Environmental and Technology Policies for Climate Change and Renewable Energy

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Abstract

We assess different policy options for reducing greenhouse gas emissions and promoting the development and diffusion of renewable energy technologies: (1) a carbon emissions price, (2) a generation subsidy for renewable energy, (3) a tax on fossil fuel generated energy, (4) a portfolio (market share) requirement for renewable energy sources, (5) a tradable performance standard for the emissions intensity of all generation, and (6) a subsidy for R&D investment in renewable energy technology. We evaluate the relative performance of the different policies according to different potential goals: emissions reduction, renewable energy production, R&D, and welfare. We also assess how the nature of technological progress—whether it occurs by learning by doing or firm-specific innovation—affects the desirability of different policy measures.

Key Words: technology, policy instruments, climate change, renewable energy

JEL Classification Numbers: Q21, Q28, Q48, O38

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Carolyn Fischer and Richard Newell*

1. Introduction

With greenhouse gas emissions a growing policy concern, much attention is being given to the potential for renewable energy to displace fossil fuel sources. In 2001, renewable energy sources provided 5.7% of the total primary energy supply for member countries of the Organization for Economic Cooperation and Development (OECD). Of the 5.7% of energy provided by renewable sources, 54% was supplied by combustible renewables and waste,[1] 35% by hydropower, and 12% by geothermal, solar, wind, and tide energy (IEA, 2002). For electricity generation, renewables represented 15% of production worldwide, but only 2.1% if one excludes hydro. The United States aims to nearly double energy production from renewable sources (excluding hydro) compared to 2000 levels by 2025.[2] Meanwhile, the European Union has a target to produce 22.1% of electricity and achieve 12% of gross national energy consumption from renewable energy by 2010. Given such ambitious targets, a great deal of focus has been placed on the role of technological innovation in lowering the cost of these nonemitting energy sources.

To reduce greenhouse gas emissions and promote technological development and diffusion of renewable energy, recent policies and proposals employ a broad range of incentives.

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[1] This category includes biomass and excludes trash and nonrenewable waste.

[2] The Department of Energy Strategic Plan, "Protecting National, Energy, and Economic Security with Advanced Science and Technology and Ensuring Environmental Cleanup," Draft: August 6, 2003.

Some focus on reducing the cost of research and development (R&D) and of investment, such as a tax credit for R&D or subsidies for capital costs. Others try to ensure viable markets for the environmentally desirable technology, such as a generation subsidy for renewable energy or a portfolio (market share) requirement for renewable sources. Alternatively, some policies create disincentives for nonrenewable energy sources by taxing these energy sources or by making greenhouse gas emissions expensive, such as with a tradable emissions permit system, carbon tax, or emissions intensity standard for generation.

Although economists typically argue that a direct price for carbon (via a tax or tradable permit system) would provide the most efficient incentives for development and use of less emitting technologies, the diversity of the present policy portfolio suggests that other forces are at play. First of all, emissions pricing policies that risk significantly reducing economic activity among energy intensive sectors have little appeal to most governments. Second, raising the price of carbon can have important distributional consequences, both for owners of fossil fuel generation sources and for consumers. Third, failures in the market for innovation, such as spillover effects, imply that emissions pricing alone will not provide sufficient incentive to improve technologies. Finally, the process of technological advance can take place not only through R&D investments, but also via learning through the production and use of new technologies; thus, encouraging output may also spur innovation. Consequently, subsidies—and output support strategies in particular—are often attractive to decisionmakers and play an important role alongside emissions regulations and R&D policies.

In environmental economics, the literature on induced innovation has focused on the role and effectiveness of environmental policy in stimulating innovation in environmentally friendly technologies (Jaffe et al., 2003). Empirical investigations have assessed the effects of energy price changes and regulations on innovations in energy efficiency, finding support for induced innovation as well as autonomous progress (Newell et al., 1999; Popp, 2002). Theoretical analysis has revealed that market-based environmental policies tend to perform better than

prescriptive regulation in inducing innovation (Downing and White, 1986; Magat, 1978; Zerbe, 1970). Furthermore, among different market-based instruments, innovation and adoption incentives may also differ (e.g., Milliman and Prince, 1989; Biglaiser and Horowitz, 1995; Jung et al., 1996; Fischer et al., 2003; Requate and Unold, 2001). However, these studies have primarily focused on comparing Pigouvian emissions pricing policies, like emissions taxes and auctioned or grandfathered permits, rather than a more pragmatic, broader set of policies such as those using performance standards and supporting renewable energy technologies.

The treatment of technological change is also important in models for assessing the impact of climate change policies. While most modeling efforts assume autonomous technical change, Popp (2003) reviews the few climate-energy models that incorporate induced technological change, dividing them into two types. So-called "bottom-up" models tend to pay great attention to energy systems and technologies, but this detail comes at the expense of overall economic structure and aggregate economic interactions. This limits the ability to compute welfare effects. "Top-down" models, on the other hand, have richer aggregate modeling of responses to environmental policies, but at the expense of technological detail. An additional dichotomy is that bottom-up models that include induced technological change tend to focus more on progress as a function of learning by doing, while top-down models tend to assume progress comes from cumulative R&D investments. On the policy front, top-down models tend to focus on the analysis of policies that change the price of emissions, such as carbon taxes or tradable permits.[3] This focus is due in part to the limited ability of these models to represent other types of policies, which often requires greater technological detail.

[3] For example, Goulder and Mathai (2000) model technological innovation through both R&D investments and learning by doing in the context of optimal carbon taxes. While these two formulations differ somewhat, they find that in practice the optimal tax is essentially the same.

In this paper, we attempt to bridge some of the gaps in the analysis of climate policies and induced innovation, considering a broad set of environmental policies, including indirect ones, and incorporating both learning by doing and R&D. We identify six of the main policy options for reducing greenhouse gas emissions in the electricity sector and evaluate their relative performance according to different potential goals: emissions reduction, renewable energy production, R&D, and welfare. We also assess how the nature of technological progress—whether it occurs by learning by doing or R&D-based innovation—affects the desirability of different policy measures.

We find that when the ultimate goal is to reduce emissions, policies that also create incentives for the fossil fuel generators to reduce emissions intensity and for consumers to conserve energy perform much better than those that rely on incentives for renewable energy producers alone. The R&D subsidy turns out to be particularly inefficient, since it postpones the vast majority of the effort to displace fossil fuel generation until after costs are brought down, requiring huge investments and forgoing many cost-effective opportunities to reduce emissions. It can give some boost to renewables production early on if learning by doing and R&D are complements, but it can lower current production if they are substitutes. Overall, we find that the nature of knowledge accumulation is far less important than the nature of the policy incentives.

1.1. Policies for renewable energy

Among the OECD countries, policies to reduce greenhouse gas emissions and support renewable energy vary widely, both in form and in degree.[4] We distinguish six policies:

[4] The IEA maintains the Renewable Energy Policies & Measures Database for IEA Member Countries, available at http://library.iea.org/dbtw-wpd/textbase/pamsdb/re_webquery.htm, and the Database of State Incentives for Renewable Energy (DSIRE) in the United States is available at http://www.dsireusa.org/.

1. A **price on carbon,** or on carbon dioxide (CO_2) emissions, provides incentives to reduce carbon intensity and makes fossil fuel sources relatively more expensive compared to renewables. Sweden, Denmark, Finland, and Norway have CO_2 taxes,[5] and the European Union is developing a program of tradable carbon emissions permits.

2. A **generation subsidy for renewable energy** improves the competitiveness of these sources vis-à-vis fossil fuels. The United States has the Renewable Energy Production Incentive of 1.5 cents per kWh, and 24 individual U.S. states have their own subsidies. Canada also has a Market Incentive Program, and several European countries (Germany has been particularly supportive), as well as Korea, have production subsidies. Many countries also support renewable energy output by subsidizing costs (like equipment or capacity installation) rather than offering a per-kWh subsidy. The United States, for example, has a 10% investment tax credit for new geothermal and solar-electric power plants.

3. A **tax on fossil fuel energy** seeks to discourage use of these sources in favor of renewables. The United Kingdom, Germany, Sweden, and the Netherlands tax fossil fuel sources, in most cases by exempting renewable sources from an energy tax.

4. **Portfolio standards** for renewable sources are a popular form of support. These market share requirements—also known as quota obligations, green certificates, and the like—may require either producers or users to derive a certain percentage of their energy or electricity from renewable sources. Such programs have been planned or established in Italy, Denmark, Belgium, Australia, Austria, Sweden, and the United Kingdom; a range of portfolio standards for electricity generation are in operation in 19 of the United States.

[5] The tax rates range widely; for example, Sweden's tax rate, currently about \$70/ton CO_2, is indexed to inflation, while Norway's has different rates for different source sectors, from \$12-47/ton CO_2.

5. A **tradable performance standard** sets the average emissions intensity of all output. Although less frequently discussed for promoting renewable energy in electricity generation, it does arise in climate policies for energy-intensive industries, such as for certain sectors in the United Kingdom's Climate Change Levy.

6. **Subsidies for R&D** investment in renewable energy are also quite common, including government-sponsored research programs, joint initiatives, grants, and tax incentives. Major programs exist in the United States, United Kingdom, Denmark, Ireland, Germany, Japan, and the Netherlands.

Myriad additional financial incentives for renewables also exist, including government grants, personal and corporate income tax credits and deductions, and lower or exempted value-added taxes on bio-fuels or renewable energy equipment. Net metering provisions help small users benefit from their excess generation of renewable source electricity. And several state and local governments have green power purchasing requirements, as do several OECD countries. However, to the extent these policies offer different incentives, they are less likely to be as significant as the broad-based mechanisms that are our focus.

2. Model

We develop a unified framework to assess the six different policy options for reducing greenhouse gas emissions and promoting the development and diffusion of renewable energy in the electricity sector.[6] The stylized model is deliberately kept simple to highlight key features. It includes two subsectors, one emitting and one nonemitting, and both are assumed to be perfectly

[6] This focus reflects both the great deal of policy attention devoted to this sector, which accounts for two-fifths of CO_2 emissions, and the availability of data to parameterize the model. However, the qualitative results will still offer intuition for other sectors—or a broad-based program to reduce CO_2.

competitive and supplying an identical product, electricity.[7] Fossil fuel production is assumed to be the marginal technology, setting the overall market price; thus, to the extent that renewable energy is competitive, it displaces fossil fuel generation. The model has two stages, each representing a specific number of years. Electricity generation, consumption, and emissions occur in both stages, while investment in knowledge takes place in the first stage and, through technological change, lowers the cost of renewables generation in the second. An important assumption is that firms take not only current prices as given, but also take prices in the second stage as given, having rational expectations about those prices.

To allow for consideration of the length of time it takes for innovation to occur, and for the lifetime of the new technologies, let the first and second stages be made up of *n* and *m* years, respectively. For simplicity, we assume that no discounting occurs within the first stage; this assures that behavior within that stage remains identical. However, let δ represent the discount factor between stages. It is possible to allow for discounting in the second stage by altering *m* to reflect such discounting; in that case *m* can be thought of as "effective" years.

2.1. The emitting fossil fuel sector

The emitting sector of the generation industry relies on fossil fuels and is denoted with superscript *F*. Total output from the emitting sector is f_t in year *t*. Marginal production costs, *MC,* are assumed to be constant with respect to output and weakly decreasing in emissions intensity, μ_t, up to some natural rate, μ^0. This form allows for a tradeoff between emissions intensity and higher costs (i.e., a carbon abatement cost function), such as by fuel switching, coal gasification technologies, or other efficiency improvements.

[7] Although large portions of the electricity sector remain regulated, policy-induced changes to marginal production costs are likely to be passed along to consumers, and in a longer horizon, a transition to more deregulated markets is also likely to make markets relatively competitive in the future.

Two policies affect the fossil fuel sector directly: an emissions price and an output tax (which may be explicit or implicit, as with the portfolio standard discussed below). Let τ_t be the price of emissions (i.e., emissions tax or equilibrium permit price) and ϕ_t be the tax on fossil fuel generation at time *t*, respectively. Other policies that stipulate quantity standards, such as renewables portfolio standards and emissions performance standards, will be specified in the next section, as they require some modifications to the generalized model.

Profits for the representative emitting firm are

$$\pi^F = n(P_1 - MC(\mu_1) - \tau_1\mu_1 - \phi_1)f_1 + \delta m(P_2 - MC(\mu_2) - \tau_2\mu_2 - \phi_2)f_2\,, \tag{1}$$

where P_t is the price of electricity. The firm maximizes profits with respect to output and emissions intensity, yielding the following first-order conditions:

$$\frac{\partial \pi^F}{\partial \mu_t} = 0: \quad -MC'(\mu_t) = \tau_t; \tag{2}$$

$$\frac{\partial \pi^F}{\partial f_t} = 0: \quad P_t = MC(\mu_t) + \tau_t\mu_t + \phi_t. \tag{3}$$

Thus, as shown in equation (2), the price of emissions (τ) determines the emissions rate. The corresponding marginal costs of output are then constant (including the output tax, ϕ, and the price of the emissions embodied in that output, $\tau\mu$). Thus, the fossil fuel sector is the "marginal technology"—as long as fossil fuel generation occurs, the competitive market price must equal the sum of these marginal costs, as shown by equation (3).

Total emissions, E_t, are the product of the emissions rate and fossil fuel output:

$$E_t = \mu_t f_t\,. \tag{4}$$

In the absence of a price on emissions, the first-order condition for emissions intensity implies $-MC'(\mu_t) = 0$. Let the solution to this equation be μ_0, the baseline emissions rate, and the corresponding baseline price of electricity generation be P_0, where $P_0 = MC(\mu_0)$.

The assumption of a single fossil energy technology is admittedly strong, but we feel that this simplification allows us to capture the key qualitative results. We later discuss why a richer modeling of the fossil fuel sector, including different emissions intensities and inframarginal technologies, is only likely to magnify our results.

2.2. The nonemitting renewable energy sector

Another sector of the industry generates without emissions by using renewable resources (wind, for example); it is denoted with superscript *R.* Annual output from the renewables sector is q_t. The costs of production, $G(K_t, q_t)$, are assumed to be increasing and convex in output, and declining and convex its own knowledge stock, K_t, so that $G_q > 0$, $G_{qq} > 0$, $G_K < 0$, and $G_{KK} > 0$, where lettered subscripts denote derivatives with respect to the subscripted variable.[8] Furthermore, since marginal costs are declining in knowledge and the cross-partials are symmetric, $G_{qK} = G_{Kq} < 0$. Note that we have simplified considerably by assuming there is technological change in the relatively immature renewable energy technologies, but none in the relatively mature fossil fuel technologies. While it is of course not strictly true that fossil fuel technologies will experience no further technological advance, incorporation of a positive, but slower relative rate of advance in fossil fuels would complicate the analysis without adding substantial additional insights.[9]

The knowledge stock $K(H_t, Q_t)$ is a function of cumulative R&D, H_t, and of cumulative experience through "learning by doing" (LBD), Q_t, where $K_H \geq 0$ and $K_Q \geq 0$, and $K_{QH} = K_{HQ}$. Cumulative R&D increases in proportion to annual investment in each stage, h_t, so

[8] Longer-term convexity of the renewables cost function is attributable to decreasing quality of available land for wind and biomass generation. Input scarcity is not as substantial a longer-term issue for fossil-based production, however, justifying the simplifying assumption of constant marginal costs (i.e., constant returns to scale).

[9] An exception is room for advancement in lowering costs of cleaner generation technologies for fossil fuels, like "clean coal." However, in terms of our model, these investments would only occur in the presence of an emissions price, the effects being to further emphasize the welfare cost disparities of policies lacking that price signal.

$H_2 = H_1 + nh_1$. Cumulative experience increases with total output during the first stage, so $Q_2 = Q_1 + nq_1$. Research expenditures, $R(h_t)$, are increasing and convex in the amount of new R&D knowledge generated in any one year, with $R_h(h) > 0$ for $h > 0$, $R_h(0) = 0$, and $R_{hh} > 0$. The strictly positive marginal costs imply that real resources—specialized scarce inputs, employees, and equipment—must be expended to gain any new knowledge.[10] An important issue is whether research and experience are substitutes, in which case $K_{HQ} < 0$, or complements, in which case $K_{HQ} > 0$.

Two price-based policies are directly targeted at renewable energy: a renewable energy production subsidy (s), and a renewables technology R&D subsidy in which the government offsets a share (σ) of research expenditures.

In our two-stage model, profits for the representative nonemitting firm are

$$\pi^R = n\left((P_1 + s_1)q_1 - G(K_1, q_1) - (1-\sigma)R\left(h_1\right)\right) + \delta m((P_2 + s_2)q_2 - G(K_2, q_2)), \tag{5}$$

where $K_2 = K(H_2, Q_2)$.

The firm maximizes profits with respect to output in each stage and R&D investment, yielding the following first-order conditions:

$$\frac{\partial \pi^R}{\partial q_1} = n\left(P_1 + s_1 - G_q(K_1, q_1)\right) - \delta m G_K(K_2, q_2) n K_Q(H_2, Q_2) = 0;$$

$$\frac{\partial \pi^R}{\partial q_2} = \delta m\left(P_2 + s_2 - G_q(K_2, q_2)\right) = 0;$$

$$\frac{\partial \pi^R}{\partial h_1} = -n(1-\sigma)R_h(h_1) - \delta m G_K(K_2, q_2) n K_H(H_2, Q_2) = 0.$$

Rearranging, we get :

[10] As a partial equilibrium model, we do not explore issues of crowding out in the general economy, but those opportunity costs may be reflected in the cost function.

$$G_q(K_1, q_1) = P_1 + s_1 - \delta m G_K(K_2, q_2) K_Q(H_2, Q_2); \tag{6}$$

$$G_q(K_2, q_2) = P_2 + s_2; \tag{7}$$

$$(1-\sigma) R_h(h_1) = -\delta m G_K(K_2, q_2) K_H(H_2, Q_2). \tag{8}$$

As shown in equation (6), the renewable energy sector produces until the marginal cost of production equals the value it receives from additional output, including the market price, any production subsidy, and the contribution of such output to future cost reduction through learning by doing (note that the last term in equation (6) is positive overall).[11] Second-stage output does not generate a learning benefit, so there is no related term in equation (7). Meanwhile, as shown in equation (8), the firm also invests in research until the discounted returns from R&D equal investment costs on the margin.

2.3. Consumer demand

Renewable energy generation and fossil fuel production are assumed to be perfect substitutes. Let $C(P)$ be the consumer demand for electricity, a function of the price, where $C'(P) < 0$. Consumer surplus is therefore $CS = \int_{P_t}^{\infty} C(P)dP$. Thus, the change in consumer surplus due to the renewable energy policy in this partial equilibrium model is

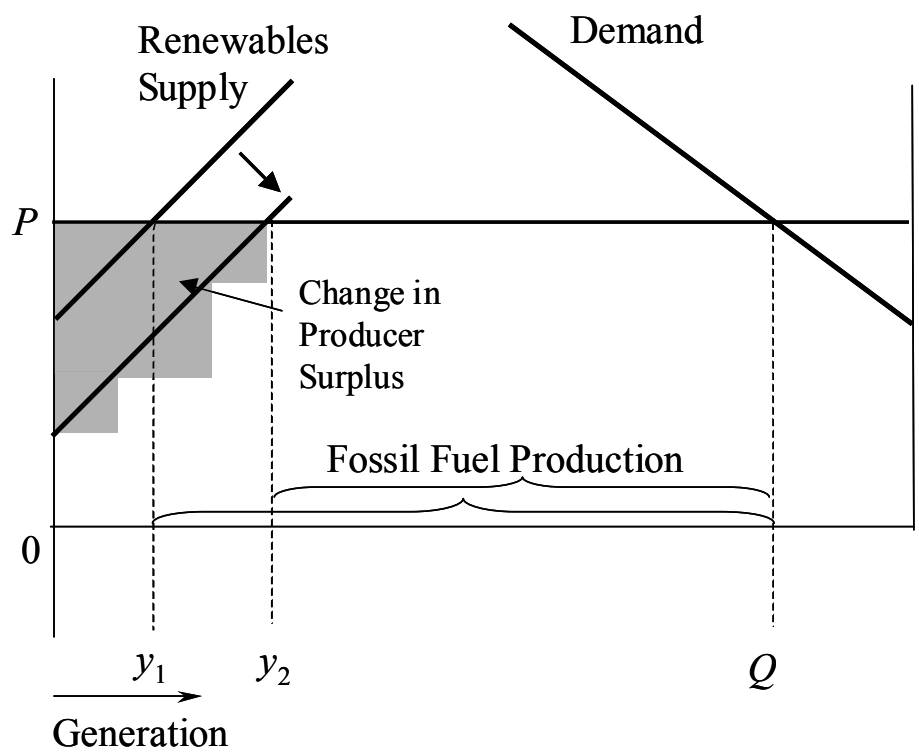
$$\Delta CS = -n \int_{P_0}^{P_1} C(P)dP - \delta m \left(\int_{P_0}^{P_2} C(P)dP \right). \tag{9}$$

[11] Note therefore that we are assuming here that firms have perfect foresight, that there are no knowledge spillovers, and that firms internalize any future returns to investments in R&D and LBD. For the present purposes we also assume that the costs of R&D and LBD are fully reflected in the market prices faced in making these investments. These assumptions are not meant to necessarily reflect reality, but rather to model a simplified situation upon which intuition can be developed and further modeling extensions can be built.

In equilibrium, total consumption must equal total supply, the sum of fossil fuel and renewable energy generation: $C(P_t) = f_t + q_t$.

To summarize, the main structure of this model is depicted in Figure 1. Fossil fuels are the marginal technology (by the assumption of flat marginal costs), and their generation costs determine the price of electricity.[12] Fossil fuel output is therefore equal to the residual after profitable renewable energy is produced: $f_t = C(P_t) - q_t$. Thus, any increase in renewable energy production—or reduction in demand— "crowds out" fossil fuel production. The figure depicts the effects of a shift in the renewable supply curve, which could represent either a subsidy or the effects of technological change.

Figure 1: Electricity Sector Model



[12] We abstract from short-run peak pricing variations and take a longer view in which the mature fossil technologies are most easily scalable to meet electricity capacity needs.

2.4. Welfare

Policies also have implications for government revenues, which we denote as V. We assume that these revenues are raised or returned in a lump-sum fashion. The change in these transfers equals the tax revenues net of the cost of the subsidies:

$$\Delta V = n\big((\phi_1 + \tau_1\mu_1)f_1 - s_1 q_1 - \sigma R(h_1)\big) + \delta m\big((\phi_2 + \tau_2\mu_2)f_2 - s_2 q_2\big) \tag{10}$$

Environmental damages are a function of the annual emissions and the length of each stage. To be able to accommodate both for flow and stock pollutants, we write this function in a general form:

$$\Delta D = D(E_1, E_2, n, m) - D(E_0, E_0, n, m) \tag{11}$$

The change in welfare due to a policy is the sum of the changes in consumer and producer surplus, net of the change in environmental damages and revenue transfers from the subsidy or tax:

$$\Delta W = \Delta CS + \Delta\pi^R - \Delta D + \Delta V. \tag{12}$$

Note that constant marginal costs in the fossil fuel sector implies zero profits, so $\Delta\pi^F = 0$.

However, welfare is unlikely to be the only metric for evaluating policy. Other indicators may be total emissions, consumer surplus, renewable energy market share, and so on. General equilibrium factors—like interactions with tax distortions, leakage, or other market failures—can also be important for determining welfare impacts. Political economy constraints may also be important for determining policy goals. To the extent that these unmodeled issues are present, this partial equilibrium presentation of welfare within the sector will not reflect the full social impacts; still, it represents a useful baseline metric.

2.5. Response of renewable energy to changes in prices, output, and R&D

While policies can affect both the market price of energy and the renewable energy subsidy, the renewable energy producer ultimately cares about the total price it receives for generation in each period, which we define as

$$P_t^R \equiv P_t + s_t. \tag{13}$$

The Appendix derives the comparative statics for the response of the renewable energy sector to changes in these prices and in the price it pays for research. The main results are as follows. First, renewable energy output in each period is increasing with the price received in that period (i.e., $dq_t / dP_t^R > 0$). Output in the second stage is also increasing in knowledge, since marginal costs are lowered ($dq_t / dK_t > 0$).

Next, R&D is increasing in the second-stage price, since higher prices imply more renewables output, which implies more scope for profits from reduced costs. Similarly, to the extent there is learning by doing, first-stage output is increasing in the second-stage price, for the same reasons. Not surprisingly, R&D is also increasing in its own subsidy, since effective investment costs to the firm decrease.

The harder questions regard how first-stage output responds to R&D, and vice-versa—in other words, how LBD and R&D interact. While both are increasing in second-stage output, the incidence across the two forms of knowledge accumulation depends on the degree of their substitutability or complementarity. That substitutability also determines whether they respond in the same or opposite directions due to changes in the first-stage price and in the R&D subsidy, since those changes affect the relative prices of LBD and R&D.

If R&D and LBD are complements, first-stage production will tend to increase with investment in R&D. That means an increase in the R&D subsidy will also increase first-stage renewables generation. Similarly, an increase in first-stage renewable energy prices can also increase R&D, if it is complemented by more LBD. On the other hand, if R&D and LBD are

substitutes in knowledge production, then more R&D makes LBD less productive, given any output level. But the increase in second-stage output resulting from lower costs due to more R&D also tends to make LBD more valuable. First-stage production may then increase or decrease with investment in R&D. But a strong substitution effect means that a larger R&D subsidy will decrease first-stage production, and a larger subsidy to first-stage production will decrease R&D investment, as R&D and LBD crowd each other out. These interactions will be important determinants of policy effects, since different policies have different implications for the prices of output in the first and second stages and the cost of R&D.

3. Policy scenarios

As developed in the modeling section, renewable energy production depends on the price received by that sector and the cost of R&D investment. Fossil fuel energy production depends on the amount of renewables sector output and the price of electricity, and emissions intensity depends on the price of emissions. Different policies vary in their effects on these different prices, resulting in different market equilibria. As we will see, the policies therefore provide varying incentives for emissions reduction along these different margins—emissions intensity, energy conservation, and renewable energy output—leading to a divergence in their relative efficiency.

3.1. No policy

We have defined μ_0 as the baseline emissions rate and P_0 as the baseline electricity price, so in the absence of policy (i.e., $\phi_t = s_t = \tau_1 = \sigma = 0$), the first-order conditions for production imply that output prices equal this baseline price in both markets and over time: $P_t = P_t^R = P_0$. We assume that an interior solution exists—that is, that some wind energy is viable without any policy. A sufficient condition would be that $G_q(K_1, 0) < P_0$. However, wind production could occur even if marginal production costs are higher than the price in the first stage, as long as the value of learning by doing for lowering second-stage costs is sufficient.

3.2. Fixed-price policies

We look first at three policies that directly set prices: an emissions price, a renewables production subsidy, and a tax on fossil-based production.

3.2.1 Emissions price

With a direct price for emissions—via either an emissions tax or a tradable emissions permit system—the fossil fuel sector has an incentive to lower its emissions rate until the marginal cost of reduction equals the emissions price $-MC'(\mu_t) = \tau_t$. The market price of electricity reflects the total marginal cost of fossil generation, inclusive of the embodied emissions cost as well as higher marginal production costs: $P_t = MC(\mu_t) + \tau_t \mu_t$ (see equation (3)). Without other subsidies, the renewables sector receives the market price for electricity ($P_t^R = P_t$), and the price increase promotes greater renewable energy generation in both stages. The prospect of more output in the second stage increases knowledge investment incentives in the renewables sector, for both R&D and learning. The higher market price also means consumers have added incentive to conserve. Thus, the emissions price provides efficient incentives for achieving a given emissions reduction goal as it provides equalized incentives for emissions reduction along all three margins—emissions intensity, output reduction (via price increase), and renewable energy production.

3.2.2 Renewable energy production subsidy

Under a renewables production subsidy, since there is no direct price on emissions, there is no reduction in fossil emissions intensity, and $P_t = P_0$, as in the no-policy scenario. While the market price of electricity remains unchanged, and thus provides no incentive for energy conservation, the effective price received by the renewable energy sector rises by the amount of the subsidy, so that $P_t^R = P_0 + s_t$. In this way, the renewables subsidy crowds out fossil fuel generation in both stages and reduces emissions.

3.2.3 Fossil fuel production tax

The analytic structure of a fossil fuel production tax is similar to the renewables subsidy, except that it takes the form of higher consumer prices for electricity, rather than a direct subsidy, that raise the price received by renewables. Thus, both the market price and the effective price received by the renewable energy sector rise by the amount of the tax: $P_t^R = P_t = P_0 + \phi_t$. Although no incentive exists to reduce emissions intensity, to the extent that demand falls due to higher prices, fossil output and emissions will be lower than under an equivalent renewable energy subsidy.

3.2.4 Renewable energy technology R&D subsidy

Without a price on emissions or subsidy/tax on output, output prices in both markets equal the baseline price ($P_t^R = P_t = P_0$). The primary effect of the R&D subsidy is to increase research expenditures and lower future renewables costs, crowding out some fossil fuel generation in the second stage. The R&D policy provides no incentive for reduction in fossil emissions intensity or energy conservation through an electricity price increase.

Regarding incentives for technological change, in the appendix we show that an increase in R&D can encourage learning either by making it more productive if R&D and learning are complements, or by inducing a sufficient expansion in second-stage output. On the other hand, if they are substitutes, R&D could discourage learning. In the latter case, although an R&D subsidy would increase renewable energy generation in the second stage, renewables output will be lower in the first stage relative to the baseline. The time path of emissions would tilt in the opposite direction, rising in the first stage and falling in the second. In the absence of a learning effect ($K_Q = 0$), the R&D subsidy would do nothing for first-stage emissions.

3.3. Rate-based policies

Two additional rate-based policies familiar to the electricity generation sector are portfolio standards and tradable performance standards. A portfolio standard requires a certain

percentage of generation to come from renewable energy sources. A tradable performance standard mandates that average emissions intensity of all generation not exceed a standard. Both policies create effective taxes on fossil fuel generation and subsidies for renewable energy sources. However, those prices are not fixed, as in the previous policies, but rather adjust endogenously according to market conditions to achieve the targeted rate.

Endogenous prices raise additional issues with respect to innovation incentives. Essentially, as increased knowledge brings down the costs of renewable energy, the standards become less costly to meet, which is then reflected in the implicit taxes and subsidies. The question is how the renewable energy sector perceives these price changes. Do firms in the sector recognize the impact of their innovation decisions on second-stage prices? Do they myopically expect prices to remain unchanged? Or do they expect the future prices, and take them as given, as do competitive firms?

Given our starting assumptions of a representative, perfectly competitive firm, we will proceed with the assumption that firms in the renewable energy sector expect price changes and take them as given. This view is most appropriate for describing firm-specific innovation in a sector of many small, competitive firms. These assumptions may be strong, and exploring alternatives will be an important extension, in particular to incorporate spillover effects. A long literature recognizes the differences in incentives depending on the structure of markets for output and for innovation.[13] But one must begin somewhere, so we examine the logical starting point of price-taking firms with rational expectations.

[13] See, e.g., Milliman and Prince (1989), Biglaiser and Horowitz (1995), Jung et al. (1996), Fischer et al. (2003), Requate and Unold (2002). Dynamic problems are also treated in Petrakis et al. (1999) and Kennedy and Laplante (1999).

3.3.1 Renewable energy portfolio standard

We model the portfolio standard as a requirement that α % of generation be from renewable energy sources in each stage (i.e., no banking allowed). We assume that responsibility lies with the emitting industry to satisfy the portfolio constraint. Thus, the fossil fuel producer must purchase or otherwise ensure at least α units of renewable energy for every $(1-\alpha)$ units of fossil fuel generation, or $\alpha/(1-\alpha)$ "green certificates" for every unit generated.

In equilibrium, the incentives correspond to a combination of the fossil fuel production tax and renewable energy subsidy cases. Assuming this constraint binds, the renewable energy sector receives a subsidy per unit output equal to the price of a green certificate, $\hat{s}_t$, where "^" denotes equilibrium values under the portfolio standard. The effective tax per unit of fossil-fueled output under this policy, $\hat{\phi}_t$, is then proportional to the effective subsidy to the renewable energy producer:

$$\hat{\phi}_t = \frac{\alpha}{1-\alpha}\hat{s}_t . \tag{14}$$

The implicit tax and subsidy are determined competitively by the market to meet the portfolio constraint. The resulting market price of electricity is $P_t = P_0 + \hat{s}_t\alpha/(1-\alpha)$, while the price received by the renewables sector is $P_t^R = P_t + \hat{s}_t = P_0 + \hat{s}_t/(1-\alpha)$.

The portfolio standard provides no incentive to lower the emissions intensity of fossil fuels, but crowds out fossil fuel generation by implicitly taxing it and subsidizing renewables compared to the market price. The rise in consumer prices is positive (unlike a pure renewables subsidy, where it is zero), but is only a fraction of the rise in the effective price received by renewables (whereas a fossil energy tax would fully pass this increase on to consumers). Thus, the portfolio standard results in only modest energy conservation incentives.

Another important difference is that, if the portfolio standard is fixed as we have assumed, the implicit tax and subsidy decline over time as renewable energy costs fall due to technological change. This occurs because the implicit tax/subsidies reflect the shadow cost of

meeting the renewables production constraint, and this shadow cost declines as the cost of renewables production declines.

3.3.2 Emissions performance standard

While a portfolio standard requires a certain percentage of renewable energy, a performance standard requires an average emissions intensity of all generation. With a tradable performance standard of $\bar{\mu}$, the emitting firm must buy emissions permits to the extent that its emissions rate exceeds that standard. The price of emissions at time *t*, $\tilde{\tau}_t$, will now be determined by a market equilibrium, denoted by "~". All firms are in effect allocated $\bar{\mu}$ permits per unit of output, which leads to an implicit subsidy of $\tilde{\tau}_t\bar{\mu}$ per unit of output. Thus, if the standard is binding, the fossil fuel sector will be a buyer of permits costing $\tilde{\tau}_t(\mu_t - \bar{\mu})$ per unit of output, and the renewables sector will be a seller of permits valued at $\tilde{\tau}_t\bar{\mu}$ per unit of output.

Thus, the emissions performance standard corresponds to a combination of an emissions price, $\tilde{\tau}_t$ and a generation subsidy for both renewable and fossil energy producers, where

$$\tilde{s}_t = \tilde{\tau}_t\bar{\mu} = -\tilde{\phi}_t. \tag{15}$$

The equilibrium values are determined in conjunction with the previous market-clearing conditions for energy supply and demand, along with the additional constraint that

$$\mu_t f_t \leq \bar{\mu}(q_t + f_t). \tag{16}$$

The resulting market price of electricity is $P_t = MC(\mu_t) + \tilde{\tau}_t\mu_t + \tilde{\phi}_t = MC(\mu_t) + \tilde{\tau}_t(\mu_t - \bar{\mu})$, reflecting both the higher cost of achieving lower emissions intensity and the cost to fossil fuel producers of emissions in excess of the standard. The price received by the renewables sector is $P_t^R = P_t + \tilde{s}_t = MC(\mu_t) + \tilde{\tau}_t\mu$, which also includes the revenues they gain from permit sales (i.e., the implicit subsidy).

Note that the price received by renewables is the same as with an equivalent pure emissions price (i.e., if $\tau_t = \tilde{\tau}_t$), assuring the same amount of renewable energy. The incentive to lower emissions intensity is also the same for the fossil fuel sector in that case. However, the

consumer price is lowered by the output subsidy, $\tilde{\tau}_t \bar{\mu}$, and the resulting larger total output is filled by additional fossil fuel generation, meaning that total emissions are higher.

As with the portfolio standard, a fixed performance standard implies a subsidy that changes over time. In this case, as costs fall in the second stage, the expansion of renewable energy allows fossil fuel sector emissions to increase. Some of this will arise from greater production, and some from increased emissions intensity, as the permit price falls.

3.4. Summary comparison of policies

Promoting renewable energy may be a policy goal in itself, such as for diversifying the energy supply portfolio and insulating it somewhat from nonrenewable energy price shocks. However, from an environmental perspective, the policy goal is more likely to be limiting emissions. In that case, as explained above, the relative performance of the different policies depends on their influence on emissions intensity, overall energy consumption, renewable energy production, and R&D. Table 1 summarizes the incentive effects from each of these policies along these different dimensions. The strength of these effects will in turn determine fossil output, emissions, and overall welfare effects. The relative efficiency of these policies in reducing emissions tends to follow the degree to which they provide incentives along all the relevant dimensions, but particularly for reducing emissions intensity and for raising electricity prices, which promote both conservation and renewable energy expansion. As one moves from the left of Table 1 to the right, therefore, efficiency tends to decrease, although the precise ranking of instruments depends on the relative strength of the different incentives in particular empirical circumstances. We will further demonstrate this ranking numerically as we parameterize the model in the next section.

The revenue and distributional implications of the different policies are also quite different. The emissions price and the fossil-based output tax raise revenue, with the primary burden placed on consumers since fossil energy producers pass on all their costs (due to the flat fossil supply curve). The renewables subsidy and R&D subsidy require outlays of public funds;

taxpayers support the renewable energy producers, while consumers are held harmless. The standards involve no net revenue change, implicitly earmarking the net costs of these policies back to consumers and producers. The net welfare effects depend on the magnitude of the efficiency loss in the process.

We note here that the differences in policy impacts are likely to be larger were we to disaggregate the fossil fuel sector. For example, if coal is used by the inframarginal technology and natural gas turbines are the marginal technology, an emissions price will raise costs more for coal, but the market price will only reflect the cost increase for natural gas (unless coal becomes no longer inframarginal), implying a loss of producer surplus for coal. In the long run, it also implies greater displacement of coal, a lower average emissions intensity, and less of a price signal for renewable energy or conservation. On the other hand, policies without an emissions price will tend to displace the marginal technology, which in this case is lower-emitting natural gas. Consequently, they will have less effect on carbon emissions. Thus, feel that a richer modeling is unlikely to change the qualitative results but rather exacerbate the welfare differences of the policies.

4. Numerical application to U.S. electricity production

In this section we apply the theory developed above to a stylized representation of the U.S. electricity production sector. We begin by specifying functional forms that have the general properties given above, that correspond to available information on the form of particular relationships, and that are empirically tractable. We also describe how we derived empirical values for necessary parameters and base levels of variables using available information. Table 2 summarizes the parameter values used in the numerical application. We then go on to describe the results of our central scenario, as well as scenarios that vary the relative importance of technological change through LBD versus R&D.

4.1. Functional form and parametric assumptions

We specify a supply curve for fossil fuel generation that is constant in output and quadratic in the rate of carbon emissions, $MC(\mu_t) = c_0 + c_1\left(\mu_0 - \mu_t\right)^2/2$, thereby yielding a linear marginal carbon abatement cost curve, $-MC'(\mu_t) = c_1\left(\mu_0 - \mu_t\right)$, per unit of output. For the baseline marginal cost of fossil fuel production (and thus the price of electricity) we use \$0.07 per kilowatt-hour (\$/kWh—all monetary values adjusted to year 2000 values) based on current and projected future values of the average price of electricity (Energy Information Administration 2003). The values of μ_0 and c_1 are from an assessment of carbon policies using the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) (EIA 1998), which has, to our knowledge, undergone more development effort, peer review, and testing than any other model of U.S. electricity energy demand. We use the projected results for the year 2010, which allows the longer-term effect of policies simulated in that study to be reflected. The baseline carbon intensity of fossil fuel electricity is thus set to $\mu_0 = 2.21\times10^{-4}$ metric tons of carbon per kWh (tC/kWh). The slope of the marginal carbon abatement cost curve is set to $c_1 = 3.71\times10^6$ \$kWh/tons^2 based on an ordinary least squares fit ($R^2 = 0.96$) of a linear relationship between carbon prices and carbon reductions from several scenarios in the EIA study.

We assume that the cost function for renewables generation is quadratic in output, $G_t\left(K_t, q_t\right) = K_t^{-1}\left(g_1 q_t + g_2 q_t^2/2\right)$, yielding a linear renewables supply curve, $G_q\left(K_t, q_t\right) = K_t^{-1}\left(g_1 + g_2 q_t\right)$. Total and marginal costs of renewables generation are proportional to the inverse of the knowledge stock, so that technological change lowers both the intercept and slope of the renewables supply curve. We normalize the initial knowledge stock to $K_1 = 1$ and set the values $g_1 = 0.0261$ \$/kWh and $g_2 = 6.49\times10^{-13}$ \$/kWh^2 based on an ordinary least squares fit ($R^2 = 0.98$) of a linear relationship between carbon prices and nonhydro renewable energy production from several scenarios in the EIA carbon policy study.

We specify a knowledge stock having a constant elasticity relationship with respect to both the stock of experience and the stock of R&D: $K_t\left(Q_t, H_t\right) = k_0 Q_t^{k_1} H_t^{k_2}$. This functional form has commonly been used for this relationship, and is empirically supported by many studies of the relationship between learning by doing and product costs. This functional form implies complementarity between R&D and learning, which is supported by the limited empirical evidence available (Lieberman 1984).

The values for k_1 and k_2 are based on several pieces of evidence. There are numerous empirical "learning curve" studies of learning by doing that estimate the elasticity of product costs (or prices) with respect to cumulative production. These studies find a peak in the distribution of estimated elasticities at about 0.30 (Dutton and Thomas 1984), which is further supported specifically for the case of electricity from wind (International Energy Agency 2000). Studies also suggest that one of the reasons for the pervasive relationship between cumulative production and product cost declines is the common decision rule in many firms of allocating a given percentage of revenues to R&D. As R&D is typically not explicitly included in learning curve analyses, the effect of output-proportionate R&D investments will be reflected in the estimated learning elasticity. In our sensitivity analysis, we explore different relative contributions of learning and R&D to knowledge, while maintaining our assumptions regarding the baseline level and rate of return to R&D (see below).

In the central scenario, we assume $k_1 = 0.10$ and $k_2 = 0.20$ based on two additional sources. The first is a recent study of electricity from wind (Klaassen et al., 2003) that includes both learning and R&D in estimation, finding estimates for k_1 and k_2 that correspond closely to the chosen values. The second is NEMS, which assumes a maximum learning rate of 0.10 for renewable energy technologies within its electricity market module (EIA 2003). We set $Q_1 = 750$ GWh so that annual renewable energy generation represents about a 10% contribution to the stock of experience, which is consistent with the current U.S. contribution of wind, solar, and biomass generation to cumulative U.S. output of these energy sources (EIA 2002). For any

particular values of k_1, k_2, and Q_1, we compute a value for k_0 by normalizing the initial knowledge stock and R&D stock so that $K_1 = 1$ and $H_1 = 1$, which produces $k_0 = 15.40$ for the base case.

A constant elasticity R&D investment function, $R(h_1) = \gamma_0 h_1^{\gamma_1}$, has the desired properties so long as $\gamma_1 > 1$. We choose parameter values for this function based on two assumptions. First, we assume that the total return to R&D investment is 30% (i.e., $m(G(K(Q_2, H_2), q_2) - G(K(Q_2, H_1), q_2))/(nR) = 1.30$). Second, we assume that annual R&D spending is $300 million in the baseline, which corresponds approximately to current U.S. renewables R&D spending. Calibrating the model to these two assumptions yields the values $\gamma_0 = 6.75 \times 10^9$ and $\gamma_1 = 1.11$ for the central scenario.

We assume a constant elasticity of aggregate electricity demand with respect to the price of electricity, ε, so that $C_t = C(P_0) + (P_t - P_0)\, dC/dP$, where $dC/dP = \varepsilon C(P_0)/P_0$. We assume $\varepsilon = -0.30$ based on the implied elasticity from the EIA-NEMS climate policy study discussed above. We set baseline energy demand at 3.04 x 10^{12} kWh based on projected fossil output of 2.98 x 10^{12} kWh in 2010 (EIA 1998) plus 7.26 x 10^{10} kWh of renewable energy output projected at a $0.07/kWh electricity price in our baseline scenario.[14] We consider a first stage of length, $n = 5$ years, which is typical of the time required for new innovations to be brought to market (Newell et al. 1999). We discount the second stage back to the present at a rate of 5% (so that $\delta = 0.78$), and consider a second stage of 20 years in length, whose flows we discounted back to the start of the second stage at 5% (so that $m = 12.46$). Twenty years is a typical cost recovery timeframe used for analysis of electricity generation technologies (EIA 2003).

[14] Thus, we omit both nuclear and hydro-based electricity in our numerical analysis. These could be incorporated, but neither is expected to change significantly in response to climate policy, so that such incorporation represents an unnecessary complication.

The baseline outcomes of this model in the absence of policy are given in Table 3. We begin the policy simulations by computing the effects of an emissions price of $25/tC in place throughout the model horizon. For the alternatives, we compute the level of the policy necessary to achieve the same total level of emissions as the emissions price. In holding total emissions constant across the alternative policies, we seek to hold the environmental benefits of the policies constant so that we can consider differences in the welfare consequences across policies as arising solely from differences in consumer surplus, producer surplus, and transfers related to electricity consumption and production. This approach is reasonable so long as the marginal benefits of emissions reduction are fairly constant in the level of reductions and over the relevant time horizon. Such an assumption is not unreasonable for carbon emissions (Pizer 1999).

4.2. Results: Central scenario

In reviewing the results of the central scenario, perhaps the first point to note is that the emissions price is indeed the most efficient, leading to the least cost in terms of welfare, and also requiring the least investment in renewable energy R&D. A $25/tC emissions price reduces electricity emissions by 5.8% in our central scenario. The carbon price reduces emissions intensity in the fossil fuel sector by 3.0%, and it reduces electricity consumption by 2.3%, meaning that less work needs to be done by renewables to displace fossil fuels. Correspondingly, less R&D investment is necessary. However, the burden on consumers may be quite large if they do not benefit from the revenue transfers.

With the tradable performance standard, the implicit output subsidy means that less of the reductions come from consumption (which falls by only 0.2%), so more reductions must come from emissions intensity and renewables. Table 5 shows that the implicit emissions price is $42 per ton of carbon in stage 1, which corresponds to a 5.2% decrease in emissions intensity in the fossil sector—significantly more than with the $25 emissions price. Furthermore, as renewables production increases in the second stage, the fossil fuel sector need not lower its emissions intensity as much, resulting in a smaller 4.8% intensity decrease compared to the baseline and an

implicit price on emissions of $39. For the renewables sector, the combination of the implicit tax and subsidy (see Table 5) implies a 0.91 and 0.85 cent/kWh increase in the price received in the first and second stages, respectively, compared to a 0.54 cent/kWh increase under the emissions price, correspondingly resulting in a near doubling of the increase in renewables output relative to the emissions price. Although the welfare costs of the tradable performance standard are roughly 60% higher than with the emissions price, from a policy perspective these additional costs from earmarking may be compared with the costs of handling the revenue transfers (which may range from squandered public funds to revenue recycling benefits).

The output tax, since it does not tax emissions directly, places more of the reduction burden on reducing consumption, thereby increasing renewables. In our central scenario, the output tax has somewhat higher costs than the performance standard, though this result is sensitive to the elasticity of demand relative to the cost of reducing emissions intensity—if demand was more elastic, so that conservation was a less costly option, the ranking would reverse. The output tax results in an equivalent price increase for renewables of 1.12 cents/kWh, 23% higher than with the performance standard in the first stage and 31% higher in the second, resulting in comparable increases in renewables output and R&D investment. The notable difference compared to the emissions price is that the fossil output tax essentially doubles the welfare and distributional effects: it is twice as costly for consumers, generates twice the producer surplus for renewables, twice the tax revenues, and twice the overall efficiency costs.

A renewables production subsidy, to generate the same emissions reductions, must be roughly six times the size of a fossil output tax, since electricity consumption is not reduced. Renewables output must expand by 12 times the increase with the emissions price, and R&D expansion must be 24 times greater. Since emissions reductions follow the expansion of renewable energy, significantly more reductions occur in the second stage compared to the preceding policies. Consumers are held harmless, but the cost to taxpayers is more than 50% greater than the gain to renewable energy producers.

A renewables portfolio standard combines features of the fossil output tax and the renewables production subsidy, but the fact that the cost of meeting the constraint changes over time significantly changes the time profile of emissions reductions. In this case, the combination of the implicit tax and subsidy imply a 7.8 cent/kWh increase in the price received by renewables in the first stage, and a 4.1 cent/kWh increase in the second. Consequently, more renewables expansion occurs in the first stage, and R&D is lower compared to the renewables production subsidy, since the second-stage support (i.e., renewables output) is lower. Since no revenues are raised, consumers bear the burden of the policy, but not to the extent of the emissions charge or output tax, since prices fall in the second stage. Similarly, producers gain, but not as much as with the subsidy, due to the relaxing constraint.

Finally, it may be of little surprise that the renewables research subsidy is by far the most costly policy for reducing emissions, since all the burden of displacing fossil output falls in the second stage. To do so without any output or emissions incentive requires costs to fall 62.1% more than they do in the baseline, or 71% overall. While second-stage output expands by 324.4%, it also expands in the first stage relative to the emissions price, a result of the complementarity of learning with R&D.

4.3. Sensitivity analysis of form of technological change

To evaluate the importance of the knowledge process in these results, we also conduct two experiments: one in which all technological progress derives from R&D, and another in which learning by doing is relatively more important than in the central scenario. These exercises require adjusting certain parameter values, while we maintain the assumptions that in the base case total annual R&D spending is $300 million, the total return to R&D is 30%, and $\gamma_1 = 1.1$. With no learning effect, $k_1 = 0$, and the remaining parameter values are then $\gamma_0 = 6.83 \times 10^9$ and $k_2 = -0.21$, which are not terribly different from the central scenario. With a strong learning effect, $k_1 = 0.51$, and the remaining parameter values are then $\gamma_0 = 6.38 \times 10^9$ and $k_2 = -0.15$. The baseline results for these scenarios are given in Table 6 and Table 9.

Table 7 and Table 8 provide the results of the policy simulations for the "no learning" case. The absence of learning by doing, and the strengthening of the effect of R&D to compensate, makes the R&D subsidy perform relatively better. But it remains by far the most costly policy. The point is that without some output or emissions incentive to use renewables, investing in those cost reductions is not very worthwhile. All emissions reductions must be gained by making renewables less expensive than fossil fuels in the absence of any emissions or conservation incentive. The other result, which is apparent across the board, is that renewables output is lower and emissions are higher than in the central scenario. Without learning, there is no incentive to engage in extra production in the first stage, and with somewhat less technical progress, there is also less cost-effective generation in the second stage. For the R&D subsidy case, there is now zero increase in renewables output in the first stage, since there is no complementarity with LBD to encourage such output. Correspondingly, growth in renewable energy production is steeper without learning, except somewhat in the case of the portfolio standard, due to the adjusting value of the market share constraint.

Table 10 and Table 11 provide the policy simulation results for the "high learning" case. The most significant change in overall policy efficiency is that, as one might expect, the performance of the renewables production subsidy improves. Nonetheless, it still has welfare costs nine times as high as for the emissions price. The relative performance of the R&D subsidy worsens due to the diminished effectiveness of the R&D stock in boosting knowledge and technological change. Further, first-period renewables output increases significantly under the R&D subsidy due to the complementarity between R&D and the more powerful LBD. However, the omission from our analysis of imperfections in the markets for LBD and R&D sets aside differences in the performance of alternative policies that would otherwise arise due to variation in the extent to which these policies would ameliorate knowledge spillover problems. This will be an important issue for further research.

5. Conclusion

We assess different policy options for promoting renewable energy and evaluate their performance in terms of emissions reduction, renewable energy production, R&D, and welfare. We find that, in the absence of spillover effects, the presence of technological progress—and whether it occurs by learning by doing or innovation based on R&D—has little effect on the relative efficiency of different policy measures. With optimizing actors, the emissions price is the most efficient at reducing emissions, since it simultaneously gives incentives for fossil energy producers to reduce emissions intensity, for consumers to conserve, and for renewable energy producers to expand production and to invest in knowledge to reduce their costs. The other policies can be described as offering different combinations of these incentives, which have different consequences for the distribution and the overall size of the burden of meeting an emissions reduction target.

For example, a renewable energy portfolio standard creates an implicit tax on fossil energy in the form of the mandate to buy green certificates, which then funds a subsidy to renewable energy through the certificate value. The combination raises the total price received by the renewable energy sector and encourages more renewable energy output and R&D than a tradable emissions performance standard or a fossil output tax, but at a greater welfare cost. The performance standard, on the other hand, also provides fossil fuel producers with the incentive to reduce their emissions intensity, which reduces the burden placed on the other margins of emissions reduction.

The fossil output tax promotes conservation and renewables output at the expense of consumer surplus, although it also raises revenues. The renewables production subsidy supports green generation at taxpayer expense, and achieving emissions reductions is costlier with no disincentive for fossil fuels. The renewable energy research subsidy is the most expensive way to achieve emissions reductions since the main driver of renewables production and R&D investment—higher prices for renewable energy—is absent. The process of technological change

turns out to be far less important than the incentive to use it. In this sense, the results suggests the importance of "demand-pull" and the frailty of "technology-push" policies in encouraging cost-effective emissions reductions. This case is reinforced where technology policies are directed at a small share of overall current electricity production. It simply becomes extremely expensive to try to reduce overall emissions by pushing on a small piece of the portfolio, and without any direct incentive for reducing emissions intensity or overall energy use.

Of course, there are several caveats and potential extensions to this analysis. A number of simplifying assumptions were imposed in both the theoretical and numerical analyses for transparency and tractability. One area open for adding more richness is the fossil fuel sector. Although it is modeled as a single technology, in reality it is composed of several technologies, particularly coal and natural gas. Inframarginal fossil generation can change the calculation of producer surplus and the incidence of price changes. Furthermore, the assumption of constant marginal costs is fairly strong for shorter time horizons, when the supply curve for fossil-based electricity may be upward sloping, especially as a function of natural gas supplies. Over the long run, on the other hand, fossil generation costs may decline due to the presence of R&D in the fossil fuel sector. Other important issues include dynamic incentives, discounting, and the horizons over which knowledge stocks take effect. We will address these issues in further research.

A larger issue is the effect of knowledge spillovers. If firms cannot appropriate all the gains to their learning or research, how does this affect the performance of policies for renewable energy? Without a second market failure, direct emissions pricing will always perform the best. However, with underprovision of knowledge, the optimal policy response would be a combination of an emissions price—which offers efficient incentives for the fossil fuel sector—and output and research support—which make up for insufficient incentives for learning by doing and R&D. The relative attractiveness of individual policies would then also change, depending on the severity of the spillover effect and the process of knowledge accumulation.

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Appendix: Comparative statics of renewable energy

To consider how changes in electricity prices affect renewables generation and investment behavior, let $P_t^R = P_t + s_t$ be the price received by the renewables sector. Totally differentiating the three first-order conditions for renewables production, we can get a sense of how the system responds to small changes in the prices of output and investment.

Differentiating equation (7), we find that in the second stage,

$$dP_2^R = G_{q_2 q_2} dq_2 + G_{q_2 K_2} dK_2 ,$$

where

$$dK_2 = nK_Q dq_1 + nK_H dh_1 .$$

Solving for dq_2, we get

$$dq_2 = \frac{dP_2^R - G_{q_2 K_2} dK_2}{G_{q_2 q_2}} . \tag{17}$$

In other words, second-stage output is increasing in the price received by renewables and in knowledge.

Differentiating equation (6), we find that in the first stage,

$$dP_1^R = G_{q_1 q_1} dq_1 + \delta m G_{K_2 q_2} K_Q dq_2 + \delta m G_{K_2 K_2} K_Q dK_2 + \delta mn G_{K_2} (K_{QH} dh_1 + K_{QQ} dq_1) .$$

Substituting the definitions of dq_2 and dK_2 into the first-stage equation, and rearranging, we get

$$dP_1^R - \frac{\delta m G_{K_2 q_2} K_Q}{G_{q_2 q_2}} dP_2^R = dq_1 \left(G_{q_1 q_1} + \delta mn \left(K_Q{}^2 \Gamma + G_{K_2} K_{QQ} \right) \right) + dh_1 \delta mn \left(G_{K_2} K_{QH} + K_Q K_H \Gamma \right), \tag{18}$$

where $\Gamma = G_{K_2 K_2} - (G_{K_2 q_2})^2 / G_{q_2 q_2}$. Recall that $G_q > 0$, $G_{qq} > 0$, $G_K < 0$, $G_{KK} > 0$, and, $G_{qK} = G_{Kq} < 0$. Let

$$\mathrm{A} = \underbrace{K_Q K_H}_{+} \Gamma + \underbrace{G_{K_2}}_{-} K_{QH}$$

$$\mathrm{B} = \underbrace{K_Q{}^2}_{+} \Gamma + \underbrace{G_{K_2} K_{QQ}}_{+} .$$

Solving (18) for dq_1 we find,

$$dq_1 = \frac{dP_1^R - \delta m K_Q G_{K_2 q_2} / G_{q_2 q_2} dP_2^R - \delta mn \mathrm{A} dh_1}{G_{q_1 q_1} + \delta mn \mathrm{B}}. \tag{19}$$

Note that for output to be increasing in own-stage price, it must be that the denominator is positive. It then follows that first-stage output is also increasing in the second-stage price, due to the LBD effect.

The variable A indicates whether LBD is crowded out by R&D. If R&D and LBD are complements, then $K_{QH} > 0$, allowing $\mathrm{A} < 0$, meaning first-stage production increases with investment in R&D. If R&D and LBD are substitutes in knowledge production, then $K_{QH} < 0$, and A may instead be positive. In this case, more R&D makes LBD less productive, given any output level. On the other hand, the corresponding increase in second-stage output makes LBD more valuable. First-stage production may then increase or decrease with investment in R&D. Note that in a scenario with no LBD, $K_Q = 0$, $K_{QH} = 0$, and $\mathrm{A} = 0$. Consequently, first-stage production is unaffected by changes in R&D and also unaffected by changes in the second-stage price.

Differentiating the first-order condition for R&D investment (equation (8)), we get

$$R_h d\sigma + (1-\sigma) R_{hh} dh_1 = \delta m K_H G_{Kq} dq_2 + \delta mn \left(K_H G_{KK} K_Q + G_K K_{HQ} \right) dq_1 + \delta mn \left(G_{KK} K_H{}^2 + G_K K_{HH} \right) dh_1.$$

Substituting the definition of dq_2 and rearranging the R&D investment equation, we get

$$R_h d\sigma - \delta m K_H \frac{G_{Kq}}{G_{q_2 q_2}} dP_2^R = \delta mn \mathrm{A} dq_1 + \delta mn \left(K_H{}^2 \Gamma + G_{K_2} K_{HH} \right) dh_1 - (1-\sigma) R_{hh} dh_1.$$

Let $\mathrm{X} = \delta mn \mathrm{A} / (G_{q_1 q_1} + \delta mn \mathrm{B})$, the sign of which depends on A.

Substituting dq_1 into the R&D condition, rearranging and solving, we get the response of R&D investment to price and subsidy changes:

$$dh_1 = \frac{R_h d\sigma - \left(\delta m K_H G_{K_2 q_2} / G_{q_2 q_2} + \mathrm{X} \right) dP_1^R + \mathrm{X} \delta m K_Q G_{K_2 q_2} / G_{q_2 q_2} dP_2^R}{-\delta mn \mathrm{AX} + \delta mn \left(K_H{}^2 \Gamma + G_{K_2} K_{HH} \right) - (1-\sigma) R_{hh}}. \tag{20}$$

When R&D incentives are well behaved, investment increases as costs decrease (or as the subsidy increases); thus, it must be that the denominator is positive. This requires that knowledge accumulation with R&D be diminishing and/or $\Gamma > 0$. Note that an increase in first-stage output prices will increase R&D if it is a complement to LBD. If R&D and LBD are substitutes, a rise in first-stage prices would lower R&D. The first effect of a rise in second-stage prices is to increase R&D; the second effect depends on the interaction with LBD. If LBD is complementary, the R&D increase is enhanced by the expansion of first-stage output with the price increase; if LBD is a substitute, the incentive to increase R&D is diminished. Logically, the net effect should remain positive, as the driving force is the greater return to knowledge in the second stage, whereas the substitutability determines the incidence across LBD and R&D.

Table 1. Incentives from alternative policies

	Emissions price	Tradable emissions perform. std.	Output tax on fossil generation	Renewables portfolio standard	Renewables production subsidy	Renewables research subsidy
Emissions intensity reduction	Yes	Yes	No	No	No	No
Energy conservation (via electricity price increase)	Yes	Yes (some)	Yes	Yes (some)	No	No
Additional subsidy for renewable energy output	No	Yes (implicit)	No	Yes (implicit)	Yes	No
Subsidy for R&D	No	No	No	No	No	Yes

Table 2. Parameter values

Parameter	Base Value (Range)
Baseline cost (price) of fossil fuel generation (c_0)	0.07 \$/kWh
Slope of marginal carbon abatement supply function (c_1)	3.71×10^6 \$kWh/ton^2
Intercept of renewables generation supply function (g_1)	0.0261 \$/kWh
Slope of renewables generation supply function (g_2)	6.49×10^{-13} \$/kWh^2
Knowledge function intercept (k_0)	15.40
Learning parameter (central scenario) (k_1)	0.10
R&D parameter (central scenario) (k_2)	0.20
R&D investment cost parameter (central scenario) (γ_0)	6.75×10^9
R&D investment cost parameter (γ_1)	1.11
Electricity demand elasticity (ε)	-0.30
Initial stock of renewables experience (Q_1)	7.5×10^{11} kWh
Initial knowledge stock and R&D stock (K_1 and H_1)	1.00

Table 3. Baseline results without policy: Central scenario

	1st stage	2nd stage
Price of electricity ($/kWh)	0.07	0.07
Carbon emissions (million metric tons per year)	658	657
Total annual electricity demand (kWh)	3.05×10^{12}	3.05×10^{12}
Emissions rate (tC/GWh)	216	215
Fossil generation (kWh/yr)	2.98×10^{12}	2.97×10^{12}
Renewables generation (kWh/yr)	7.26×10^{10}	7.81×10^{10}
Renewables share	2.4%	2.6%
Renewables R&D investment (million $/yr)	300	—
Rate of renewables cost reduction	8.8%	—

Table 4. Annual effects of alternative policies relative to base case: Central scenario

	Emissions price	Tradable emissions perform. std.	Output tax on fossil generation	Renewables portfolio standard	Renewables production subsidy	Renewables research subsidy
Policy level for 5.8% emissions reduction	25 $/tC	203 tC/GWh	1.1 ¢/kWh	6.7%	6.5 ¢/kWh	99.5%
Electricity price						
1st stage	7.8%	0.7%	15.9%	7.5%	0.0%	0.0%
2nd stage	7.8%	0.7%	15.9%	3.9%	0.0%	0.0%
Carbon emissions						
1st stage	-5.7%	-5.9%	-5.5%	-6.5%	-3.8%	-0.4%
2nd stage	-5.8%	-5.7%	-5.9%	-5.4%	-6.7%	-8.5%
Renewables output						
1st stage	12.8%	21.4%	26.3%	174.6%	157.9%	15.9%
2nd stage	17.4%	27.8%	36.8%	158.0%	256.8%	324.4%
Fossil output						
1st stage	-2.7%	-0.7%	-5.5%	-6.5%	-3.8%	-0.4%
2nd stage	-2.9%	-0.9%	-5.9%	-5.4%	-6.7%	-8.5%
Total electricity output						
1st stage	-2.3%	-0.2%	-4.8%	-2.2%	0.0%	0.0%
2nd stage	-2.3%	-0.2%	-4.8%	-1.2%	0.0%	0.0%
Renewables R&D	80%	132%	182%	1,012%	1,941%	283,691%
Additional renewables cost reduction	3.1%	4.8%	6.1%	20.2%	25.8%	62.1%
ΔConsumer surplus ($B)	-16.41	-1.49	-33.25	-10.87	0.00	0.00
ΔProducer surplus ($B)	0.45	0.75	0.99	7.33	10.31	4.20
ΔTransfers ($B)	15.49	0.00	31.30	0.00	-16.18	-286.79
ΔWelfare (excluding environ. benefits) ($B)	-0.47	-0.74	-0.96	-3.54	-5.88	-282.59
ΔWelfare relative to emissions price	1.0	1.6	2.0	7.5	12.5	600.6

Table 5. Explicit and implicit taxes and subsidies of alternative policies: Central scenario
(first/second stage)

Policy	Explicit and implicit taxes and subsidies: Emissions price ($/tC)	Output tax on fossil generation (¢/kWh)	Renewables subsidy (¢/kWh)	Price received by renewables (¢/kWh)
Fixed-price policies				
Emissions price	25/25	—	—	7.54/7.54
Output tax on fossil generation	—	1.12/1.12	—	8.12/8.12
Renewables production subsidy	—	—	6.53/6.53	13.53/13.53
Rate-based policies				
Emissions performance standard	42/39	-0.86/-0.80	0.86/0.80	7.91/7.85
Renewables portfolio standard	—	0.52/0.28	7.29/3.85	14.82/11.12

Note: The negative implicit output tax for the emissions performance standard indicates a subsidy.

Table 6. Baseline results without policy: No learning scenario

	1st stage	2nd stage
Price of electricity ($/kWh)	0.07	0.07
Carbon emissions (million metric tons per year)	659	658
Total annual electricity demand (kWh)	3.05×10^{12}	3.05×10^{12}
Emissions rate (tC/GWh)	216	216
Fossil generation (kWh/yr)	2.98×10^{12}	2.98×10^{12}
Renewables generation (kWh/yr)	6.76×10^{10}	7.38×10^{10}
Renewables share	2.2%	2.4%
Renewables R&D investment (million $/yr)	300	—
Rate of renewables cost reduction	5.4%	—

Table 7. Annual effects of alternative policies relative to base case: No learning scenario

	Emissions price	Tradable emissions perform. std.	Output tax on fossil generation	Renewables portfolio standard	Renewables production subsidy	Renewables research subsidy
Policy level for 5.8% emissions reduction	25 $/tC	204 tC/GWh	1.1 ¢/kWh	6.5%	7.1 ¢/kWh	99.4%
Electricity price						
1st stage	7.8%	0.7%	16.1%	7.5%	0.0%	0.0%
2nd stage	7.8%	0.7%	16.1%	4.2%	0.0%	0.0%
Carbon emissions						
1st stage	-5.6%	-5.9%	-5.5%	-6.5%	-3.7%	-0.0%
2nd stage	-5.8%	-5.7%	-5.8%	-5.3%	-6.8%	-8.7%
Renewables output						
1st stage	12.4%	21.0%	25.6%	185.0%	161.2%	0.0%
2nd stage	17.3%	27.6%	36.8%	163.9%	274.3%	349.9%
Fossil output						
1st stage	-2.7%	-0.7%	-5.5%	-6.5%	-3.7%	-0.0%
2nd stage	-2.8%	-0.9%	-5.8%	-5.3%	-6.8%	-8.7%
Total electricity output						
1st stage	-2.3%	-0.2%	-4.8%	-2.3%	0.0%	0.0%
2nd stage	-2.3%	-0.2%	-4.8%	-1.2%	0.0%	0.0%
Renewables R&D	80%	133%	183%	1,097%	2,159%	255,464%
Additional renewables cost reduction	2.9%	4.6%	5.9%	19.2%	26.0%	65.6%
Δconsumer surplus ($B)	-16.41	-1.44	-33.47	-11.20	0.00	0.00
ΔProducer surplus ($B)	0.42	0.71	0.94	7.50	10.85	4.24
ΔTransfers ($B)	15.52	0.00	31.57	0.00	-17.17	-258.03
ΔWelfare (excluding environ. benefits) ($B)	-0.47	-0.74	-0.96	-3.70	-6.31	-253.79
ΔWelfare relative to emissions price	1.0	1.6	2.1	7.9	13.5	541.5

Table 8. Explicit and implicit taxes and subsidies of alternative policies: No learning scenario (first/second stage)

Policy	Explicit and implicit taxes and subsidies			Price received by renewables (¢/kWh)
	Emissions price ($/tC)	Output tax on fossil generation (¢/kWh)	Renewables subsidy (¢/kWh)	
Fixed-price policies				
Emissions price	25/25	—	—	7.54/7.54
Output tax on fossil generation	—	1.12/1.12	—	8.12/8.12
Renewables production subsidy	—	—	7.08/7.08	14.08/14.08
Rate-based policies				
Emissions performance standard	43/40	-0.87/-0.81	0.87/0.81	7.927.85
Renewables portfolio standard	—	0.53/0.29	7.60/4.21	15.12/11.50

Note: The negative implicit output tax for the emissions performance standard indicates a subsidy.

Table 9. Baseline results without policy: High learning scenario

	1st stage	2nd stage
Price of electricity ($/kWh)	0.07	0.07
Carbon emissions (million metric tons per year)	653	651
Total annual electricity demand (kWh)	3.05×10^{12}	3.05×10^{12}
Emissions rate (tC/GWh)	214	213
Fossil generation (kWh/yr)	2.95×10^{12}	2.95×10^{12}
Renewables generation (kWh/yr)	9.71×10^{10}	10.51×10^{10}
Renewables share	3.2%	3.4%
Renewables R&D investment (million $/yr)	300	—
Rate of renewables cost reduction	25.8%	—

Table 10. Annual effects of alternative policies relative to base case: High learning scenario

	Emissions price	Tradable emissions perform. std.	Output tax on fossil generation	Renewables portfolio standard	Renewables production subsidy	Renewables research subsidy
Policy level for 5.8% emissions reduction	25 $/tC	201 tC/GWh	1.1 ¢/kWh	7.8%	4.5 ¢/kWh	99.7%
Electricity price						
1st stage	7.8%	0.7%	15.3%	8.3%	0.0%	0.0%
2nd stage	7.8%	0.7%	15.3%	2.7%	0.0%	0.0%
Carbon emissions						
1st stage	-5.8%	-5.9%	-5.7%	-7.2%	-4.1%	-1.4%
2nd stage	-6.0%	-5.7%	-6.1%	-5.3%	-6.9%	-8.3%
Renewables output						
1st stage	14.1%	21.4%	28.1%	140.5%	125.7%	43.9%
2nd stage	18.6%	27.8%	38.1%	125.8%	193.7%	232.3%
Fossil output						
1st stage	-2.9%	-0.7%	-5.7%	-7.2%	-4.7%	-1.4%
2nd stage	-3.1%	-0.9%	-6.1%	-5.3%	-7.5%	-8.3%
Total electricity output						
1st stage	-2.3%	-0.2%	-4.6%	-2.5%	0.0%	0.0%
2nd stage	-2.3%	-0.2%	-4.6%	-0.8%	0.0%	0.0%
Renewables R&D	82%	132%	180%	646%	1,228%	392,037%
Additional renewables cost reduction	3.7%	4.8%	7.1%	21.7%	23.6%	46.5%
ΔConsumer surplus ($B)	-16.41	-1.49	-33.25	-10.87	0.00	0.00
ΔProducer surplus ($B)	0.45	0.75	0.99	7.33	10.31	4.20
ΔTransfers ($B)	15.49	0.00	31.30	0.00	-16.18	-286.79
Δ Welfare (excluding environ. benefits) ($B)	-0.47	-0.74	-0.96	-3.54	-5.88	-282.59
ΔWelfare relative to emissions price	1.0	1.5	2.0	6.1	8.7	814.3

Table 11. Explicit and implicit taxes and subsidies of alternative policies: High learning scenario (first/second stage)

Policy	Explicit and implicit taxes and subsidies			Price received by renewables (¢/kWh)
	Emissions price ($/tC)	Output tax on fossil generation (¢/kWh)	Renewables subsidy (¢/kWh)	
Fixed-price policies				
Emissions price	25/25	—	—	7.54/7.54
Output tax on fossil generation	—	1.07/1.07	—	8.07/8.07
Renewables production subsidy	—	—	4.46/4.46	11.46/11.46
Rate-based policies				
Emissions performance standard	43/38	-0.86/-0.77	0.86/0.77	7.92/7.82
Renewables portfolio standard	—	0.58/0.19	6.81/2.26	14.39/9.45

Note: The negative implicit output tax for the emissions performance standard indicates a subsidy.