Mandates and the Incentives for Innovation

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Abstract

One prominent feature of the US biofuels sector is its reliance on mandates to enforce use. The performance of this policy tool has been mixed, with corn-based ethanol production successfully meeting targets but cellulosic ethanol falling well short of them. A crucial difference in this setting is that corn-based ethanol relies on a mature technology whereas the prospect of meeting cellulosic ethanol mandates was always predicated on the development of new technologies. Is it reasonable to expect that mandates would work well as an incentive for innovation? To address this question, we develop a partial equilibrium model with endogenous innovation to examine the incentives for innovation in production under a mandate and compare this policy to two benchmark situations: *laissez-faire* and a carbon tax. We find that a mandate creates relatively strong incentives for investment in R&D in low-quality innovations, but relatively weak incentives to invest in high-quality innovations. Moreover, mandates are likely to underperform carbon taxes in welfare terms.

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1. Introduction

The use of "mandates" is one of the distinctive features of the 2007 Energy Independence and Security Act (EISA), which envisioned overall biofuel consumption in the United States growing to 36 billion gallons by 2022, a major part of which was to be accounted for by advanced biofuels such as cellulosic ethanol. Mandates have been effective at spurring the growth of the corn-based ethanol industry, which steadily accumulated the capacity required to produce the mandated targets in a timely fashion.[1] This stands in sharp contrast to the case of cellulosic ethanol. Indeed, for the fifth year in a row, the US Environmental Protection Agency (EPA) has waived the mandate for cellulosic ethanol: for 2014 the EPA proposes to blend a mere 17 million gallons of cellulosic ethanol into the fuel supply, down from the EISA statutory requirement of 1,750 million gallons (EPA 2013). In order to explain such a drastically different performance of biofuel mandates, this paper focuses on the incentives to innovate that are provided by such a policy. Our main result is that this policy is less likely to spur the development of production technologies capable of competing with fossil fuels compared to alternative policies.

We describe a market with a clean and dirty fuel that are close substitutes, such as cellulosic ethanol and conventional fuel. The dirty fuel imposes a negative externality on society, for example via its impact on climate change. The clean fuel has no such externality, and the cost of producing it can be lowered through research and development (R&D), for which innovators receive patents. Patents provide a second-best solution to the problem of incentivizing innovation for most markets (Clancy and Moschini, 2013). However, for a market where there is an additional externality, as implied by the presumed benefit of substituting clean for dirty fuel, innovation may be further under-provided even in the presence of patents (Jaffe, Newell and Stavins, 2005). A policy maker can intervene to correct this inefficiency, but his information about the likely cost and outcome of R&D is not as good as the innovator's.

In our model, an optimal carbon tax completely neutralizes the environmental externality effect. Indeed, when there is a carbon tax, the model is equivalent to an externality-free market with a more expensive cost to producing dirty fuel. However, because the innovation process is itself fraught with market failures (Jaffe, Newell and Stavins, 2005), such a policy does not necessarily maximize welfare. Specifically, in our setting, patents are an imperfect instrument to spur innovation (e.g., the *ex post* market power due to intellectual property rights restricts use of new technologies). Since our paper is about the innovation challenges posed specifically by environmental externalities, rather than innovation per se, we treat the second-best nature of patents as an unavoidable loss. We consider a carbon tax as the benchmark case against which an alternative corrective policy, the mandate, can be compared. One interpretation of our paper is the impact of alternative externality corrections, once the over-riding problem of providing incentives for innovation has been "fixed" (at least in a second-best sense). We show how a mandate, besides leading to a sub-optimal static

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[1] Other federal policies that played a significant role in the development of the corn-based ethanol industry included a blender tax credit (i.e., a subsidy) and a specific duty on ethanol imports, both of which were discontinued at the end of 2011 (Moschini, Cui and Lapan, 2012).

equilibrium compared to an optimal carbon tax, also leads to different innovation outcomes. We will show that a mandate is relatively good at incentivizing incremental innovation but a poor spur to radical innovation, while a carbon tax has opposite effects. Moreover, we will argue an optimal mandate (addressing innovation and environmental market failures) will usually lead to lower welfare than a carbon tax designed to correct the environmental externality alone.

The paper is organized as follows. In Section 2 we provide a brief overview of the relevant theoretical and empirical literature on environmental policy and innovation. The majority of our paper is in Section 3, which lays out our model and derives our results. Section 4 explicitly compares the mandate policy with the carbon tax. In Section 5 we discuss further the relevance of our model to biofuel sector issues. Finally, in Section 6 we conclude and offer some thoughts about further research.

2. Background

As noted by Jaffe, Newell, and Stavins (2005), innovation has the potential to greatly ease, or even eliminate, the cost of addressing specific environmental problems. For this reason, the impact of a policy on the direction and rate of technological progress is of paramount concern. But innovation and environmental policy face distinct yet interacting market failures that pose unique challenges.

Magat (1978) is one of the first to consider how innovation is impacted by different environmental policies. He developed a model where firms discharge an effluent as part of their production process, and examined the impact on R&D under an effluent tax and a fixed effluent quota. We will be adopting a similar comparison between mandates and taxes. Magat (1978) showed the choice of policy affects R&D spending, but was unable to draw firm conclusions about the relative size of R&D spending under the policies.

In another early paper in this area, Downing and White (1986) used the abatement approach, wherein firms spend resources to "abate" their pollution and face different incentives to develop lower-cost abatement technologies under different policies. They are among the first to appreciate that much hinges on assumptions about the damage function of pollution. For example, imagine a policy maker sets a pollution tax equal to the marginal damage from pollution. After an innovation, firms will abate more pollution, until doing so costs more than the pollution tax. However, if all firms have abated more pollution, this may reduce the marginal damage from pollution, so that the tax is now too high. In such a case, firms will over-invest in improving their abatement technologies.

Our model assumes a "dirty" technology causes constant marginal damage, which we imagine to be carbon-induced climate change. This approach is valid if changes in the industry's carbon output have a small effect on the global carbon stock, which is the main determinant of climate change. When Downing and White (1986) also assume constant marginal damage from pollution, they find that firms under-invest in improving their technology under mandates, since they do not take into account possible savings from exceeding their abatement mandate.

Requate (2005) provides a nice summary of the theoretical literature on environmental policy tools and innovation, emphasizing the difficulty in definitively ranking alternative policies, but concluding that price-based incentives tend to perform better on the whole. Our paper broadly supports this conclusion. Turning to the empirical literature, Johnstone, Hascic and Popp (2010) is one of the most comprehensive studies of different policies across the world on environmental innovation. They use counts of patents in different renewable energy fields – wind, solar, geothermal, ocean, and biomass/waste – as proxies for innovation. With their international data set, the authors exploit variation in national level policies across different fields, including renewable energy credits and obligations. The variable "renewable energy credits" is measured by the percent of electricity in a nation that must be provided by renewable energy sources, while the variable "obligations" is a dummy variable for the presence of guaranteed markets or production quotas.

The results in Johnstone, Hascic and Popp (2010) are mixed. Quota policies such as renewable energy credits and obligations were both significant and positive predictors of patent applications for wind energy alone (although renewable energy credits were significant for geothermal too). In the biofuel and waste category, only investment incentives (which included risk guarantees, grants, and low-interest loans) were significantly related to patent activity. Across the five renewable energy fields, the policy that is most often effective at generating patents is public R&D spending, which is hardly surprising.

Karmarker-Deshmukh and Pray (2009) perform essentially the same exercise on biofuel patents alone, and again find weak results. In some of their specifications, lagged oil prices and grants are significant predictors of biofuel patent applications, but a dummy variable for the Renewable Fuel Standard is not, nor are ethanol subsidies (indeed, the coefficient is in the wrong direction). In general it is very difficult to measure the effect of policies on environmental innovation for a number of reasons. The data is noisy and there is not a lot of it (approximately 28 yearly observations in the above two papers). It is difficult to observe the counterfactual, especially since knowledge generated in one country, using policy A, can spill over into another country using policy B. Furthermore, most countries use a suite of policies, which makes it difficult to identify individual effects. Finally, reverse causality is a concern, since policy makers may decide to implement policies that aid struggling technologies or technologies they believe are primed to break through.

There is scant other literature on the economics of innovation and biofuels. Miranowski (2014) provides a summary and qualitative analysis of US policies that have been used to incentivize biofuel innovation. Hettinga et al. (2009) and van den Wall Bake et al. (2009) document a decrease in the production costs of conventional ethanol over many years, which they attribute to passive learning-by-doing effects. These two papers are based on a simple comparison of cumulative production and production costs, and so it is impossible to rule out that the cost reductions are instead due to R&D spending, or even exogenous technical change.

3. The Model

In this paper we choose to model innovation as a purposeful economic activity undertaken by innovators seeking to profit from licensing their ideas. Our basic model of innovation is based on the space of ideas approach discussed in Scotchmer (2004, chapter 4), where innovators decide whether or not to conduct R&D after obtaining a draw from the space of all ideas. In our model, we extend this approach by assuming that these draws give the innovator a signal about the likely quality of innovation, as well as the cost of R&D needed to realize the innovation. Rather than using an abatement approach, as is popular in the theoretical literature discussed in the previous section, we focus on the introduction of a clean product that can substitute for an existing product that has a negative environmental externality (the dirty sector). This approach has recently been used in the context of climate change (e.g., Acemoglu et al. 2012), and fits the ethanol versus conventional fossil fuel debate well. Our model of consumer demand for biofuels is most similar to de Gorter and Just (2009) and Lapan and Moschini (2012).

To simplify the derivation of meaningful results, we represent the relevant demand and marginal cost functions by linear parameterizations. Consumers have preferences for a *numeraire* good and fuel Q (expressed in energy units), with the aggregate inverse demand for Q given by:

$$p(Q) = A - BQ \tag{1}$$

where $A > 0$ and $B > 0$. This curve is depicted by the line connecting tz in Figure 1. There are two sources of fuel, Q_1 and Q_2, which are perfect substitutes from the consumer's perspective. Consumers purchase fuel from perfectly competitive blenders who produce a blended fuel mix according to:

$$Q = Q_1 + Q_2 \tag{2}$$

The fuel Q_1 corresponds to an older "dirty" technology, e.g., conventional fossil fuel. This industry is perfectly competitive and produces fuel at constant marginal cost c_1, so that in equilibrium the price paid by the blenders for input Q_1 is

$$P_1 = c_1 \tag{3}$$

The fuel Q_2 corresponds to a new "clean" technology, such as cellulosic ethanol. This industry is also perfectly competitive, but with an upward-sloping marginal cost function. Specifically, the marginal of the clean technology is given by:

$$\frac{\partial c_2(Q_2, \theta)}{\partial Q_2} = c_1 + d + Q_2 - \theta \tag{4}$$

where θ is a parameter corresponding to the quality of the production technology (marginal costs decrease as θ rises), and d is a parameter that represents the externality (the marginal "damage") of the dirty technology. Note that we are postulating decreasing returns to scale for the clean fuel, consistent with the presumption that increasing cellulosic ethanol production will need to compete for land with other uses, and may also face increasing costs of transporting bulky biomass from more distant agricultural production sites.

Initially, $\theta = 0$ but there is an innovating sector that can develop new methods of producing Q_2. These possible new technologies are indexed by a new $\theta > 0$ in the cost function $c_2\left(Q_2, \theta\right)$. Innovation is understood as producing know-how, and this knowledge is patentable. Innovators produce a blueprint for a new technology, and can license these blueprints to the competitive production sector in exchange for a fixed royalty λ per unit of Q_2.

To develop a new production technique, innovators first receive a draw of $\left(k, \omega\right)$ from a joint uniform distribution with probability density function (PDF) given by:

$$g\left(k,\omega\right) = \begin{cases} 1/\left(\bar{k}\bar{\omega}\right) & \text{if } k \in \left[0,\bar{k}\right] \text{ and } \omega \in \left[0,\bar{\omega}\right] \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

The draw $\left(k, \omega\right)$ corresponds to industry-specific knowledge about the outlook for innovation, and is not observed by the policy maker, although the distribution $g\left(k, \omega\right)$ is common knowledge. If an innovator decides to conduct R&D after observing $\left(k, \omega\right)$, she must spend k on R&D to obtain a draw θ from a uniform distribution with PDF given by:

$$f\left(\theta \mid \omega\right) = \begin{cases} 1/\omega & \text{if } \theta \in \left[0,\omega\right] \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

A draw from $g\left(k, \omega\right)$ can be interpreted as describing two dimensions of technological opportunity. The k dimension indexes the inputs to innovation, with low values of k corresponding to low-hanging fruit in innovation space that are cheap to implement. The ω dimension indexes the potential outputs to innovation. This choice of functional form for $f\left(\theta \mid \omega\right)$ implies researchers know the upper bound on the quality of innovations they build. Better draws of ω increase this upper bound, as well as increasing the probability of better draws overall, but since even the most promising innovation can fail, the lower bound on innovation quality is always 0.

3.1. The Innovator's Problem

We assume there is only one firm capable of innovating.[2] In the absence of government policy, the clean production sector can be interpreted as facing an inverse residual demand curve:

$$P_2 = \begin{cases} c_1 & \text{if } Q_2 \le \dfrac{A-c_1}{B} \\ p(Q_2) & \text{if } Q_2 > \dfrac{A-c_1}{B} \end{cases} \tag{7}$$

Denote the inverse residual demand curve under a *laissez-faire* policy, given by equation (7) as

$$P_2 = p_2^L(Q_2) \tag{8}$$

We illustrate $p_2^L(Q_2)$ by the lines connecting wyz in Figure 1.

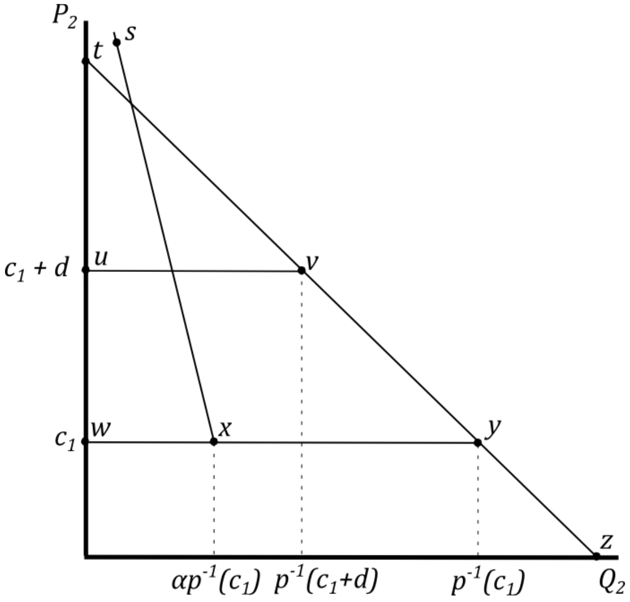

Figure 1. Demand Curves

$$p(Q): tz,\ p_2^L(Q_2): wyz,\ p_2^T(Q_2): uvz,\ p_2^M(Q_2): sxyz$$

Because the clean production sector is competitive, its equilibrium output is given by equating marginal cost to price. When the innovator sets a royalty rate, the royalty is added to the producer's marginal cost, affecting the equilibrium output decision. The innovator's problem is therefore:

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[2] The analysis of the multiple innovators case is the object of ongoing work.

$$\max_{\lambda}\left[\lambda Q_2\right] \tag{9}$$

such that

$$c_1 + d + Q_2 - \theta + \lambda = p_2^L\left(Q_2\right) \tag{10}$$

$$Q_2 \geq Q_2' \tag{11}$$

$$c_1 + d + Q_2' = p_2^L\left(Q_2'\right) \tag{12}$$

Equation (10) sets the effective marginal cost for producers, after taking into account royalties, equal to price. Equations (11) and (12) capture the constraint on the choice of royalty imposed by the perfect competition equilibrium using the pre-innovation technology. We assume that if equation (11) is not satisfied there is scope for one of the firms to deviate and steal the market by forgoing the new technology and charging the old price $p_2^L\left(Q_2'\right)$.

Note that the model is calibrated such that $\partial c_2\left(0,0\right)/\partial Q_2 > c_1$. Hence, we maintain the hypothesis that the clean fuel is never produced in a *laissez-faire* setting, which motivates interest in policies such as mandates and/or a carbon tax.

3.2. The Mandate

As noted earlier, it is assumed that production of Q_1, the conventional fuel, has a negative externality that imposes on society marginal damage d per unit produced (e.g., the dirty fuel may contribute to global climate change). Because producers and consumers do not internalize this negative externality, there is over-production of the dirty fuel. Moreover, given our assumptions, the supply of the clean fuel is zero under *laissez faire*. This is sub-optimal if the marginal cost of producing the clean fuel is less than $c_1 + d$. The natural way to address such an externality is by taxing production of the dirty fuel at rate d. We will consider such a policy in the next section.

For various reasons, a carbon tax may be infeasible and the policy maker may be forced to rely on different instruments to address the externality. One option is a mandate, which may be implemented in one of two ways. What we call an *absolute* mandate requires that $Q_2 \geq Q_2^0$, so that clean production must exceed some target supply Q_2^0. What we call a *proportional* mandate requires that $Q_2 \geq \alpha Q$, so that blended fuel sold to consumers must consist of at least a fraction α of clean fuel.

US biofuel policy, for example, can be viewed both in terms of absolute or proportional mandates. In the medium term, the EISA sets absolute targets for the production of various kinds of biofuels. However, in any given year, these policies are implemented as a proportional mandate, with the proportion required computed from the absolute target and the anticipated demand for fuel. In what follows, we represent a mandate policy specifically in terms of a proportional mandate. In any event, under certain conditions, discussed next, absolute and proportional mandates are equivalent.

Under a mandate, blenders are required to insure that

$$Q_2 \geq \alpha Q \tag{13}$$

where $\alpha \in [0,1]$ is the parameter quantifying the extent of the mandate, which is chosen by the policy maker. Whenever $P_2 > c_1$ blenders will minimize costs by choosing Q_2 so that equation (13) holds with equality. When this is the case, the price of fuel for consumers is

$$P = (1-\alpha)c_1 + \alpha P_2 \tag{14}$$

Conversely, when $P_2 \leq c_1$ the mandate is not binding. Equations (13) and (14) imply the inverse residual demand curve faced by innovators under a mandate is

$$P_2 = \begin{cases} \dfrac{A-(1-\alpha)c_1}{\alpha} - \dfrac{B}{\alpha^2}Q_2 & \text{if } Q_2 \leq \alpha\dfrac{A-c_1}{B} \\ p_2^L(Q_2) & \text{if } Q_2 > \alpha\dfrac{A-c_1}{B} \end{cases} \tag{15}$$

Denote the inverse residual demand curve in equation (15) by $p_2^M(Q_2)$, illustrated by the lines connecting $sxyz$ in Figure 1. This curve follows $p(Q_2)$ for $P_2 < c_1$, and has a horizontal segment connecting $\alpha p^{-1}(c_1)$ and $p^{-1}(c_1)$ for $P_2 = c_1$. The curve $p_2^M(Q_2)$ has a steeper slope than $p(Q_2)$ when the mandate binds because demand is not as responsive to changes in the price of clean fuel, which are only partially passed onto consumers. It passes through $p(Q_2)$ at

$$Q_2 = \frac{\alpha}{1+\alpha}\frac{A-c_1}{B} \tag{16}$$

which is less than the point where the mandate binds, given by $Q_2 = \alpha\dfrac{A-c_1}{B}$.

Note that in the absence of innovation, the supply of cellulosic ethanol is given by the intersection of the binding portion of $p_2^M(Q_2)$ and the industry marginal cost. This competitive supply level, denoted Q_C, is therefore:

$$Q_C = \alpha\frac{A-c_1-\alpha d}{\alpha^2+B} \tag{17}$$

In the presence of innovation, the optimal supply an innovator should induce (through their choice of royalties) may be discontinuous under a mandate, given the kinked demand curve. To simplify our exposition, we make the following assumption:

$$\alpha < \frac{A - c_1}{\bar{\omega} + d} \tag{18}$$

This assumption implies the binding mandate portion of $p_2^M(Q_2)$ is steep enough that the innovator will always set the royalty as high as feasible. Given the pre-innovation equilibrium, this implies $\lambda = \theta$, so that post-licensing production costs are equal to pre-innovation levels and optimal supply is Q_C. Under this assumption, the proportional mandate is equivalent to an absolute mandate.

Solving equations (9)-(12), with $p_2^M(Q_2)$ and assumption (18) we obtain the following optimal responses:

$$Q_2 = Q_C \quad \lambda = \theta \quad \pi^M(\theta) = \theta Q_C \tag{19}$$

where $\pi^M(\theta)$ denotes the maximum licensing profit an innovator with θ can obtain, under a mandate. Note the profit increases with the quality of the innovation. Since $\pi^M(\theta)$ is just θ multiplied by a scalar,

$$E\left[\pi^M(\theta) \mid \omega\right] = \frac{1}{2} Q_C \omega \tag{20}$$

We now turn to calculating the expected quality of innovation, given a mandate.

Recall that the innovator observes a draw (k, ω) before deciding whether or not to invest. We assume the innovator is risk-neutral so that she will pay k to conduct R&D whenever

$$k \le E\left[\pi^T(\theta) \mid \omega\right] \tag{21}$$

We will also assume $\bar{k} \ge E\left[\pi^T(\theta) \mid \bar{\omega}\right]$, so that for each draw of $\omega \in [\theta, \bar{\omega}]$ the probability investment occurs is $E\left[\pi^M(\theta) \mid \omega\right] / \bar{k}$. Moreover, given a signal ω, the probability of drawing θ is $1/\omega$. Therefore, the post-innovation PDF for θ, denoted $h_1^M(\theta)$, for $\theta > 0$, is equal to:

$$h_1^M(\theta) = \int_{\theta}^{\bar{\omega}} \frac{E\left[\pi^M(\theta) \mid \omega\right]}{\omega \bar{k}} \frac{1}{\bar{\omega}} d\omega \tag{22}$$

or

$$h_1^M(\theta) = \frac{Q_C(\bar{\omega} - \theta)}{2\bar{\omega}\bar{k}} \tag{23}$$

Note that the post-innovation probability of obtaining any given $\theta > 0$ is increasing in the size of the mandate and decreasing in the upper bound on research costs, since these increase the probability investment occurs.

Integrating over θ we obtain the expected quality of the innovation under the mandate policy:

$$E[\theta \mid M] = \frac{Q_C \bar{\omega}^2}{12\bar{k}} \tag{24}$$

Ultimately, the expected post-innovation technology under a mandate is increasing in the size of the mandate and the upper bound on technological opportunity, and decreasing in research costs.

Next, we turn to computing expected welfare under a mandate.

Welfare, in our partial equilibrium framework, is the sum of consumer surplus (given by $B(Q_1 + Q_2)^2 / 2$), clean industry profits ($Q_2^2 / 2$) and the innovator's license income ($\pi^i(\theta)$), less externality damages (dQ_1) and R&D costs (k). Given the constraints we imposed, $Q_1 + Q_2 = Q_C / \alpha$ and $Q_2 = Q_C$, where Q_C is determined by the policy-maker's choice of α . As discussed above, $\pi^M(\theta) = \theta Q_C$. Given θ, ω and k, welfare under a carbon tax is:

$$W(\theta, \omega, k) = \begin{cases} \dfrac{Q_C^2}{2\alpha^2}\left(B + \alpha^2\right) - \dfrac{dQ_C(1-\alpha)}{\alpha} + \theta Q_C - k & \text{if } k < \omega Q_C/2 \\ \dfrac{Q_C^2}{2\alpha^2}\left(B + \alpha^2\right) - \dfrac{dQ_C(1-\alpha)}{\alpha} & \text{otherwise} \end{cases} \tag{25}$$

where the upper term in equation (25) is welfare when R&D occurs and the lower term is welfare in the absence of R&D. Expected welfare under the mandate policy is therefore given by:

$$E[W \mid M] = \frac{Q_C^2}{2\alpha^2}\left(B + \alpha^2\right) - \frac{dQ_C(1-\alpha)}{\alpha} + \frac{1}{\bar{\omega}\bar{k}} \int_0^{\bar{\omega}} \int_0^{\omega Q_C/2} \int_0^{\omega} (\theta Q_C - k)\, d\theta\, dk\, d\omega \tag{26}$$

Performing the integration yields:

$$E[W \mid M] = \left\{ \frac{Q_C^2}{2\alpha^2}\left(B + \alpha^2\right) - \frac{dQ_C(1-\alpha)}{\alpha} \right\} + \frac{Q_C^2 \bar{\omega}^2}{24\bar{k}} \tag{27}$$

The terms in braces on the right hand side of equation (27) represent welfare in the absence of innovation, and the second term is the increase in welfare due to innovation. Using equation (17), we can rewrite the equation for expected welfare in the absence of innovation, denoted $E\left[W_S \mid M\right]$ (where the subscript S stands for *status quo*), as:

$$E\left[W_S \mid M\right] = \frac{A - c_1 - \alpha d}{B + \alpha^2}\left[\frac{A - c_1}{2} - d\left(1 - \alpha / 2\right)\right] \tag{28}$$

The social planner's problem, in the absence of innovation, is to find the level of α which maximizes equation (28). A closed-form solution for such an optimal mandate, given our parameterization, is not possible. However, at $\alpha = 0$, which is equivalent to the *laissez-faire* setting, we find that:

$$\left.\frac{\partial E\left[W_S \mid M\right]}{\partial \alpha}\right|_{\alpha=0} = \frac{d^2}{B} \tag{29}$$

Because this is greater than zero, it follows that expected static welfare can be improved by using a positive mandate. The optimal choice of α will imply an optimal clean fuel supply Q_C, such that deviations away from Q_C leads to a fall in welfare.

When the social planner takes into account the potential for innovation, however, there is an additional benefit to Q_C, captured by the last term in equation (27). Since higher values of Q_C can lead to more innovation, and since this is not accounted for when innovation is neglected, the optimal value of Q_C is higher when innovation is possible. The implications of the above discussion can be summarized as follows.

Result 1: In the absence of innovation, the welfare-maximizing mandate level Q_C^S is greater than zero.

Result 2: In the presence of innovation, the welfare-maximizing mandate level Q_C^I is greater than Q_C^S.

Thus, a mandate can improve welfare relative to the *laissez-faire* case in two ways: it restricts consumption of total fuel by increasing the blended price, and it provides an incentive for innovations that reduce the cost of clean fuel production.

Comparison of the mandate policy with the *laissez-faire*, however, is not the only relevant one. We next turn to a tougher benchmark – a myopically optimal carbon tax.

3.3. The Carbon Tax

As stated earlier, a carbon tax is the natural solution to a negative externality, since it forces producers to completely internalize pollution costs. Indeed, in the absence of innovation, a carbon tax that sets $t = d$ yields the first-best allocation. Such a tax raises the cost of producing dirty fuel to $c_1 + d$ and thereby transforms the inverse residual demand curve faced by clean producers to:

$$P_2 = \begin{cases} c_1 + d & \text{if } Q_2 \leq \dfrac{A - c_1 - d}{B} \\ p(Q_2) & \text{if } Q_2 > \dfrac{A - c_1 - d}{B} \end{cases} \tag{30}$$

Denote the inverse residual demand curve given by equation (30) as $p_2^T(Q_2)$. We illustrate $p_2^T(Q_2)$ by the lines connecting uvz in Figure 1. A carbon tax shifts consumption of the dirty good to the clean one, until it is no longer cost effective to do so, and also has the effect of reducing the overall consumption of fuel. Given our assumptions about the marginal cost of clean fuel production, $Q_2 = 0$ in the absence of innovation and $Q_2 > 0$ if there is innovation.

Note that the innovator's optimal choice of royalty may again have a discontinuity, due to the kink in demand at $Q_2 = \dfrac{A - c_1 - d}{B}$. To simplify our exposition, we assume:

$$\bar{\omega} < 2\left[A - (c_1 + d)\right] / B \tag{31}$$

This ensures that the optimal royalty is always chosen such that $Q_2 \leq (A - c_1 - d)/B$, so that the kinked demand function never comes into play (i.e., even the best clean technology does not completely eliminate fossil fuel production).

Setting $Q_2' = 0$ and solving equations (9)-(12), we obtain the following optimal responses:

$$Q_2 = \frac{\theta}{2} \quad \lambda = \frac{\theta}{2} \quad \pi^T(\theta) = \left(\frac{\theta}{2}\right)^2 \tag{32}$$

where $\pi^T(\theta)$ denotes the maximum licensing profit attainable in the presence of a carbon tax when the innovator possesses technology θ. Note that output, royalties, and profit, are all increasing in the quality of the innovation. Using $E\left[\pi^T(\theta) \mid \omega\right] = \int_0^{\omega} \dfrac{\pi^T(\theta)}{\omega} d\theta$ we obtain

$$E\left[\pi^T(\theta) \mid \omega\right] = \frac{\omega^2}{12} \tag{33}$$

Note that profit from innovation licensing is expected to be higher when technological opportunity is high (modeled here by better draws of ω). Following the same procedure as in the mandate case, we next calculate the expected post-innovation technology under a carbon tax. The innovator will pay k to conduct R&D whenever

$$k \leq E\left[\pi^T(\theta) \mid \omega\right] \tag{34}$$

We will also assume $\bar{k} \geq E\left[\pi^T(\theta) \mid \bar{\omega}\right]$, so that there are no draws of ω where R&D occurs with certainty.

Instead, for each draw of $\omega \in \left[\theta, \bar{\omega}\right]$ the probability investment occurs is $E\left[\pi^T(\theta) \mid \omega\right] / \bar{k}$, and the probability of drawing θ is $1/\omega$. Therefore, the post-innovation PDF for θ, denoted $h_1^T(\theta)$, for $\theta > 0$, is equal to:

$$h_1^T(\theta) = \int_{\theta}^{\bar{\omega}} \frac{E\left[\pi^T(\theta) \mid \omega\right]}{\omega \bar{k}} \frac{1}{\bar{\omega}} d\omega \tag{35}$$

or

$$h_1^T(\theta) = \frac{\bar{\omega}^2 - \theta^2}{24 \bar{\omega} \bar{k}} \tag{36}$$

Integrating over θ we obtain the expected quality of the innovation under a carbon tax policy:

$$E\left[\theta \mid T\right] = \frac{\bar{\omega}^3}{96 \bar{k}} \tag{37}$$

The anticipated post-innovation θ under a carbon tax is increasing in $\bar{\omega}$, the upper bound on innovation quality, and decreasing in $\bar{k}$, the upper bound on the costs of R&D.

Next, we turn to computing expected welfare under a carbon tax. The welfare computation is the same as in the mandate case, except now externality damages are offset by carbon tax revenues.

Given the constraints we have imposed, $Q_1 + Q_2 = \left(A - c_1 - d\right) / B$ for all innovations under a carbon tax. Moreover, as shown above, $Q_2 = \theta / 2$ and $\pi^T(\theta) = \left(\theta / 2\right)^2$. Given θ, ω and k, welfare under a carbon tax is:

$$W(\theta, \omega, k) = \begin{cases} \dfrac{\left(A - c_1 - d\right)^2}{2B} + \dfrac{3}{8}\theta^2 - k & \text{if } k < \omega^2 / 12 \\ \dfrac{\left(A - c_1 - d\right)^2}{2B} & \text{otherwise} \end{cases} \tag{38}$$

where the upper term in equation (38) is welfare when R&D occurs and the lower term is welfare in the absence of R&D. Expected welfare under the carbon tax is therefore given by:

$$E\left[W\mid T\right]=\frac{\left(A-c_1-d\right)^2}{2B}+\frac{1}{\bar{\omega}\bar{k}}\int_0^{\bar{\omega}}\int_0^{\omega^2/12}\int_0^{\omega}\left(\frac{3}{8}\theta^2-k\right)d\theta dk d\omega \tag{39}$$

Performing the integration yields:

$$E\left[W\mid T\right]=\frac{\left(A-c_1-d\right)^2}{2B}+\frac{\bar{\omega}^4}{720\bar{k}} \tag{40}$$

The first term on the right hand side is welfare in the absence of innovation, and the second term is the increase in welfare due to innovation. As anticipated, the component of welfare due to innovation is increasing in $\bar{\omega}$ and decreasing in $\bar{k}$.

4. Mandates vs. Carbon Tax: A Comparison

A key difference between a mandate and a carbon tax is the flexibility of output under a carbon tax. In our model, the difference in flexibility is extreme, since a mandate fixes supply at Q_C for all innovations, while a carbon tax's supply increases linearly with the quality of innovation. However, this stylized result also holds in more general settings. Intuitively, a mandate – absolute or proportional – always creates relatively inelastic demand for clean fuel over a range of innovation qualities, which makes supply relatively unresponsive to innovation quality. In contrast, a carbon tax creates highly elastic demand near the price threshold of c_1+d, so that optimal supply (again, over a range) is primarily driven by the quality of innovation.

The differential supply responses drive most of the following results. For example, from equations (20) and (33), the probability that investment in R&D occurs under a carbon tax is higher than the probability it occurs under a mandate whenever:

$$\frac{1}{2}Q_C\omega<\frac{\omega^2}{12} \tag{41}$$

This condition is satisfied whenever $6Q_C<\omega$. This implies:

Result 3: The probability that R&D occurs is higher under a carbon tax, compared to a mandate, when the outlook for research outputs is sufficiently good (ω is above some threshold).

Intuitively, each policy's optimal royalty is increasing in the quality of innovation, though the optimal royalty under a mandate increases at a faster rate. However, optimal supply is fixed under a mandate and increasing under a carbon tax, so that when the expected quality of innovation is high enough –

given by the condition $6Q_C < \omega$ – expected revenue under a carbon tax is higher. Note that the threshold for ω depends on Q_C, since the higher the mandated quantity of clean fuel, the higher must be the quality of innovation for optimal supply under a carbon tax to exceed it.

The same threshold effect applies to the expected quality of innovation. From equations (24) and (37), the expected quality of the post-innovation technology is higher under a carbon tax whenever:

$$\frac{Q_C \bar{\omega}^2}{12\bar{k}} < \frac{\bar{\omega}^3}{96\bar{k}} \tag{42}$$

This condition is satisfied whenever $8Q_C < \bar{\omega}$.

Again, when the upper bound on technological opportunity $\bar{\omega}$ is sufficiently high relative to the mandate, it is likely that a high quality R&D opportunity that favors a carbon tax will materialize. Moreover, the distribution of post-innovation technologies has a higher variance under a carbon tax. From equations (23) and (36) the probability that some innovation θ is in use after innovation is higher under a carbon tax when

$$\frac{Q_C\left(\bar{\omega}-\theta\right)}{2\bar{\omega}\bar{k}} < \frac{\bar{\omega}^2-\theta^2}{24\bar{\omega}\bar{k}} \tag{43}$$

This condition is satisfied whenever $\bar{\omega}+\theta > 12Q_C$.

For example, when $8Q_C = \bar{\omega}$ so that $E\left[\theta \mid M\right] = E\left[\theta \mid T\right]$, the probability of obtaining $\theta > 4Q_C$ is higher under a carbon tax and the probability of obtaining $\theta < 4Q_C$ is higher under a mandate. Intuitively, a carbon tax is very likely to induce innovation when technological opportunity is high and unlikely to induce innovation otherwise, so that $h_1^T\left(\theta\right)$ has a lot of mass under high regions and little mass under low regions. In comparison, the distribution of mass in $h_1^M\left(\theta\right)$ is more equitably distributed. This implies:

Result 4: When the expected technology is the same under a mandate and a carbon tax, the distribution of realized technologies under a carbon tax, as compared to a mandate, is characterized by the more disperse outcomes (both high quality innovations and no innovation are more likely).

Finally, turning to welfare, expected welfare under a carbon tax is higher when:

$$\left\{\frac{Q_C^2}{2\alpha^2}\left(B+\alpha^2\right)-\frac{dQ_C\left(1-\alpha\right)}{\alpha}\right\}+\frac{Q_C^2\bar{\omega}^2}{24\bar{k}} < \frac{\left(A-c_1-d\right)^2}{2B}+\frac{\bar{\omega}^4}{720\bar{k}} \tag{44}$$

Recall that the terms in braces on the left-hand side of equation (44) and the first term on the right hand side each correspond to static welfare in the absence of innovation. Since a carbon tax induces the first-best allocation in the absence of innovation, it must be that

$$\left\{\frac{Q_C^2}{2\alpha^2}\left(B+\alpha^2\right)-\frac{dQ_C\left(1-\alpha\right)}{\alpha}\right\}<\frac{\left(A-c_1-d\right)^2}{2B} \tag{45}$$

for all feasible values of Q_C. Thus, whenever

$$\frac{Q_C^2\bar{\omega}^2}{24\bar{k}}<\frac{\bar{\omega}^4}{720\bar{k}} \tag{46}$$

is satisfied expected welfare under a carbon tax is higher. This (sufficient) condition is satisfied when $\sqrt{30}Q_C<\bar{\omega}$. This, together with the earlier discussion on expected technology, implies:

Result 5: The expected quality of technology in use, and expected welfare, are higher under a carbon tax, compared to a mandate, when the upper bound on feasible research outputs is sufficiently high ($\bar{\omega}$ is greater than some threshold).

4.1. Numerical Results

Whenever equation (46) is not satisfied, it may be that a mandate offers higher expected welfare. To check, we must compare the dynamic gain from higher rates of innovation to the static loss from a sub-optimal allocation in the absence of innovation. This is a non-linear problem and to examine it, we numerically solve this problem for a large combination of parameter values. First, without loss of generality, we set

$$A=1 \quad c_1=0 \tag{47}$$

Marginal damage d spans the interval $A-c_1=1$, so we solve the problem for 49 evenly spaced intervals between

$$d\in\left[0.02,0.98\right] \tag{48}$$

For B, we choose values that range from very flat to very steep demand curves:

$$B\in\left\{0.01,\ 0.03,\ 0.1,\ 0.31,\ 1,\ 3.1,\ 10\right\} \tag{49}$$

Given $A=1$, $c_1=0$, d, and B, equation (31) implies

$$\bar{\omega}\in\left[0,2\left(1-d\right)/B\right] \tag{50}$$

We solve the problem for the 49 evenly spaced intervals between $0.02\times\left(2\left(1-d\right)/B\right)$ and $0.98\times\left(2\left(1-d\right)/B\right)$.

Our model is built on the assumption that $\bar{k}$ is greater than the maximum profit attainable under either policy. A smaller $\bar{k}$ means innovation is more likely. Since it is a trivial result that a carbon tax outperforms a mandate when there is no innovation, our results are most interesting when innovation is important. Accordingly, we set $\bar{k}$ equal to the smallest value consistent with our model:

$$\bar{k}=\max\left\{\frac{\bar{\varpi}^2}{12},\frac{\bar{Q}_C\bar{\varpi}}{2}\right\} \tag{51}$$

where $\bar{Q}_C=\max_{\alpha}\left[Q_C\right]$, solved numerically. Equation (51) insures $\bar{k}$ is always no less than the maximum expected profit under either policy. For every $\left(B,d,\bar{\varpi},\bar{k}\right)$ we numerically solve for the optimal α, denoted α^*, that maximizes equation (27). Given $\left(B,d,\bar{\varpi},\bar{k},\alpha^*\right)$ we next compute expected welfare under a carbon tax and mandate using equations (27) and (40).

This yields 16,807 model estimates, from which we conclude the following.

Result 6: In all cases considered in the foregoing numerical analysis, we find that expected welfare under a mandate is always lower than expected welfare under a carbon tax.

More specifically, expected welfare under a mandate comes closest to expected welfare under a carbon tax for comparatively low values of d. When d is small, the laissez-faire outcome is close to optimal. Since carbon taxes and mandates are both low when the externality is small, both policies obtain an equilibrium close to the laissez-faire outcome, and therefore close to each other. As d increases, an optimal mandate begins to fare increasingly worse compared to a simple carbon tax. It is notable that this result is obtained despite us "stacking the deck" against a carbon tax, since we numerically solved for the optimal mandate in each case but always set $t=d$ (rather than solving for the optimal tax in the presence of innovation).

5. Discussion and Relation to Biofuels

The preceding model showed that when technological opportunity is sufficiently high, and environmental externalities relatively large, a simple carbon tax tends to create better incentives for the development of very efficient production technologies than a mandate. However, when these conditions do not hold, a carbon tax tends to provide low incentives to innovate, so that R&D is unlikely to occur. In contrast, a mandate will create incentives to conduct R&D even when technological opportunity is low. Moreover, we argued that a carbon tax is likely to outperform a proportional mandate in terms of expected welfare too.

In developing this model, we were seeking to understand how biofuel policies are likely to impact innovation in this sector. As we noted at the outset, the performance of the US biofuel sector has been mixed. Corn-based ethanol has seen steady expansion, whereas cellulosic ethanol has fallen far short of targets for several years now.

One framing of the cellulosic versus corn-based ethanol debate is in terms of a young versus a mature technology. A mature technology, such as corn-based ethanol, can be thought of as one with a low probability of radical improvement, so that high draws of ω are very unlikely. In such a setting, a proportional mandate is more likely to yield higher innovation than a carbon tax.[3] This is consistent with the steady improvement in the cost of producing conventional ethanol (see Hettinga et al. 2009 and van den Wall Bake et al. 2009). Moreover, it will be recalled that Johnstone, Hascic and Popp (2010) found mandate policies were only effective at spurring innovation for wind and geothermal energy – both of which can also be considered mature compared to solar, ocean and biofuel.

In contrast, a young technology like cellulosic ethanol can be thought of as one with the potential of major breakthroughs, so that high draws of ω are more likely. Although very good technologies may be possible, they may still be unlikely (as when draws are uniformly distributed between 0 and ω in our model), so that very high profits conditional on success are needed to induce innovation. A carbon tax provides such incentives better than a mandate. While we did not discuss the distribution of k in our paper, it may well be that young technologies require more up front R&D spending, since the supply of expertise is low and research equipment needs to be custom-built. If the costs of research in a young field are higher, then the fact that

$$E\left[\pi^M\left(\theta\right)|\,\omega\right] < E\left[\pi^T\left(\theta\right)|\,\omega\right] \tag{52}$$

when ω is high may be a significant impediment to innovation in the sector. We illustrate in Figure 2, which depicts expected licensing break-even revenue curves for different values of (k,ω) when $Q_C = 1$. R&D occurs whenever, for a given ω, a k is drawn below these curves. We have suggested that the distribution of $\left(\omega, k\right)$ may be centered in the upper right for cellulosic ethanol.

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[3] That said, we have argued the benefits of faster innovation may well be overshadowed by distributional inefficiency, relative to a carbon tax.

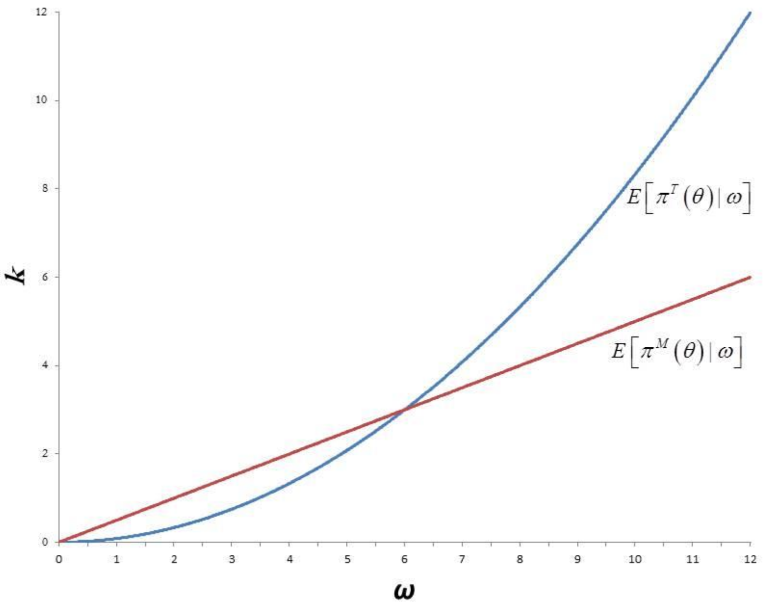

Figure 2: Expected Licensing Revenues Under Alternative Policies, $Q_C = 1$

Another wrinkle in the economics of biofuels is the so-called "blend wall," which refers to the fact that fuel consisting of more than 10% ethanol damages the engines of most motor vehicles (the new flex-fuel cars excepted). This maximum 10% blend limit constrains the choice of absolute targets for the policy-maker, and has the effect of forcing them to adopt a *de facto* proportional mandate due to technological limitations. Indeed, in 2013, the EPA proposed revising its absolute mandates for precisely the reason that they risk exceeding the blend wall.

By neglecting the blend wall, one may conjecture that our model overstates the advantages of a carbon tax. This is because a carbon tax's advantages largely stem from its ability to expand output when high quality innovations are achieved and this is impossible if blend wall effects are strong (as they have been recently). However, the blend wall is precisely the kind of technological limitation that entrepreneurs need an incentive to get around. Perhaps in a counterfactual world where biofuel policy was reliant on carbon taxes, entrepreneurs would have put more effort in getting around the blend wall, either by pushing out flex fuel cars more quickly and aggressively, or developing alternative technological fixes such as so-called "drop-in fuels" (Savage, 2011).

Finally, it is important to note that our model does *not* say further advances in biofuel technology are impossible under current policy mandates. While we have argued the incentives to conduct R&D on high-quality innovations is low under current policies, if a sufficiently good (k,ω) draw comes up, R&D will be conducted and cellulosic ethanol production will make major advances. Instead, our model argues that current policies may be insufficiently suited to the challenge at hand, by providing insufficient incentives to conduct R&D for (k, ω) draws that are good, but not great.

5. Conclusions and Directions for Future Research

Whereas the analysis of this paper was motivated by the poor performance of mandates for cellulosic ethanol, its results are also applicable to other industries. Many European countries and US states require that a fixed fraction of electricity be supplied by renewable energy technology. Our model suggests such policies create excess incentives to pursue low-quality technologies, and insufficient incentives to invest in high quality technologies, relative to a carbon tax.

Furthermore, while we contrasted the performance of a mandate relative to a carbon tax, we note that a clean technology subsidy would work essentially as a carbon tax as far as its impact on R&D and the post-innovation technology in use. This is because subsidies create the same highly elastic demand curve near a threshold price, which allows innovators to expand supply when they discover high quality innovations. However, a subsidy's welfare implications are less clear, since they would not reduce consumption of overall fuel.

Our model could also be extended to encompass different assumptions about innovation. First, innovation is an ongoing cumulative process, rather than a once-and-for-all investment decision. Modeling this process in time may also impact the relative merits of proportional mandates and carbon taxes. A carbon tax favors strong investment in technologies that meet a given threshold, namely, an ability to compete with appropriately taxed older technologies, and weak investment in technologies that do not meet the threshold. When innovation is cumulative, it may be necessary to pass through several low quality innovation stages before this threshold is surpassed. A carbon tax may earn zero profit during these early stages if it cannot compete with the taxed dirty technology. These investments may still be worth doing because the profits from later stages are sufficiently high. However, if an innovator is unsure that he will be the one to secure these profits, perhaps because he faces competition and has no way to lay claim on profits from innovations that build on his earlier ideas, he will not want to make the initial investment (see Scotchmer 2004, chapter 5 for more discussion). In contrast, a mandate creates incentives for investment in these low-quality innovations, even if the patent system makes it difficult or impossible to lay claim on profits from follow-on innovations.

We have also simplified matters by assuming there are just two dimensions of research projects – the quality of the output, and the cost of R&D inputs. In reality, there are many dimensions, and different policies favor different dimensions. We could also have distinguished between the fixed cost of producing the clean fuel and the "scalability" of innovation, for example. Since a carbon tax's advantages come from its ability to scale up production, it may be that a mandate leads to a greater emphasis on reducing the fixed cost of producing ethanol and a carbon tax to greater emphasis on scalability. Indeed, biofuel production is likely characterized by sharply decreasing returns to scale at the industry level. Of course, this mainly reflects the nature of biofuel production and the cost of transporting inputs, but it is notable that the incentives also do not favor investment in scalability. As we have noted earlier, better incentives to reduce costs for large quantities, as a carbon tax provides, may have increased entrepreneurial attention to the blend wall constraint.

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