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The Environmental Effects of Clean Energy Innovations under Rate-Based Regulation

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Abstract

Despite the popularity of this class of policy, the economics of rate-based approaches have not been well developed. In this paper we show that technological advances that reduce the cost of clean energy will increase use of the dirty energy source whenever the regulation is fixed and binding. Since environmental damage depends on the level of dirty energy and not its proportion, these otherwise desirable clean technology innovations result in additional pollution. We set up simple analytical models to show how the basic result applies to each of the three canonical cases: a renewable portfolio standard, an emissions rate standard, and a vehicle fuel economy standard.

Key Words: renewable portfolio standard, emissions rate standard, CAFE standard, greenhouse gas emissions

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Introduction

A large number of environmental regulations are based on proportions or averages of "clean" and "polluting" sources, a regulatory approach we call *rate-based*. Three prominent examples are renewable portfolio standards (RPS), a regulation many states use to determine the share of renewables in total electricity generation; emissions rate standards (ERS), which set rates of emissions per unit of electricity generation, such as the US Clean Power Plan governing greenhouse gas emissions from electricity generation; and fuel economy standards for passenger vehicles, such as the US Corporate Average Fuel Economy (CAFE) standards.

Despite the popularity of this class of policy, the economics of rate-based approaches have not been well developed. In this short paper, we show a serious potential problem with these regulations. In a nutshell, technological advances that reduce the cost of clean energy will increase use of the dirty energy source whenever the regulation is fixed and binding. Since environmental damage depends on the level of dirty energy and not its proportion, these otherwise desirable clean technology innovations result in additional pollution.[1] This is an unexpected outcome; improvements in clean technology should lead to pollution reduction. This result strengthens the case—as if any such strengthening were needed—for bare bones carbon taxes or cap and trade; that is, a uniform carbon price not accompanied by other inefficient regulations.

We set up simple analytical models to show how the basic result applies to each of the three canonical cases in which the stringency of the regulation is held fixed. The RPS result is fully general, provided the standard applies to all suppliers in the power system. The result for an emissions rate standard is not fully general, but we derive the conditions under which a reduction

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[1] The claim that environmental damage depends on the level of pollution and not its proportion is not generalizable to all environmental problems but does apply in all of the cases we examine.

in the cost of clean technology raises emissions. These conditions hold for all states under the Clean Power Plan, although we abstract from the complications of interstate trading. The fuel economy standard result shows that innovation increases emissions from new vehicles, although the net effect on emissions is ambiguous when we account for the effect on the used vehicle market.

With an ERS, clean technology innovation unambiguously increases emissions when the ERS is relatively stringent. Clean technology innovation with a mild ERS causes gas-fired generation to decrease and coal-fired generation to increase. Because of the resulting ambiguous effect on emissions, innovation can reduce emissions in certain cases with a mild ERS, but we find that these conditions are unlikely to apply in the United States.

The case of fuel economy standards is further enlightening because it highlights the role of incomplete regulation. The standards in a particular year apply only to new vehicles sold during that year. We consider technological progress that reduces the cost of producing those new vehicles with high fuel economy. The cost reduction raises the total number of new vehicles sold and therefore total emissions from new vehicles if the fuel economy standards remain binding. However, the cost reduction also reduces the cost of new vehicles relative to the cost of existing vehicles and leads to retirement of some existing vehicles with lower fuel economy. The net effect on emissions is ambiguous, although we argue that under reasonable parameter values, aggregate emissions will indeed decrease. This result is similar to that of Fowlie (2009), who demonstrates the perverse outcomes that can occur with incomplete regulation of the power sector; in our case, the new car market is regulated but the used car market is unregulated (in terms of fuel economy). Note that the used car market introduces a perverse effect: the larger the unregulated source of emissions, the more responsive total emissions are to an improvement in technology.

Previous conceptual research on rate-based policies has focused on their overall efficiency or incentives for innovation.[2] The literature has therefore largely sidestepped the consequences of technological innovation once it occurs. The effects of the innovation itself, as opposed to the incentive to engage in research and development, remain important because

[2] Rate-based policies have gone by a variety of names, including pollution per unit of output (Helfand 1991), performance standards (Fischer and Newell 2008; Jaffe and Stavins 1995), and carbon intensity (proposed Clean Energy Standard Act of 2012). In the majority of cases, particularly in early years, authors focused on rate-based regulation in the context of a single polluter rather than overall demand and supply conditions over an entire sector.

technological innovations may come from other sectors or from other countries or areas outside the regulation area. Fischer and Newell (2008) come closest to our paper by noting that a drop in renewables costs decreases the subsidy to renewables created by a fixed performance standard and that fossil emissions increase with renewables generation, but they do not establish the generality of this claim nor emphasize its broader implications. The connection between rate-based policies applied to point sources and vehicles also has not been widely recognized.

Empirically, this issue remains unexplored. As Wizer and Barbose (2008), Barbose et al. (2015), and, in a separate context, Jacobsen (2013) have pointed out, it can be difficult to determine whether rate-based standards are binding. Renewable portfolio standards, for example, have multiple tiers and carve-outs and have been imposed in stages.

Our model builds on Fischer (2010), who shows that an increase in the required clean energy proportion has an ambiguous effect on pollution. Our technology result, unlike the stringency result, is unambiguous for the RPS and effectively unambiguous for ERS. We therefore consider it to be a significant problem for rate-based regulation.

1. Basic Result: Renewable Portfolio Standards

We consider a simple competitive market for electricity with one zero-emissions source, call it wind, and one positive-emissions source, say gas. The RPS requires that proportion $1 > k > 0$ of total electricity be generated by renewable sources.[3] If W is aggregate wind-supplied electricity and G is aggregate gas-supplied electricity, the RPS regulation is

$$W/(W+G) \geq k \tag{1}$$

or equivalently, $W \geq aG,$ where $a = \frac{k}{1-k}$. Since there is a one-to-one relationship between a and k, we express our results in terms of a rather than k. We are interested in situations where the regulation is binding:

[3] Our simplified model assumes that a single RPS applies to all states or to any single state with a stand-alone electricity market. Neither of these conditions holds in the real world. Real-world application of this result depends on the set of renewable portfolio standards applied by different states and on how states, in administering an RPS, treat out-of-state generation; Fowlie (2009) makes a similar point regarding a state-level cap and trade. These interstate factors lead to a complex economic and regulatory environment that we do not attempt to model. Our result points out perverse implications of the rate-based approach even if it were to be applied in a situation in which the RPS might otherwise be expected to perform with greatest efficacy.

(2) $$W = aG.$$

The RPS is implemented by a tradable credit system resulting in an equilibrium credit price of t. Wind producers receive a price premium t, and gas producers receive a price reduced by at. Thus for electricity price p faced by consumers, wind supply is $W(p+t)$ and gas supply is $G(p-at)$. The market-clearing condition is

(3) $$W(p+t) + G(p-at) = D(p)$$

where $D(p)$ is demand. It is straightforward to check that when the RPS is implemented this way, the enhanced revenue received by wind, tW, equals the reduced revenues received by gas, atG, so that (2) holds. We assume that consumers are indifferent to the source of the electricity.

Let δ represent the level of wind technology. We redefine wind supply as $W(p,\delta)$ and index δ such that a higher δ represents a cost-saving innovation that shifts out the wind supply curve, $W_2 = dW(p,\delta)/d\delta > 0$, for all p. We continue to assume $W_1 = dW(p,\delta)/dp > 0$. The gas supply curve is unaffected by δ.

We treat δ as an exogenous parameter and examine the effects of an increase in δ on emissions. We also assume a fixed policy stringency, so that a does not respond to changes in the renewable power technology. These exogeneity assumptions highlight the perverse effect of renewable portfolio standards, but they are also likely to be consistent with real-world policy choices, particularly in the short run. The final section of this paper discusses implications of relaxing this assumption.

Because wind creates zero emissions, aggregate emissions, E, are proportional to G, $E = \beta G$. To show our result, we solve (2) and (3) to yield t and p as functions of δ. These give

(4) $$\frac{dp}{d\delta} = \frac{W_2 a(1+a)G'}{\Delta} < 0$$

and

(5) $$\frac{dt}{d\delta} = \frac{W_2((1+a)G' - D')}{\Delta} < 0$$

where $\Delta = (W_1 - aG')^2 - (W_1 + a^2G')(W_1 + G' - D') < 0$. (See Appendix.)

The result is demonstrated by (4) alone. If the price paid by consumers falls, it must be because total supply, $W + G$, has expanded. If (2) is binding, then any increase in supply must include an increase in gas production and thus an increase in pollution.

To see the result more explicitly, we have

$$\frac{dG}{d\delta} = \left\{\frac{\partial G}{\partial p}\frac{dp}{d\delta} + \frac{\partial G}{\partial t}\frac{dt}{d\delta}\right\} \tag{6}$$

with $\frac{\partial G}{\partial p} = G'$ and $\frac{\partial G}{\partial t} = -aG'$. Since $dE = \beta dG$, we have

$$\frac{dE}{d\delta} = \beta \frac{W_2 aG'D'}{\Delta} > 0. \tag{7}$$

Equation (7) is our basic result for an RPS. Because wind is a zero-emissions source and gas a positive-emissions source, the consequence of an increase in δ is clearly environmentally deleterious—the increase in wind is matched by an increase in gas, which leads to an increase in aggregate emissions. The equation shows that a decrease in the cost of an emissions-free source (that is, the source to which the portfolio standard applies) increases emissions whenever the portfolio standard continues to bind. We further show in the Appendix that the result in (7) generalizes to two sources of carbon electricity, in which case the technological innovation affects the generation shares of the two carbon-based sources.[4]

The model can also be used to show the effect for an increase in δ when the RPS is not binding. As δ rises, eventually it is cheap enough to produce wind power, on the margin, without any transfer. The regulation becomes nonbinding and t goes to zero. At $t = 0$, the market-clearing condition (3) yields $dp/d\delta = -W_2/(W_1 + G' - D') < 0$, and thus the effect of technological progress on pollution is $\frac{dG}{d\delta} = G' \frac{dp}{d\delta} < 0$.

It is straightforward to show that this result does not hold for a carbon tax without an accompanying RPS. The market-clearing condition is $W(p, \delta) + G(p - \tau) = D(p)$ for carbon tax τ. (Wind has zero emissions and pays no carbon tax.) This scenario yields $dp/d\delta < 0$ and $dG/d\delta = G'dp/d\delta < 0$; a reduction in wind costs reduces carbon-based electricity generation.

[4] Böhringer and Rosendahl (2010) also analyze the effect of an RPS on multiple carbon sources, but in the absence of innovation.

2. Emissions Rate Standard

An RPS treats all forms of carbon electricity the same. In contrast, an ERS differentiates among different forms of electricity based on their carbon content. Therefore, in this section we generalize the RPS model to include coal as a second source of carbon-based electricity. We show that under an ERS, an improvement in carbon-free technology raises carbon emissions under current supply conditions whenever the standard remains binding.

We assume the ERS is implemented through tradable allowances. Market clearing for the electricity market is given by

$$W(p+RA,\delta)+G(p+(R-\lambda)A)+C(p+(R-1)A)=D(p) \tag{8}$$

where A represents the price of a rate-based allowance, R is the rate-based target in tons of CO_2 per MWh, λ is the ratio of the gas to coal emissions rate, and $C(p)$ is coal supply. Allowances and the target are denominated in terms of the carbon dioxide emissions from a MWh of coal electricity, with the coal electricity emissions rate normalized to 1 and the ratio of gas electricity emissions to coal electricity emissions equal to $\lambda<1$.[5] The allowance price must clear the market such that

$$\frac{\lambda G+C}{W+G+C}\leq R \tag{9}$$

or $RW+(R-\lambda)G+(R-1)C\geq 0$. As before, analysis is based on this constraint being met as an equality.

When the ERS is binding, emissions are proportional to total generation, according to (9). Therefore, as before, the result rests on the sign of $\frac{dp}{d\delta}$. We show in the Appendix that

$$sign\frac{dp}{d\delta}=sign\,\{\lambda(R-\lambda)G'+(R-1)C'\}. \tag{10}$$

[5] Emissions from coal and gas are approximately 2,000 lbs CO_2/MWh and 800 lbs CO_2/MWh, respectively, in which case $\lambda=0.4$. If the rate-based target is 1,000 lbs CO_2/MWh, then R = 0.5.

Our attention focuses on the conditions under which $dp/d\delta < 0$. When R < λ, the standard is below the relative gas emissions rate, and these conditions are clearly met. For a less stringent standard, 1 > R > λ, we have

$$\frac{dp}{d\delta} < 0 \ if \ Z(R) = \frac{\beta(R-\beta)}{(1-R)} < \frac{\varepsilon_C}{\varepsilon_G}\frac{C}{G}\theta \quad (11)$$

where ε_C and $\varepsilon_G$are the supply elasticities for coal and gas and $\theta = \frac{p+(R-\beta)A}{p+(R-1)A} > 1$. At any level of R, coal receives a tax and with $R > \beta$, gas receives a subsidy. The increase in δ reduces the price of allowances, A, and causes gas generation to fall and coal generation to increase, with an ambiguous effect on total emissions. Equation (11) shows that $dp/d\delta$ is more likely to be negative the higher the relative supply elasticity of coal and the greater the proportion of coal in fossil fuel generation. If coal is relatively more elastic or is a large source of emissions, then entities find it profitable with the now-cheaper wind to substitute gas for coal and increase production.

To examine the likelihood that (11) will hold, we calculate $Z(R)$ using the interim and final Rs specified under the Clean Power Plan (EPA 2015, Appendix 5) and $\beta = 0.4$. These Rs range from 0.42 to 0.76 for the interim goals and from 0.39 to 0.65 for the final goals, yielding final-goal $Z(R)$~0.13 and as high as 0.29. To calculate the right-hand side of (11), we use each state's 2012 coal:gas ratio (EPA 2015, Appendix 3) and $\theta = 1.06$, as implied by Table 1.[6] Supply elasticities depend on the variation in marginal costs across plants by fuel type, and that variation in turn depends on variation in fuel prices, nonfuel costs, and efficiency. Linn et al. (2014) show that there is substantial cross-sectional variation in both coal prices and coal plant efficiencies, suggesting that coal supply is fairly elastic. To test the limit of our condition, we set $\varepsilon_C/\varepsilon_G$ = 1. Under these parameter values, condition (11) holds in all states for which C > 0. When C = 0 (Rhode Island), the ERS approach is identical to an RPS. Thus we have $dp/d\delta$ < 0 in all cases.

[6] Our analysis constructs R based on coal emissions of 2,000 lbs/MWh rather than using state-specific emissions rates. In constructing (11), we also ignore oil-generated electricity. This latter treatment simplifies the analysis considerably. Because our results are conclusive, we do not explore more detailed calculations.

The result $\frac{dp}{d\delta} < 0$ implies that the change in electricity production resulting from $d\delta$ is $dW + dG + dC > 0$. The accompanying change in emissions is equal to the weighted increase in gas and coal generation, $dE = \lambda dG + dC$. When the ERS is binding, we have, for positive $d\delta$,

$$sign\ dE = sign\{(dW + dG + dC) \times R\} > 0 \quad (12)$$

As with an RPS, under an ERS an improvement in carbon-free electricity production leads to an increase in overall emissions whenever the emissions-rate target is binding.

The Clean Power Plan points out an issue that our model does not tackle, which is that most rate-based policies (including fuel economy standards covered below) are designed to become progressively more stringent over time. Policymakers may introduce this feature because of anticipated technological improvement, a desire to reduce transition costs, or other reasons. This dynamic feature has unclear effects. Under an invariable policy, continuing improvement in δ would eventually lead the emissions rate standard to become nonbinding, and future δ improvements would indeed be beneficial. Under an increasing-stringency policy, the rate-based standard is likely to remain binding, thus negating the effects of technological improvements, according to our results in equation (7) or (11); however, emissions improvements would come from the more stringent standard. Policymakers might wonder, for example, whether a built-in increase in stringency is needed or desired, or more precisely, they might wonder how the policy might best take advantage of anticipated improvements in δ. We leave this issue for future research.

3. Fuel Economy Standards

3.1. New Car Market

We next show that this effect extends to another prominent form of rate-based regulation, fuel economy standards. Various features of the car market lead to a more narrow result than in the electricity case, but our basic finding remains in force and is important for understanding the overall performance of fuel economy standards. Analogous results hold for greenhouse gas emissions rate standards, which many countries use instead of or in addition to fuel economy standards (An and Sauer 2004).

To see the basic result, let γ measure fuel economy (miles per gallon) and let $n(\gamma)$ be the quantity of new cars with fuel economy γ. New car production is $N = \int n(\gamma)d\gamma$. We assume that all car models are driven the same number of miles per year; this assumption is unrealistic but provides a useful starting point. Greenhouse gas emissions from the set of cars with fuel economy γ are then $\theta n(\gamma)/\gamma$, where θ is analogous to λ in the previous model and represents greenhouse gas emissions per gallon of fuel combusted. Total emissions, E, from the set of new cars are

$$E = \theta \int n(\gamma)/\gamma d\gamma. \tag{13}$$

In the United States, the fuel economy standard is calculated on a manufacturer-by-manufacturer basis using the formula $\frac{\int n(\gamma)d\gamma}{\int n(\gamma)/\gamma d\gamma}$, with $n(\gamma)$ now restricted to cars produced by a single manufacturer. Alternatively, our analysis can be interpreted as applying to cars produced across all manufacturers when the standard is tradable. When the standard, μ, is binding, we have[7]

$$\frac{\int n(\gamma)d\gamma}{\int n(\gamma)/\gamma d\gamma} = \mu. \tag{14}$$

We use equation (13) to rewrite (14) as

$$\frac{\theta N}{\mu} = E. \tag{15}$$

Consider an improvement in passenger vehicle technology, again referred to as $\Delta\delta > 0$, which shifts the aggregate supply curve outward. The set of technological advances that might shift the supply curve outward is quite broad, but it is useful for the moment to think of a technological advance that reduces the production cost of high miles-per-gallon cars. Because the passenger car market is complex, with demand and supply depending on the spectrum of vehicles offered for sale, we do not attempt to model demand and supply interactions. Instead, we simply note that for any outward shift in the supply curve that increases the equilibrium quantity of all cars sold, $\Delta N = \frac{dN}{d\delta}\Delta\delta > 0$, we have an increase in emissions,

$$\Delta E = \theta \Delta N/\mu > 0 \tag{16}$$

[7] See equation (1) in Jacobsen (2013) for the discrete analogue. As before, the fuel economy standard is properly a weak inequality, but we are interested in the case where it is binding, so the relevant equations are written as equalities. For comparability with the RPS and ERS, the fuel economy standard does not change over time.

whenever the standard is binding.

Equation (16) is our basic fuel economy result. Under plausible assumptions, an improvement in clean-car technology leads to an increase in greenhouse gas emissions from new cars so long as the fuel economy standard continues to bind.[8] This is again an unexpected and unwelcome result.

The underlying principle is the same as under RPS and ERS: fuel economy standards regulate average fuel economy, but pollution is due to the number of gallons of gasoline consumed, which is the product of fuel economy, vehicle miles traveled, and the number of new cars sold. A technological improvement lowers the costs of clean cars, but because the standard remains binding, the average fuel economy is unchanged. However, the lower cost increases the number of new cars and therefore increases emissions.

The inefficiencies of fuel economy standards relative to gasoline taxes are well understood (e.g., Goldberg 1998). These inefficiencies have primarily been attributed to the failure of fuel economy standards to internalize the number of miles driven per car. Inefficiencies due to the failure also to “regulate” the number of new cars sold—independent of the miles driven—have not been as widely recognized. Our result in equation (16) shows yet another inefficient property of fuel economy standards for controlling greenhouse gas emissions from vehicles.

Our result relies on several assumptions. (i) Vehicle miles traveled (VMT) are the same for all new cars. This assumption can be easily relaxed, but doing so would require us to specify the set of cars for which technology has shifted the supply curve. (ii) A shift outward in the supply curve for one type of car necessarily results in more cars in aggregate being sold. This assumption is reasonable in a normal market. (iii) Either the standard is tradable across manufacturers and remains binding with the introduction of the technological advance, or it applies on a manufacturer-by-manufacturer basis and the technological advance does not substantially affect a) the set of companies for which the standard is binding; and b) vehicle sales for manufacturers that do not meet the standard (and thus pay fines for not meeting the standard).

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[8] When the fuel economy standard is applied at the manufacturer level and not tradable across manufacturers, equation (16) applies to the set of manufacturers for which the standard is binding. The result holds for any improvement in technology that increases aggregate vehicles sold over the set of companies for which the standard is binding, with no change in this set.

(iv) Shifts in the supply of new cars do not substantially affect the used car market. This assumption is weak and has the greatest potential for affecting (16). We take up this issue next.

3.2. Joint Model of New and Used Car Markets

The applicability of (16) is affected by the presence of the used car market. As technological improvements make new cars more desirable, used car demand decreases and some used cars will be retired. Since used cars tend to have lower fuel economy than new ones, this effect mitigates the result in (16).

Let $u(\gamma)$ be the distribution of used cars, with aggregate quantity $U = \int u(\gamma)d\gamma$ and emissions $F = \theta \int u(\gamma)/\gamma d\gamma$, again under the assumption that vehicle miles traveled are the same for all car types. Suppose that on the margin, for every N new cars, b used cars are retired, so that the effect of the technology on the new car market has the effect $\Delta U = -b\Delta N$ on the used car market, where $\Delta N = N'\Delta\delta$. We again use a reduced-form approach in which we recognize that an increase in new car technology, $\Delta\delta$, increases the number of new cars sold (and the number of used cars retired) without laying out all demand and supply pathways.

To see the emissions effect of ΔU, note that some current car owners will purchase new cars and sell used cars, and buyers of those used cars will in turn sell their current cars, also used. Some cars will ultimately be retired. We assume that the retired used cars will primarily be those with the lowest fuel economy. This assumption is reasonable in a regime in which standards tighten steadily over time, which is the current situation in the United States and many other countries. We make this assumption concrete by defining a cut-off γ^c such that all used cars with $\gamma \leq \gamma^c$ are retired, with γ^c defined implicitly by

$$b\Delta N = \int^{\gamma^c} u(\gamma)d\gamma. \quad (17)$$

The fuel economy of these retired cars is $\int^{\gamma^c} u(\gamma)d\gamma / \int^{\gamma^c} \frac{u(\gamma)}{\gamma} d\gamma = \mu^c$. The reduction in emissions is

$$\Delta F = -\theta \int^{\gamma^c} \frac{u(\gamma)}{\gamma} d\gamma = -\frac{\theta b\Delta N}{\mu^c} < 0 \quad (18)$$

and the net effect on emissions, $\Delta E + \Delta F$, given by:

$$\Delta E + \Delta F = \theta \left\{\frac{\Delta N}{\mu} - \frac{b\Delta N}{\mu_c}\right\}. \quad (19)$$

By (19), net emissions will decrease only if the term in brackets is negative, or

$$b > \frac{\mu^c}{\mu}. \tag{20}$$

Emissions decrease if a sufficient number of used cars are retired (b is large) or if their average fuel economy is low relative to the fuel economy of new cars. If either of these two conditions fails (that is, if (20) is false), then the technological advance for new cars increases aggregate emissions.[9]

As (20) shows, the used car market introduces a perverse effect: the larger the unregulated source of emissions, the more responsive total emissions are to an improvement in technology. This perverseness of this result is even deeper than (20) because a more responsive used car market, represented by a higher b, means that fuel standards are less efficient, even without the role of technological innovation as Gruenspecht (1982) famously showed.

4. Numerical Examples

4.1. Electricity Market

To give a sense of the magnitude of these effects in the electricity market, we simulate a static market with three sources of electricity. We simulate two rate-based regulatory policies, RPS and ERS, and show how they perform when the renewable technology improves.[10] For comparison, we also examine a carbon tax.

We use the following functions, denominated in dollars and million megawatt hours:

$$D(p) = 495 - 3.3p \tag{21}$$

$$W(p) = -700 + 14p \tag{22}$$

$$G(p) = -450 + 12p \tag{23}$$

$$C(p) = -239.4 + 8p \tag{24}$$

[9] Even in the case where emissions may fall as a result of $d\delta$, the reduction is less under fuel economy standards than would occur under a fuel economy tax applied to new vehicles.

[10] The RPS example includes both coal and gas electricity.

Under these curves, the no-regulation outcome yields a price of roughly $50/MWh and electricity supplies of 7, 156, and 165 million MWh of wind,[11] gas, and coal, respectively, for a total of roughly 330 million MWh (the equilibrium approximates values in the Texas power system in 2008).[12] The no-regulation wind percentage is 2 percent. The demand curve was chosen to yield a price elasticity of –0.5 at equilibrium price and quantity. Results are shown in Table 1.

Table 1. Market and environmental outcomes under initial wind technology, $\boldsymbol{W(p) = -700 + 14p}$

	No regulation	RPS	ERS[13]	Carbon tax[14]
Electricity price ($/MWh)	$50.52	$49.33	$49.43	$52.06
Renewable premium (RPS) or allowance price (ERS)	—	$4.23	$5.11	$4.47
Renewables proportion: W/(W + G + C)	0.02	0.15	0.11	0.09
Emissions (million lbs CO_2)	454,515	405,063	405,063	405,063
Emissions rate (lbs CO_2/MWh)	1,385	1,219	1,221	1,253

Table 2 shows the same set of outcomes when the wind supply curve shifts outward to

$$W(p) = -700 + 15.12p. \tag{25}$$

The new technology slope parameter has increased by 8 percent relative to equation (22). This leads to a relatively large change in wind supply at low levels of W. For example, at p = $50.50, wind supply would increase from 7 to 67.6 MWh, a 10-fold increase.

[11] Recall that we use wind to refer to all nonhydro renewable sources.

[12] These supply curves can be presumed to include other existing Clean Air Act regulations and renewable electricity tax preferences. Our no-regulation case therefore really means no additional regulations.

[13] The emissions rate standard was chosen to equal the emissions achieved under an RPS = 0.15.

[14] The tax was chosen to give the emissions achieved under an RPS of 0.15.

Table 2. Market and environmental outcomes under new wind technology, $W(p) = -700 + 15.12p$

	No regulation	RPS	ERS	Carbon tax
Electricity price ($/MWh)	$49.05	$48.80	$48.84	$50.54
Renewable premium (RPS) or allowance price (ERS)	—	$0.80	$0.94	$4.47
Renewables proportion: W/(W + G + C)	0.12	0.15	0.14	0.20
Emissions (lbs CO_2)	416,813	406,964	407,456	366,216
Emissions rate (million lbs CO_2/MWh)	1,251	1,219	1,219	1,116
Change in emissions (million lbs CO_2)	–37,702	+1,901	+2,393	–38,847

We focus on the environmental consequences of these policies rather than welfare analysis because they do not require us to assign a dollar value to the emissions effects. The technology improvement embodied in equation (25) versus (22) would reduce emissions by 37,702 million pounds even if greenhouse gas emissions from electricity were unregulated. The same improvement would *increase* emissions by 1,902 million pounds under an RPS of 0.15 and by 2,393 million pounds under an ERS of 0.61. Emissions increase with rate-based approaches, whereas emissions decrease under a carbon tax regime; emissions are about 11 percent higher under an RPS or ERS than with the carbon tax.

Table 1 shows an incidental consequence of an RPS and ERS that is not often remarked on but Fischer (2010) demonstrates: these policies can reduce electricity prices to consumers relative to a no-regulation situation and, more important, relative to a carbon tax. The result is due to the differential in wind and fossil fuel elasticities; it is not the result of renewables being less expensive, despite widespread belief that an RPS reduces costs (e.g., Barbose et al. 2015). In essence, the RPS or ERS transfers producer surplus from carbon electricity producers to wind producers, and this can result in a lower overall price when supply elasticities differ. Consumers receive an electricity market benefit from an RPS or ERS, relative to a carbon tax, but producers lose. If consumer surplus is valued by regulators more highly than producer surplus, and if the technology is static, then an RPS or ERS will be appealing. The overall welfare lessons of economics remain valid, however. If consumer and producer surplus are weighted equally and if environmental benefits are valued by at least as much as the marginal allowance price or carbon tax, the carbon tax remains clearly superior.

4.2. Fuel Economy Standards

Equation (20) shows that with a binding fuel economy standard, technological advances that reduce the cost of producing vehicles with high fuel economy reduce emissions if a sufficient number of vehicles are retired or if the retired vehicles have sufficiently low fuel economy relative to the standard. To get a rough handle on the possibilities for (20), suppose the ex ante distribution of miles per gallon across used cars is a power function over $[A, B]$ with parameter α and mean $m = \frac{\alpha(B-A)}{\alpha+1} + A < \mu$. Then the cut-off γ satisfies

$$\gamma^c = b^{\frac{1}{\alpha}}(B-A) + A. \tag{26}$$

Let $A = 5$, $B = 32$, and $\alpha = 1.5$. Under these parameters, the average miles per gallon of all used cars is ≈ 21.2, which is similar to the fleet-wide average fuel economy. The average fuel economy of retired cars is $\mu_c = \frac{\alpha(\gamma^c - A)}{\alpha+1} + A$. Substituting in (26), we find that under a standard of $\mu = 34.1$ (the US standard in 2016), the condition (20) fails whenever b is less than ≈ 0.41—that is, whenever 4 or fewer used cars are retired for every 10 (marginal) new cars purchased.[15] The average miles per gallon of these retired cars is 13.9. Since estimated values of b are around 0.75 (based on the historical evolution of the US on-road vehicle fleet), condition (20) will fail. In this case, an improvement in new car technology leads to a reduction in aggregate vehicle emissions.

5. Conclusions

This paper shows that a technological improvement that reduces the cost of clean energy can lead to an increase in overall emissions under rate-based regulations. We consider three prominent examples of rate-based regulation: an RPS, an ERS for electricity generation, and new passenger vehicle fuel economy standards. With a binding RPS, reducing the cost of clean energy unambiguously raises emissions. With a binding ERS, under parameter values that are

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[15] New car sales are typically greater than the retirement of used cars, so the total stock of cars is growing each year. The coefficient b captures a marginal effect. Thus $b\Delta N$ is the additional used car retirement when new car sales rise by more than "normal."

likely to be relevant to the Clean Power Plan, reducing the cost of clean energy raises emissions. Because new vehicle standards affect only new and not used vehicles, the effect of a cost reduction for new vehicles on total emissions is ambiguous. If the emissions rate of retired used vehicles is sufficiently low relative to the emissions rate of new vehicles, or if a sufficient number of used vehicles are retired relative to new vehicle sales, the cost reduction reduces emissions; otherwise, emissions increase.

The results for fuel economy standards suggest that a fruitful direction for future research is to analyze the effects of technological progress when the rate-based regulation does not apply evenly across emissions sources. This is the case with vehicle standards because used vehicles are not subject to a standard, and it will be the case with the Clean Power Plan if states face different emissions rate standards, apply different rates to different generating units, or omit new fossil sources from the standards. The numerical simulations in this paper illustrate the directional effects of clean energy innovation on emissions, but more careful modeling or statistical analysis could refine these estimates.

In our model, cost-reducing innovation is exogenous. But the rate-based standard could itself induce innovation and undo some of the emissions reductions. Exploring the welfare effects of rate-based policies when innovation is an endogenous outcome could be a useful direction for future research.

An implication of these results for policy is that technological progress to clean energy, which rate-based regulation incentivizes, will undermine the emissions reductions from the regulation itself. Policymakers could counteract this effect by tightening the standards over time as innovation occurs, but future research is needed to characterize the optimal dynamics of rate-based regulation.

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Appendix

Result 1: Technological Progress under a Renewable Portfolio Standard

Equilibrium is the solution to the following two equations:

a) $$W(p+t) - aG(p-at) = 0$$

b) $$W(p+t) + G(p-at) - D(p) = 0$$

We take the differential with respect to t, p, and δ and solve for

$$\begin{bmatrix} W_1 - aG' & W_1 + a^2G' \\ W_1 + G' - D' & W_1 - aG' \end{bmatrix} \begin{bmatrix} dp \\ dt \end{bmatrix} = \begin{bmatrix} -W_2 \\ -W_2 \end{bmatrix} d\delta$$

The determinant is $\Delta = (W_1 - aG')^2 - (W_1 + G' - D')(W_1 + a^2G') =$

$$W_1^2 - 2aW_1G' + a^2G'^2 - (W_1^2 + W_1a^2G' + G'W_1 + a^2G'^2 - D'W_1 - D'a^2G') =$$

$$-2aW_1G' - W_1a^2G' - G'W_1 + D'W_1 + D'a^2G' < 0.$$

The negative sign follows from $W_1 > 0, G' > 0,$ and $D' < 0$.

The comparative statics $dp/d\delta$ and $dt/d\delta$ are given by

$$\begin{bmatrix} dp/d\delta \\ dt/d\delta \end{bmatrix} = 1/\Delta \begin{bmatrix} W_1 - aG' & -(W_1 + a^2G') \\ -(W_1 + G' - D') & W_1 - aG' \end{bmatrix} \begin{bmatrix} -W_2 \\ -W_2 \end{bmatrix}$$

yielding

c) $$\frac{dp}{d\delta} = \frac{W_2a(1+a)G'}{\Delta}$$

d) $$\frac{dt}{d\delta} = \frac{W_2((1+a)G' - D')}{\Delta}$$

When there are two sources of carbon electricity, (a) and (b) are replaced by

a') $$W(p+t) - aG(p-at) - aC(p-at) = 0$$

b') $$W(p+t) + G(p-at) + C(p-at) - D(p) = 0$$

using the notation of Section 2. Define $K = G + C$ and thus $K' = G' + C'$. Then the elements of the matrix above are the same with K' replacing G'. Thus $\frac{dp}{d\delta} = \frac{W_2a(1+a)K'}{\Delta_{new}}$ with a new denominator identical to Δ with K' replacing G'.

The effect on emissions of a change in δ is $(\beta G' + C')\frac{dp}{d\delta} - a(\beta G' + C')\frac{dt}{d\delta}$. Equation (7) can now be rewritten:

$$\frac{dE}{d\delta} = \frac{W_2 a(\gamma\beta G' + C')D'}{\Delta_{new}} > 0$$

Result 2: Technological Progress in the Context of a Rate-Based Target

Market clearing and the emissions rate standard (ERS, assumed binding) require the following two equations, where A is an allowance price:

e) $$W(p + RA; \delta) + G(p + (R - \beta)A) + C(p + (R - 1)A) - D(p) = 0$$

f) $$RW + (R - \beta)G + (R - 1)C = 0$$

Because the comparative statics are complex, we write down each of the stages so that our claims can be readily confirmed. We take the differential with respect to p, A, and δ from (a) and (b), respectively, to define J, K, L, and M:

g) $$Jdp + KdA + W_2 d\delta = 0$$

h) $$Ldp + MdA + RW_2 d\delta = 0$$

with

$$J = W_1 + G' + C' - D'$$

$$K = L = RW_1 + (R - \beta)G' + (R - 1)C'$$

$$M = R^2 W_1 + (R - \beta)^2 G' + (R - 1)^2 C'$$

This yields the system of equations

$$\begin{bmatrix} J & K \\ L & M \end{bmatrix} \begin{bmatrix} dp \\ dA \end{bmatrix} = \begin{bmatrix} -W_2 \\ -RW_2 \end{bmatrix} d\delta$$

The comparative statics $dp/d\delta$ and $dA/d\delta$ are

$$\begin{bmatrix} dp/d\delta \\ dA/d\delta \end{bmatrix} = 1/\Delta \begin{bmatrix} M & -K \\ -L & J \end{bmatrix} \begin{bmatrix} -W_2 \\ -RW_2 \end{bmatrix}$$

The determinant is $\Delta = JM - KL$ =

$$(W_1 + G' + C' - D')(R^2W_1 + (R-\beta)^2G' + (R-1)^2C')$$
$$-(RW_1 + (R-\beta)G' + (R-1)C')^2$$

Multiplying out these terms gives

$$R^2W_1^2 + (R-\beta)^2W_1G' + (R-1)^2W_1C'$$
$$+R^2W_1G' + (R-\beta)^2{G'}^2 + (R-1)^2G'C'$$
$$+R^2W_1C' + (R-\beta)^2G'C' + (R-1)^2{C'}^2$$
$$-(R^2W_1 + (R-\beta)^2G' + (R-1)^2C')D'$$
$$-\{R^2{W_1}^2 + (R-\beta)^2{G'}^2 + (R-1)^2{C'}^2$$
$$2R(R-\beta)W_1G' + 2R(R-1)W_1C' + 2(R-\beta)(R-1)G'C'\}$$

The terms $R^2{W_1}^2 + (R-\beta)^2{G'}^2 + (R-1)^2{C'}^2$ cancel out. Collect the remaining terms to get

$$W_1G'\{(R-\beta)^2 + R^2 - 2R(R-\beta)\}$$
$$+ W_1C'\{(R-1)^2 + R^2 - 2R(R-1)\}$$
$$+ G'C'\{(R-\beta)^2 + (R-1)^2 - 2(R-1)(R-\beta)\}$$

plus terms involving D'. Each of the bracketed terms is itself a square. They simplify to $W_1G'\beta^2$, W_1C', and $G'C'(1-\beta)^2$. We have

$$\Delta = \beta^2W_1G' + W_1C' + (1-\beta)^2G'C' - \{R^2W_1 + (R-\beta)^2G' + (R-1)^2C'\}D' > 0$$

The comparative static of interest is $\frac{dp}{d\delta} = [RK - M]W_2/\Delta$. Since $W_2, \Delta > 0$, the sign depends on the relative magnitudes of

$$RK = R^2W_1 + R(R-\beta)G' + R(R-1)C' \text{ and}$$
$$M = R^2W_1 + (R-\beta)^2G' + (R-1)^2C'$$

Subtracting these, we have

$$sign\frac{dp}{d\delta} = sign\ [\ \beta(R-\beta)G' + (R-1)C']$$

To form (11) we write this as

$$sign\frac{dp}{d\delta} = sign\ [\frac{\beta(R-\beta)}{(1-R)} - \frac{C'}{G'}]$$

The supply elasticity of coal is $\varepsilon_C = \frac{p_c C'(p_c)}{C}$ where $p_c = p + (R-1)A$, and likewise for the supply elasticity of gas. Thus

$$sign\frac{dp}{d\delta} = sign\ [\frac{\beta(R-\beta)}{(1-R)} - \frac{\varepsilon_C}{\varepsilon_G}\frac{C}{G}\frac{p+(R-\beta)A)}{p+(R-1)A}]$$