants running, p^{RIN} is 0 as well. Figure 7 depicts the relationship between p^{RIN} and p_2. Mathematically we have

$$(13) \qquad\qquad p^{RIN} = \max\{G^{-1}(X_1) - p_2, 0\}.$$

Intuitively, equation (13) can be explained as follows. As in Case 1 of the NWM policy scenario, the purpose of the mandate is to place a floor on the value of cellulosic biofuel. When WM level $M \in (G(\bar{c}), 1]$, then the floor is $G^{-1}(X_1)$. If p_2 is less than $G^{-1}(X_1)$, then the RIN market will start working. The value of p^{RIN} will increase so that $p_2 + p^{RIN}$, the total value of cellulosic biofuel, can reach the floor, $G^{-1}(X_1)$. However, if p_2 is greater than $G^{-1}(X_1)$, then the floor has been reached and hence the RIN market will be dormant, which implies $p^{RIN} = 0$. Since the mandate level M is waivable and $X_1 < M$ in this case, the mandate will be waived to X_1 as long as p_2 is not high enough to induce new investment. So M does not enter equation (13). Moreover, because the purpose of the RIN price here is to keep available plants running instead of stimulating investment because of the waivability, fixed cost f does not appear in equation (13).

We define c^w as the marginal cost of a break-even investor in the WM policy scenario. That is, $\Delta^w(c^w) = 0$, where $\Delta^w(\cdot)$ denotes $\Delta(\cdot)$ function in the WM policy scenario. In equilibrium $X_1^w = G(c^w)$, i.e., all investors with $c \leq c^w$ invest in period one. Here X_1^w is

the equilibrium capacity realized in period one. Plugging equation (13) into equation (3) and applying the equilibrium condition $X_1^w = G(c^w)$, we obtain

$$(14) \qquad\qquad p_1 - c^w - (1-\beta)f - \beta \int_{c^w}^{c^w+f} J(p_2)dp_2 = 0,$$

which implicitly determines c^w. The algebra behind equation (14) is shown in the supplemental materials, Item E. Comparing equations (14) and (7), we find that they are exactly the same. Therefore we can conclude that $c^w = c^{lf}$. This means that the WM policy has no effect on the investment level in period one when investors' marginal costs are constant. The reason is that the policy cannot affect the expected profit of break-even investors. According to equation (13), when p_2 is high enough, then p^{RIN} is 0 and hence p^{RIN} has no effect on the investment decision in period one. If p_2 is low, then the sum of p_2 and p^{RIN} is only high enough to keep the refinery with marginal cost $c = c^{lf}$ running. However, this does not improve break-even investors' profit. So the RIN price does not affect the break-even investor's decision, and the realized capacity in period one is not affected.

Case 2. $M \in (G(c^{lf}), G(\bar{c})]$

In this case we arrive at the same conclusion as in Case 1, i.e., $c^w = c^{lf}$. We leave the analysis to the supplemental materials, Item F.

We summarize the results in this sub-section as follows.

Result 5. *Suppose the mandate is waivable and investors' marginal costs are constants. Then the investment level in period one is unique and equal to the equilibrium investment level in the laissez-faire scenario. That is, the WM policy does not have any effect on the investment level in period one when investors' marginal costs are constants.*

Even though WM policy has no effect on the period-one investment level when the

21

marginal costs are constants, the expected profit of investors may change. We study this issue in the following subsection.

The Effect on Investors' Expected Profits in Period Two — Constant Marginal Costs

Under the WM policy scenario, we have $X_1 = G(c^{lf})$ in equilibrium. By equation (13), $p^{RIN} = 0$ whenever $p_2 \geq c^{lf}$. In this case RINs have no effect on investors' expected profits. When $p_2 < c^{lf}$, however, then $p^{RIN} = c^{lf} - p_2$. Hence, the revenue of the operating refineries is guaranteed at $\max\{p_2, c^{lf}\}$. Essentially, the WM policy provides a put option. In the *laissez-faire* scenario, however, the revenue of a running refinery is only p_2. Clearly the expected profit of a running refinery is higher in the WM scenario when compared with the *laissez-faire* scenario. We will use an example to better illustrate this conclusion.

Example 1. Consider the example in which p_2 only has two states, p^h and p^l. We assume p^h is high enough so that $p^{RIN} = 0$ when p^h is the realization and p^l is low enough such that $p^l < c^{lf}$.

Figure 8 depicts the effect of the WM policy on investors' profit when p^l is the realization. To ease exposition, we assume that $G(c)$ is a uniform distribution in this figure. If there is no WM policy, then under p^l only plants with $c \leq p^l$ will continue to run. The aggregate operating profit of the running refineries in period two is $\int_0^{p^l}(p^l - c)dG(c)$, which is area A. If there is WM policy, then all refineries with $c \leq c^{lf}$ can keep running. The aggregate operating profit is $\int_0^{c^{lf}}(c^{lf} - c)dG(c)$, which is area $A + B + C$. Hence, the aggregate operating profit is increased by area $B + C$ due to the WM policy. Specifically, area B is the increased aggregate operating profit of refineries with $c \leq p^l$ whose revenue is improved from p^l to c^{lf}. The aggregate magnitude of increase is $\int_0^{p^l}(c^{lf} - p^l)dG(c)$, which is area B. Area C is the increased aggregate operating profit of plants with $c \in (p^l, c^{lf}]$.

In the *laissez-faire* scenario these refineries will shut down under realization $p_2 = p^l$. But they can keep running under the WM policy. Each of them receives revenue c^{lf}. So their aggregate operating profit is $\int_{p_l}^{c^{lf}} (c^{lf} - c)dG(c)$, which is area C.

We summarize the analysis in this sub-section as Result 6.

Result 6. *When compared with the laissez-faire scenario, WM policy will improve the expected profit of investors with marginal cost less than c^{lf}. That is, only more efficient investors can benefit from the WM policy.*

The above result identifies a transfer implication of WM policy. While a mandate is "revenue neutral" as shown in Lapan and Moschini (2009), it is not "transfer neutral." WM policy does not affect the period-one investment level when investors' marginal costs are constants, but it does improve the expected profit of more efficient investors. This means that WM policy could encourage investors to adopt more cost-efficient production technologies, a matter that is beyond the scope of this paper and may require future research.

The Effect on Investment Level in Period One — Increasing Marginal Costs

The conclusions in Result 5 and Result 6 are based on the constant marginal cost assumption. If marginal cost curves of refineries are increasing, the WM policy may have a positive effect on the first-period investment. Here we utilize an example to illustrate this point.

Example 2. We again assume that p_2 only has two states: a high price $p^h = 2$ with probability $k \in [0, 1]$, and a low price $p^l = 0$ with probability $1 - k$. We also assume that

23

the total cost function is quadratic. Specifically,

$$(15) \qquad c(q) = \begin{cases} \frac{q^2}{2} + sq + \frac{1}{2} & \text{if } q \in [0,1] \\ \infty & \text{if } q > 1, \end{cases}$$

where q is the quantity of output and $s \in [0,1]$ is a constant that varies across investors and is uniformly distributed on $[0,1]$. So s can also be seen as an index of investor efficiency. The capacity of each plant is normalized to 1. To produce the same quantity q, the plant with a higher s will endure a higher marginal cost. The fixed cost, f, for each refinery is 1/2 and the price in period one, p_1, is equal to 1. The marginal cost of an investor can be written as

$$(16) \qquad u(q) = \begin{cases} q+s & \text{if } q \in [0,1] \\ \infty & \text{if } q > 1 \end{cases}$$

Let $u^{lf}(q) \equiv q + s^{lf}$ denote the marginal cost function of break-even investors in the *laissez-faire* scenario. If an investor's marginal cost is lower than $u^{lf}(q)$, then she will invest in period one. Otherwise she will not. Therefore, in the *laissez-faire* scenario the aggregate investment level in period one will be s^{lf}. Next, we calculate the value of s^{lf}. Figure 9 provides a visual presentation of this example.

If the break-even investor invests in period one, then in that period she will produce at level q_1 such that $u^{lf}(q_1) = p_1$, i.e., $q_1 = p_1 - s^{lf}$. So the operating profit is $p_1 q_1 - \int_0^{q_1} u^{lf}(q)dq = \frac{1}{2}(p_1 - s^{lf})^2$, which is the area $p_1 a s^{lf}$ in figure 9. In period two, if p^h is the realization, then the break-even investor's plant will operate to its full capacity and the operating profit would be $p^h \cdot 1 - \int_0^1 u^{lf}(q)dq = p^h - s^{lf} - \frac{1}{2}$, which is the area of $p^h dcs^{lf}$ in figure 9. If p^l is realized in period two, however, then this plant will be shut down and the operating profit is 0. In sum, for the break-even investor the expected profit of

investing in period one is

$$(17) \qquad B^{lf}(I_1) \;=\; \frac{1}{2}(p_1 - s^{lf})^2 - f + \beta\{k(p^h - s^{lf} - \frac{1}{2}) + (1-k)\cdot 0\},$$

where $B^{lf}(\cdot)$ means the benefit of investors in the *laissez-faire* scenario and β is the discount factor.

If the break-even investor does not invest in period one, then her strategy in period two is as follows. She will invest and produce at full capacity when p^h is the realization; and she will not invest at all when p^l is the realization. So the expected profit is

$$(18) \qquad B^{lf}(NI_1) \;=\; \beta\{k[p^h - s^{lf} - \frac{1}{2} - f] + (1-k)\cdot 0\}.$$

For the break-even investor the equation $B^{lf}(I_1) = B^{lf}(NI_1)$ must hold. Assuming $\beta = 1$ and plugging the values of parameters (i.e., $p_1 = 1$, $p^h = 2$, $p^l = 0$, and $f = 1/2$) into equations $B^{lf}(I_1)$ and $B^{lf}(NI_1)$ we arrive at

$$(19) \qquad s^{lf} = 1 - \sqrt{1-k},$$

which shows that the realized capacity in period one is increasing in k, with $s^{lf} = 0$ when $k = 0$ and $s^{lf} = 1$ when $k = 1$. That is, the more likely p^h is realized, the more investments occur in period one.

Now let us study the effect of WM policy. For simplicity but without loss of generality we assume the mandate level, M, is 1. If p^l is realized, the RIN market will work to keep available refineries running at their full capacity. The reason is that EISA only allows the mandate to be waived to the available capacity. Let $u^w(q) \equiv q + s^w$ denote the marginal cost function of a break-even investor in this WM policy scenario. Then the realized

investment level in period one is s^w because s is uniformly distributed on $[0,1]$. When p^h is the realization, then $p^{RIN} = 0$ because p^h is high enough to induce investment even from the most inefficient investors. When p^l is realized and the mandate is waived to s^w, then $p^{RIN} = 1 + s^w$ because the RIN market has to keep the available plants running at full capacity to meet the waived mandate.[7] The RIN price can be written as

$$(20) \qquad p^{RIN} = \begin{cases} 0 & \text{if } p_2 = p^h \\ 1 + s^w & \text{if } p_2 = p^l. \end{cases}$$

If the break-even investor invests in period one, then her period-one profit is $\frac{1}{2}(p_1 - s^w)^2 - f$. In period two, if $p^h = 2$ is realized, then her period-two profit is $p^h - s^w - \frac{1}{2}$. However, if $p^l = 0$ is realized, then the RIN market will start working to keep the break-even investor's plants running at full capacity, which consequently generates period-two profit $p^{RIN} \cdot 1 - \int_0^1 u^w(q)dq = 1/2$. Hence, the break-even investor's expected profit from investing in period one is

$$(21) \qquad B^w(I_1) \;=\; \frac{1}{2}(p_1 - s^w)^2 - f + \beta\{k[p^h - s^w - \frac{1}{2}] + (1-k)\cdot\frac{1}{2}\}.$$

If the break-even investor chooses action NI_1 in period one, then her strategy in period two will be as follows. When $p_2 = p^h$, then she invests and produces at full capacity. Hence, the profit is $p^h \cdot 1 - \int_0^1 u^w(q)dq - f = p^h - s^w - \frac{1}{2} - f$. When $p_2 = p^l$, then $p^{RIN} = 1 + s^w$ and the profit is $\max[0, p^{RIN} \cdot 1 - \int_0^1 u^w(q)dq - f]$. So the expected profit of choosing NI_1 in period one is

$$(22) \qquad B^w(NI_1) \;=\; \beta\{k[p^h - s^w - \frac{1}{2} - f] + \\ (1-k)(\max[0, p^{RIN} \cdot 1 - \int_0^1 u^w(q)dq - f])\}.$$

26

For the break-even investor we must have $B^w(I_1) = B^w(NI_1)$. Plugging in the value of parameters (i.e., $\beta = 1$, $p_1 = 1$, $p^h = 2$, $p^l = 0$, and $f = 1/2$) and solving this equation gives us $s^w = 1$. Item G in the supplemental materials contains the algebra to obtain this result.

Clearly we can see that $s^w \geq s^{lf}$, where the equality holds only when $k = 1$. This means the WM policy has a positive impact on the investment level in period one. The intuition here is as follows. In the *laissez-faire* scenario, the plants of the break-even investor will be shut down when p^l is the realization of p_2. Therefore, the operating profit is 0 when $p_2 = p^l$. However, in the WM policy scenario, the investor can obtain a positive operating profit even when p^l is realized in period two as a result of the price RINs. The cause of the positive operating profit is that to keep the available plants running at their *full capacity*, the price of RINs must be not lower than $1 + s^{lf}$ (please recall that $p^l = 0$). Clearly it is higher than s^{lf}, the shut-down price. But if the marginal cost is constant, then to keep a plant running at its *full capacity* it is only necessary that the price be as high as the shut-down price. This is why a WM policy can stimulate more investment in period one when the marginal cost is increasing but fails to achieve this when the marginal cost is constant. One can also understand this difference from the perspective of intensive and extensive margins. When investors' marginal costs are increasing, then the RIN price can improve the intensive margin and consequently increase the profit of a running plant. That is, the incentive to invest is enhanced. Therefore, more investors invest in period one and the extensive margin is enlarged as well. However, when investors' marginal costs are constant, the RIN price cannot improve the intensive margin. Therefore, it has no effect on the extensive margin either.

Concluding Remarks

In this paper we construct a conceptual model to study the impact of RINs on stimulating investment in cellulosic biofuel refineries. In a two-period model, the first-period investment levels in three scenarios are compared. These scenarios are (1) laissez-faire, (2) NWM policy, and (3) WM policy. We find that the investment impact of RINs, whether they are under NWM policy or WM policy, depends on the distribution of the cellulosic biofuels' price in the second period and also on the investors' marginal costs. When the price distribution is such that almost surely every realization is sufficiently high, and when the marginal costs are constants, then neither RINs under NWM policy nor RINs under WM policy affect the investment level in the first period. If the price distribution does not satisfy that condition and if the marginal costs are constant, then the RINs under WM policy have no effect on the investment level. But they still can increase, at least weakly, the expected profit of more efficient investors. This increase may provide a "cash cushion" for these efficient investors and prevent them from shutting down when the price of ethanol is low. In 2009 we did observe that some grain-based ethanol plants were shut down because they hit cash flow problems (Wisner, 2009). However, when marginal costs are increasing, then RINs under both NWM policy and WM policy can stimulate the investment level in period one.

We emphasize the waivability aspect of the mandates and study the conditions under which mandates will be waived. Many studies about the effects of U.S. biofuel mandates, such as the ones we reviewed in this paper, implicitly assumed that a mandate is non-waivable. However, if a mandate can be waived (as did occur for cellulosic biofuels in 2010), then policymakers should re-evaluate the conclusions of these studies when making further biofuel policies. Moreover, we show that WM policy has the effect of rewarding more efficient investors or refineries, which will encourage the adoption of

cost-reducing technologies in the cellulosic biofuel industry. However, a tax credit policy may not have such an effect because it subsidizes refineries based on quantity of output (gallons of biofuels produced). That is, two refineries producing equal quantity of biofuels will get the same amount of tax credits, no matter how their production efficiency differs. From this perspective, a mandate may be preferable to a tax credit as an instrument to promote long-run growth in the biofuel industry.

Moreover, that a waivable mandate may not induce investment in biofuels plants raises the question of how the EISA objective of 36 billion gallons of biofuels by 2022 is going to be met. At least some backers of EISA have likely believed that even a waivable mandate would induce investment because if a plant comes on line, then RIN price will increase enough to keep it running. But this article demonstrates that a waivable mandate may not impact the marginal profit of break-even investors. Thus, aggregate investment may not increase. If the United States is serious about producing 36 billion gallons of biofuels, then it may be that more policies besides waivable mandates will be needed. Supply-side policies that will increase investment include investment tax credits and the funding of research that leads to cost-reducing technology improvements. On the demand side, increased taxes on gasoline and diesel and tax credits on biofuels will both work to increase biofuel prices and induce investment.

Notes

[1]We assume the marginal cost of an investor does not change over time. It is likely that the marginal cost will fall in the future because of technological advances. This would increase the advantage of waiting but would not change the effect of a mandate with waivers on an investor's decision. Also, there likely is a trade-off between fixed costs and marginal costs, with higher fixed cost refineries having lower marginal costs. For simplicity we assume that refineries have the same fixed cost but different marginal costs.

[2]One may argue that, since there is a biofuel blending mandate and a new refinery will take about two years to build, the available refineries can charge an arbitrarily high price for their products. But if producers charge a very high price, then the obligated party can petition the EPA to grant a waiver according to EISA. Therefore an arbitrarily high price is unlikely. Also, EISA effectively set an upper bound of RIN prices by issuing cellulosic biofuel credits when a waiver happens (Thompson, Meyer, and Westhoff 2010).

[3]Since renewable biofuel is only a small part of the fuel market, it is reasonable to assume that p_1 is determined by the price of gasoline (Feng and Babcock, 2010). To save on notation, here we assume that p_1 includes the RIN value in the first period.

[4]Suppose in figure 3 the value of c is $\bar{c}$. Since $J(p_1 + \beta f) = 0$, then almost surely every realization of p_2 will be greater than $p_1 + \beta f = c + f$. Therefore from figure 3 we can see $z = f$. Then we have $\Delta^{lf}(\bar{c}) = p_1 - (\bar{c}) - f + \beta f = 0$.

[5]There is a good reason for $\Delta^{lf}(c)$ to have the sigmoid shape. We know that $\partial^2 \Delta^{lf}(c)/\partial c^2 = -\beta[J'(c + f) - J'(c)]$. If p_2 has a unimodal distribution, then $J'(c + f) - J'(c)$ could be positive when c is small and could be negative when c is large. Consequently, we have negative $\partial^2 \Delta^{lf}(c)/\partial c^2$ for c small and positive $\partial^2 \Delta^{lf}(c)/\partial c^2$ for c large. Then the curve of $\Delta^{lf}(c)$ would be concave when c is small and convex when c is large.

[6]Here we implicitly assume that the mandate without waivers is the outcome of a subgame perfect equilibrium, in which a government's commitment is credible. If the government's commitment is not credible, investors will expect that waivers will occur whenever production is less than the mandate level. Then the situation becomes the same as what we will analyze in the WM policy scenario.

[7]RIN prices will have an upper bound at the higher of $0.25 per gallon or the difference between $3 per gallon and the average gasoline price when a waiver happens (EISA 2007). Therefore, in reality the available plants may not be running at full capacities just because of RIN prices. But for simplicity of

exposition, we assume that available plants will be running at full capacity.

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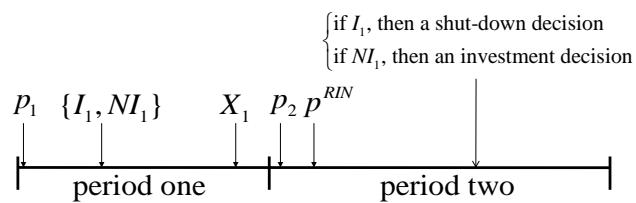
$$
\begin{cases} \text{if } I_1, \text{ then a shut-down decision} \\ \text{if } NI_1, \text{ then an investment decision} \end{cases}
$$

$p_1 \quad \{I_1, NI_1\} \qquad X_1 \quad p_2 \, p^{RIN}$

period one | period two

Figure 1. The Timeline of an Investor's Decisions

profit in period one   profit in period two

$p_1 - c - f$ $\max[p_2 + p^{RIN} - c, 0]$

invest — yes / no

0 $\max[p_2 + p^{RIN} - c - f, 0]$
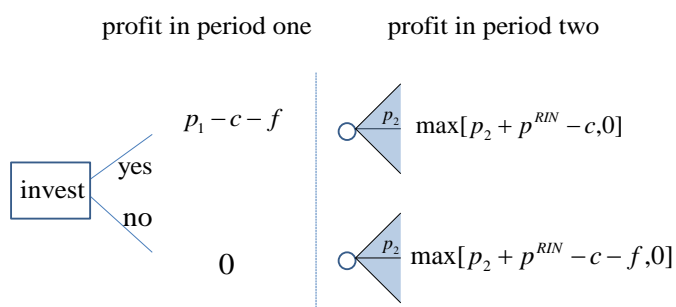
Figure 2. An Investor's Decision Tree

$45°$

$0 \qquad c \qquad c + f \qquad p_2 + p^{RIN}$
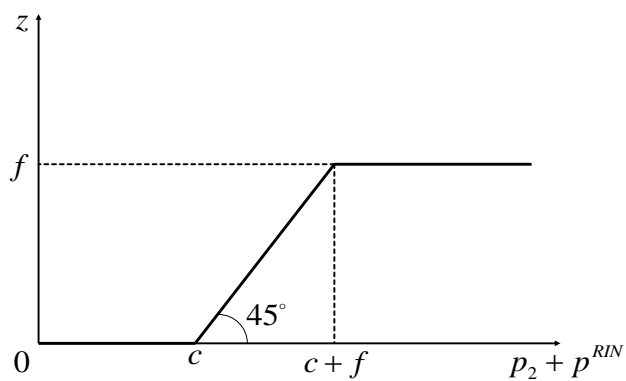
Figure 3. The Value of z as a Function of $p_2 + p^{RIN}$
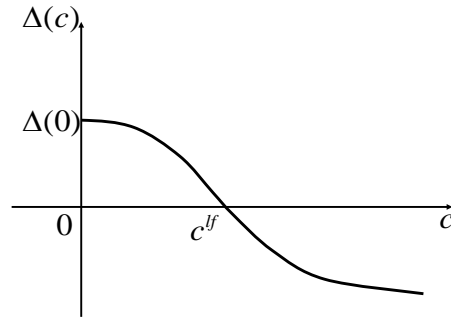
Figure 4. Baseline Scenario: The Investment
Level in Period One
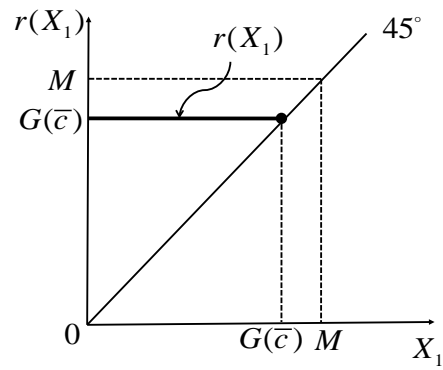
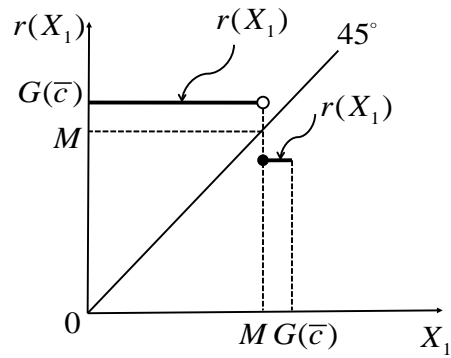Figure 5. $X_1^{nw} = G(\overline{c})$ in Case 1 of the NWM Policy
Scenario

Figure 6. Equilibrium X_1^{nw} Does Not Exist in Case 2 of
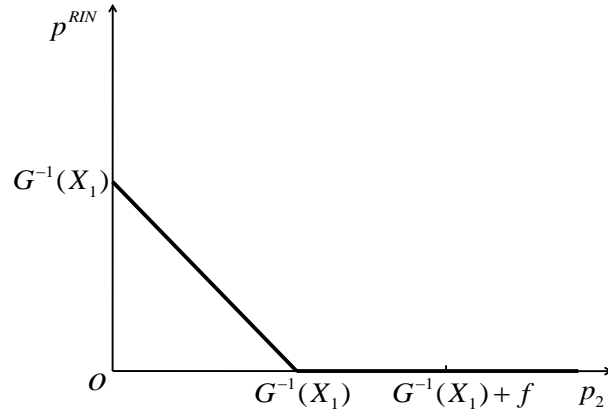the NWM Policy Scenario

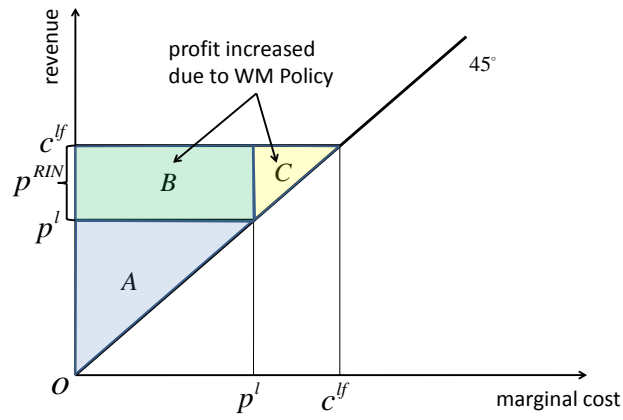Figure 7. Relationship between p^{RIN} and p_2 when $X_1 < M$ in the WM Policy Scenario

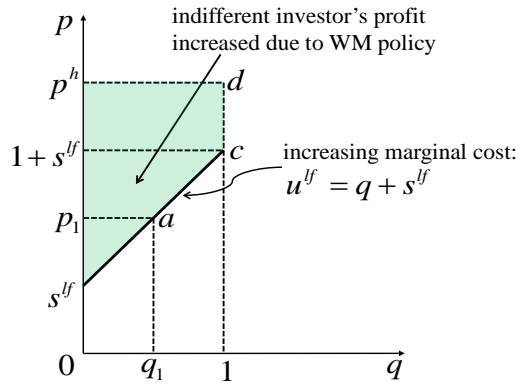Figure 8. Profit Effect of the WM Policy when $p_2 = p^l$ in Example 1

Figure 9. The WM Policy's Profit Effect under Increasing Marginal Cost in Example 2

Supplemental Materials

Item A

In this item we show how to obtain equation (9). Plugging equation (8) into equation (3), we get

$$
\begin{aligned}
\Delta^{nw}(c) &= p_1 - c - f + \beta \left\{ \int_0^\infty \{\max[p_2 + \max[c^M + f - p_2, 0] - c, 0] \right. \\
&\quad \left. - \max[p_2 + \max[c^M + f - p_2, 0] - c - f, 0]\} dJ(p_2) \right\} \\
&= p_1 - c - f + \beta \left\{ \int_0^\infty \{\max[\max[c^M + f, p_2] - c, 0] \right. \\
&\quad \left. - \max[\max[c^M + f, p_2] - c - f, 0]\} dJ(p_2) \right\} \\
&= p_1 - c - f + \beta \left\{ \int_0^{c^M + f} \{\max[c^M + f - c, 0] - \max[c^M - c, 0]\} dJ(p_2) \right. \\
&\quad \left. + \int_{c^M + f}^\infty \{\max[p_2 - c, 0] - \max[p_2 - c - f, 0]\} dJ(p_2) \right\}.
\end{aligned}
$$

Since we only consider investors with marginal cost $c \leq \bar{c} < c^M$, then $\max[c^M + f - c, 0] = c^M + f - c$ and $\max[c^M - c, 0] = c^M - c$. Therefore we have

$$
\begin{aligned}
&\int_0^{c^M + f} \{\max[c^M + f - c, 0] - \max[c^M - c, 0]\} dJ(p_2) \\
&= \int_0^{c^M + f} \{(c^M + f - c) - (c^M - c)\} dJ(p_2) \\
&= \int_0^{c^M + f} f \, dJ(p_2),
\end{aligned}
$$

and

$$\int_{c^M+f}^{\infty} \{\max[p_2-c,0] - \max[p_2-c-f,0]\}dJ(p_2)$$
$$= \int_{c^M+f}^{\infty} \{(p_2-c) - (p_2-c-f)\}dJ(p_2)$$
$$= \int_{c^M+f}^{\infty} f dJ(p_2).$$

So

$$\Delta^{nw}(c) = p_1 - c - f + \beta \left\{ \int_0^{c^M+f} f dJ(p_2) + \int_{c^M+f}^{\infty} f dJ(p_2) \right\}$$
$$= p_1 - c - f + \beta f$$
$$= p_1 - c - (1-\beta)f.$$

Item B

In this item we are show how to obtain equation (12).

If $X_1 \geq M$, then $p^{RIN} = \max\{c^M - p_2, 0\}$. Plugging this RIN price into equation (3), we get

$$\Delta^{nw}(c)$$
$$= p_1 - c - f + \beta \left\{ \int_0^{\infty} \{\max[p_2 + \max[c^M - p_2,0] - c,0] \right.$$
$$\left. - \max[p_2 + \max[c^M - p_2,0] - c - f,0]\}dJ(p_2) \right\}$$
$$= p_1 - c - f + \beta \left\{ \int_0^{\infty} \{\max[\max[c^M,p_2] - c,0] \right.$$
$$\left. - \max[\max[c^M,p_2] - c - f,0]\}dJ(p_2) \right\}$$

38

$$
\begin{aligned}
= \ & p_1 - c - f + \beta \Bigg\{ \int_0^{c^M} \{\max[c^M - c, 0] - \max[c^M - c - f, 0]\} dJ(p_2) \\
& + \int_{c^M}^{\infty} \{\max[p_2 - c, 0] - \max[p_2 - c - f, 0]\} dJ(p_2) \Bigg\}. \\
= \ & p_1 - c - f + \beta \Bigg\{ \int_0^{c^M} \min\{\max[c^M - c, 0], f\} dJ(p_2) \\
& + \int_{c^M}^{\infty} \min\{\max[p_2 - c, 0], f\} dJ(p_2) \Bigg\}.
\end{aligned}
$$

This is equation (12).

Item C

In this item we prove that in the NWM policy scenario if $X_1 \geq M$ then $c^{lf} \leq c^{nw} < c^M$. In the text we have discussed that in Case 2 we have $c^{lf} < \bar{c}$ and $c^{lf} < c^M$. These two inequalities will be utilized in the following proof.

From equation (12) we know that when $X_1 \geq M$, then

$$
\begin{aligned}
\Delta^{nw}(c) \ = \ & p_1 - c - f + \beta \Bigg\{ \int_0^{c^M} \{\max[c^M - c, 0] - \max[c^M - c - f, 0]\} dJ(p_2) \\
& + \int_{c^M}^{\infty} \{\max[p_2 - c, 0] - \max[p_2 - c - f, 0]\} dJ(p_2) \Bigg\}.
\end{aligned}
$$

By definition, c^{nw} is such that $\Delta^{nw}(c^{nw}) = 0$. From the above equation we know that $\Delta^{nw}(c)$ is strictly decreasing with c. To show that $c^{lf} \leq c^{nw} < c^M$ is to show $\Delta^{nw}(c^{lf}) \geq 0$ and $\Delta^{nw}(c^M) < 0$.

Step 1. Show $\Delta^{nw}(c^{lf}) \geq 0$.

Since in this case we have $M \in (G(c^{lf}), G(\bar{c})]$, then $c^M > c^{lf}$. Therefore equation (12)

becomes

(A-1) $\quad \Delta^{nw}(c^{lf}) \;=\; p_1 - c^{lf} - f$

$$+\beta\left\{\int_0^{c^M}\{c^M - c^{lf} - \max[c^M - c^{lf} - f, 0]\}dJ(p_2)\right.$$

$$\left.+\int_{c^M}^{\infty}\{p_2 - c^{lf} - \max[p_2 - c^{lf} - f, 0]\}dJ(p_2)\right\}.$$

Then in this step we have two subcases to consider.

Subcase 1. $c^M - c^{lf} - f \geq 0$

If $c^M - c^{lf} - f \geq 0$, then equation (A-1) is

$$\Delta^{nw}(c^{lf}) \;=\; p_1 - c^{lf} - f + \beta\left\{\int_0^{c^M} f dJ(p_2) + \int_{c^M}^{\infty} f dJ(p_2)\right\}$$

$$=\; \bar{c} - c^{lf}$$

In this case we have $c^{lf} < \bar{c}$ (required by the existence of Case 2). Therefore from Result 2 we get $\Delta^{nw}(c^{lf}) > 0$.

Subcase 2. $c^M - c^{lf} - f < 0$

If $c^M - c^{lf} - f < 0$, then the equation (A-1) becomes

$$\Delta^{nw}(c^{lf})$$

$$=\; p_1 - c^{lf} - f + \beta\left\{\int_0^{c^M}\{c^M - c^{lf}\}dJ(p_2)\right.$$

$$\left.+\int_{c^M}^{c^{lf}+f}\{p_2 - c^{lf}\}dJ(p_2) + \int_{c^{lf}+f}^{\infty} f dJ(p_2)\right\}$$

$$=\; p_1 - c^{lf} - f + \beta\left\{(c^M - c^{lf})J(c^M) + \int_{c^M}^{c^{lf}+f} p_2 dJ(p_2) - c^{lf}(J(c^{lf}+f) - J(c^M))\right.$$

$$\left.+f(1 - J(c^{lf}+f))\right\}$$

$$
\begin{aligned}
= \quad & p_1 - c^{lf} - f + \beta \Bigg\{ (c^M - c^{lf}) J(c^M) + p_2 J(p_2) \Big|_{c^M}^{c^{lf}+f} - \int_{c^M}^{c^{lf}+f} J(p_2) dp_2 \\
& - c^{lf} (J(c^{lf} + f) - J(c^M)) + f(1 - J(c^{lf} + f)) \Bigg\} \\
= \quad & p_1 - c^{lf} - f + \beta \Bigg\{ (c^M - c^{lf}) J(c^M) + (c^{lf} + f) J(c^{lf} + f) - c^M J(c^M) - \int_{c^M}^{c^{lf}+f} J(p_2) dp_2 \\
& - c^{lf} (J(c^{lf} + f) - J(c^M)) + f(1 - J(c^{lf} + f)) \Bigg\} \\
= \quad & p_1 - c^{lf} - (1 - \beta) f - \beta \int_{c^M}^{c^{lf}+f} J(p_2) dp_2.
\end{aligned}
$$

From equation (7) we know that

(A-2)
$$
p_1 - c^{lf} - (1 - \beta) f - \beta \int_{c^{lf}}^{c^{lf}+f} J(p_2) dp_2 = 0.
$$

Since $c^{lf} \leq c^M$, then $\int_{c^{lf}}^{c^{lf}+f} J(p_2) dp_2 \geq \int_{c^M}^{c^{lf}+f} J(p_2) dp_2$. Hence we have

$$
\Delta^{nw}(c^{lf}) \geq 0.
$$

The equality holds when $J(c^{lf} + f) = 0$.

Step 2. Show $\Delta^{nw}(c^M) < 0$.

Plugging c^M into equation (12) we have

$$
\begin{aligned}
\Delta^{nw}(c^M) \quad = \quad & p_1 - c^M - f + \beta \Bigg\{ \int_{c^M}^{\infty} \{ \max[p_2 - c^M, 0] - \max[p_2 - c^M - f, 0] \} dJ(p_2) \Bigg\} \\
= \quad & p_1 - c^M - f + \beta \Bigg\{ \int_{c^M}^{\infty} (p_2 - c^M) dJ(p_2) - \int_{c^M+f}^{\infty} (p_2 - c^M - f) dJ(p_2) \Bigg\}
\end{aligned}
$$

$$
\begin{aligned}
&= p_1 - c^M - f + \beta \left\{ \int_{c^M}^{c^M+f} (p_2 - c^M) dJ(p_2) + \int_{c^M+f}^{\infty} f dJ(p_2) \right\} \\
&= p_1 - c^M - f + \beta \left\{ (p_2 - c^M) J(p_2) \Big|_{c^M}^{c^M+f} - \int_{c^M}^{c^M+f} J(p_2) dp_2 + f - \int_{0}^{c^M+f} f dJ(p_2) \right\} \\
&= p_1 - c^M - f + \beta \left\{ f - \int_{c^M}^{c^M+f} J(p_2) dp_2 \right\}.
\end{aligned}
$$

From equation (7) we know that

(A-3)
$$
\Delta^{lf}(c^{lf}) = p_1 - c^{lf} - (1-\beta)f - \beta \int_{c^{lf}}^{c^{lf}+f} J(p_2) dp_2 = 0.
$$

Since in this case $c^M > c^{lf}$ and $\partial \Delta^{lf}/\partial c < 0$, then $\Delta^{nw}(c^M) < 0$.

Item D

In this item we show that the equilibrium investment level in period one does not exist whenever an NWM level M is in the range of $(G(c^{lf}), G(\bar{c})]$. That is, if $M \in (G(c^{lf}), G(\bar{c})]$, then there does not exist an X_1^{nw} such that $X_1^{nw} = r(X_1^{nw})$.

Suppose there is an X_1^{nw} such that $X_1^{nw} = r(X_1^{nw})$. Then it must be true that either $X_1^{nw} \geq M$ or $X_1^{nw} < M$. If neither $X_1^{nw} > M$ nor $X_1^{nw} \leq M$ is true, then we can conclude that such a fixed point X_1^{nw} does not exist.

Suppose $X_1^{nw} < M$. By equation (11) we know that the RIN price in period two is $\max\{c^M + f - p_2, 0\}$. As we show in Case 1, if $p^{RIN} = \max\{c^M + f - p_2, 0\}$ then we have $r(X_1^{nw}) = G(\bar{c})$. But in Case 2 we know that $M \leq G(\bar{c})$. Hence $X_1^{nw} < M \leq r(X_1^{nw})$. So $X_1^{nw} \neq r(X_1^{nw})$ when $X_1^{nw} < M$.

Now suppose $X_1^{nw} \geq M$. By equation (11) we know that $p^{RIN} = \max\{c^M - p_2, 0\}$. We have already shown in Item C that $c^{lf} \leq c^{nw} < c^M$ for any $X_1 \geq M$. Therefore we have

42

$r(X_1^{nw}) < M \le X_1^{nw}$. So $X_1^{nw} \ne r(X_1^{nw})$ when $X_1^{nw} \ge M$.

In sum, there does not exist an X_1^{nw} such that $X_1^{nw} = r(X_1^{nw})$. Hence, the equilibrium investment level in period one does not exist if an NWM level M is in the range of $(G(c^{lf}), G(\bar{c})]$.

Item E

In this item we show the algebra to arrive at equation (14). Plugging equation (13) into equation (3), we get

$$
\begin{aligned}
\Delta^w(c) &= p_1 - c - f + \beta \left\{ \int_0^\infty \{\max[p_2 + \max[G^{-1}(X_1) - p_2, 0] - c, 0] \right. \\
&\quad - \max[p_2 + \max[G^{-1}(X_1) - p_2, 0] - c - f, 0]\}dJ(p_2) \Big\} \\
&= p_1 - c - f + \beta \left\{ \int_0^\infty \{\max[\max[G^{-1}(X_1), p_2] - c, 0] \right. \\
&\quad - \max[\max[G^{-1}(X_1), p_2] - c - f, 0]\}dJ(p_2) \Big\} \\
&= p_1 - c - f + \beta \left\{ \int_0^{G^{-1}(X_1)} \{\max[G^{-1}(X_1) - c, 0] - \max[G^{-1}(X_1) - c - f, 0]\}dJ(p_2) \right. \\
&\quad + \int_{G^{-1}(X_1)}^\infty \{\max[p_2 - c, 0] - \max[p_2 - c - f, 0]\}dJ(p_2) \Big\}.
\end{aligned}
$$

Apply the equilibrium condition $G^{-1}(x_1) = c^w$; then

$$
\begin{aligned}
\Delta^w(c^w) &= p_1 - c - f + \beta \left\{ \int_{c^w}^\infty \{\max[p_2 - c^w, 0] - \max[p_2 - c^w - f, 0]\}dJ(p_2) \right\} \\
&= p_1 - c^w - f + \beta \left\{ \int_{c^w}^{c^w+f} (p_2 - c^w)dJ(p_2) + \int_{c^w+f}^\infty f dJ(p_2) \right\}
\end{aligned}
$$

43

$$= p_1 - c^w - f + \beta \left\{ \int_{c^w}^{c^w+f} p_2 dJ(p_2) - c^w[J(c^w+f) - J(c^w)] + f(1 - J(c^w+f)) \right\}$$

$$= p_1 - c^w - f + \beta \left\{ p_2 dJ(p_2) \Big|_{c^w}^{c^w+f} - \int_{c^w}^{c^w+f} J(p_2) dp_2 \right.$$

$$\left. - c^w[J(c^w+f) - J(c^w)] + f(1 - J(c^w+f)) \right\}$$

$$= p_1 - c^w - f + \beta \left\{ (c^w+f)J(c^w+f) - c^w J(c^w) - \int_{c^w}^{c^w+f} J(p_2) dp_2 \right.$$

$$\left. - c^w[J(c^w+f) - J(c^w)] + f(1 - J(c^w+f)) \right\}$$

$$= p_1 - c^w - f + \beta \left\{ f - \int_{c^w}^{c^w+f} J(p_2) dp_2 \right\}$$

$$= p_1 - c^w - (1-\beta)f - \beta \int_{c^w}^{c^w+f} J(p_2) dp_2 = 0.$$

Item F

In this item we show that the WM policy has no effect on first-period investment level when $M \in (G(c^{lf}), G(\bar{c})]$ and when investors' marginal costs are constant. If M is in this range, then X_1 can be either greater than or less than M. In the following analysis we show that no matter $X_1 < M$ or $X_1 \geq M$, we will have $c^w = c^{lf}$.

Subcase 1. $X_1 < M$

In this case $p^{RIN} = \max[G^{-1}(X_1) - p_2, 0]$. The situation is exactly the same as what we discuss in Case 1 of section "The Effects of WM Policy ". Then in equilibrium $c^w = c^{lf}$.

Subcase 2. $X_1 \geq M$

When $X_1 \geq M$, no new investment is needed in the second period to meet the mandate. The RIN market will not start working until p_2 cannot keep M plants running. In this case

we have $p^{RIN} = \max[c^M - p_2, 0]$. Plugging this RIN price into equation (3), we get

$$
\begin{aligned}
\Delta^w(c) &= p_1 - c - f + \beta \left\{ \int_0^\infty \{\max[p_2 + \max[c^M - p_2, 0] - c, 0] \right. \\
&\quad \left. - \max[p_2 + \max[c^M - p_2, 0] - c - f, 0]\} dJ(p_2) \right\} \\
&= p_1 - c - f + \beta \left\{ \int_0^\infty \{\max[\max[c^M, p_2] - c, 0] \right. \\
&\quad \left. - \max[\max[c^M, p_2] - c - f, 0]\} dJ(p_2) \right\} \\
&= p_1 - c - f + \beta \left\{ \int_0^{c^M} \{\max[c^M - c, 0] - \max[c^M - c - f, 0]\} dJ(p_2) \right. \\
&\quad \left. + \int_{c^M}^\infty \{\max[p_2 - c, 0] - \max[p_2 - c - f, 0]\} dJ(p_2) \right\}.
\end{aligned}
$$

If in equilibrium $X_1 = G(c^w) \geq M$, then we have $c^w \geq c^M$. Therefore,

$$
\begin{aligned}
\text{(A-4)} \quad \Delta^w(c^w) &= p_1 - c^w - f + \\
&\quad \beta \left\{ \int_{c^M}^\infty \{\max[p_2 - c^w, 0] - \max[p_2 - c^w - f, 0]\} dJ(p_2) \right\} \\
&= p_1 - c^w - f + \beta \left\{ f - \int_{c^w}^{c^w+f} J(p_2) dp_2 \right\} = 0.
\end{aligned}
$$

Comparing equation (7) and (A-4), we can see $c^w = c^{lf}$.

Item G

In this item we show from Example 2 how to obtain $s^w = 1$ using equations (21) and (22). First, plug $\beta = 1$, $p_1 = 1$, $p^h = 2$, and $f = 1/2$ into equation (21); then it can be written

as

(A-5)
$$
\begin{aligned}
B^w(I_1) &= \frac{1}{2}(1-s^w)^2 - \frac{1}{2} + \{k[2-s^w-\frac{1}{2}] + (1-k)\cdot\frac{1}{2}\} \\
&= \frac{1}{2}(1-s^w)^2 - \frac{1}{2} + \{\frac{1}{2} + k(1-s^w)\}.
\end{aligned}
$$

Second, plug $\beta = 1$, $p^{RIN} = 1+s^w$, $u^w(q) = s^w + q$, $p^h = 2$, and $f = 1/2$ into equation (22); then it can be written as

(A-6)
$$
\begin{aligned}
B^w(NI_1) &= \{k[2-s^w-\frac{1}{2}-\frac{1}{2}] + \\
&\quad (1-k)(\max[0,(1+s^w)\cdot 1 - \int_0^1 s^w + qdq - \frac{1}{2}])\} \\
&= \{k(1-s^w) + (1-k)(\max[0,1+s^w-(s^w+\frac{1}{2})-\frac{1}{2}])\} \\
&= k(1-s^w).
\end{aligned}
$$

For the break-even investor we must have $B^w(I_1) = B^w(NI_1)$. From equations (A-5) and (A-6) we have

$$
\begin{aligned}
& B^w(I_1) = B^w(NI_1) \\
\implies & \frac{1}{2}(1-s^w)^2 - \frac{1}{2} + \frac{1}{2} + k(1-s^w) = k(1-s^w) \\
\implies & \frac{1}{2}(1-s^w)^2 = 0 \\
\implies & s^w = 1.
\end{aligned}
$$

46