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Environmental and Technology Policies for Climate Mitigation

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Abstract

We assess different policies for reducing carbon dioxide emissions and promoting the innovation and diffusion of renewable energy. We evaluate the relative performance of policies according to incentives provided for emissions reduction, efficiency, and other outcomes. We also assess how the nature of technological progress through learning and R&D, and the degree of knowledge spillovers, affect the desirability of different policies. Due to knowledge spillovers, optimal policy involves a portfolio of different instruments targeted at emissions, learning, and R&D. Although the relative cost of individual policies in achieving reductions depends on parameter values and the emissions target, in a numerical application to the U.S. electricity sector, the ranking is roughly as follows: (1) emissions price, (2) emissions performance standard, (3) fossil power tax, (4) renewables share requirement, (5) renewables subsidy, and (6) R&D subsidy. Nonetheless, an optimal portfolio of policies achieves emissions reductions at significantly lower cost than any single policy.

Key Words: environment, technology, externality, policy, climate change, renewable energy

JEL Classification Numbers: Q21, Q28, Q48, O38

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1. Introduction

To reduce greenhouse gas emissions and promote technological development and diffusion of renewable energy, recent policies and proposals employ a broad range of incentives. Some policies create disincentives for emitting energy sources by taxing these energy sources or by making greenhouse gas emissions expensive, such as with a tradable emissions permit system, a tax on carbon dioxide (CO_2), or an emissions intensity standard for generation. Alternatively, 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. Still other polices 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. Similar policy initiatives are growing not only for renewables, but also for relatively clean coal technologies, advanced nuclear power, and a range of technologies in the transportation sector.

Much attention is being given particularly to the potential for renewable energy to displace fossil-fueled sources. In 2001, renewable energy sources provided 5.7% of the total primary energy supply for OECD countries, with 54% coming from 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%

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

if one excludes hydro. The United States aims to nearly double energy production from renewable sources by 2025 (excluding hydro), compared to 2000 levels.[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 (International Energy Agency 2003). 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.

Although economists typically argue that a direct price for CO_2 (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 CO_2 can have important distributional consequences, both for owners of fossil-fueled 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. Nor can governments credibly use the promise of high future emissions prices to boost current innovation, since such high prices would no longer be needed once the resulting cost reductions arrive.[3] 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.

The environmental economics literature on induced innovation has focused on the role and effectiveness of environmental policy in stimulating innovation in environmentally friendly

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[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.

[3] See Kennedy and Laplante (1999) and Montgomery and Smith (forthcoming).

technologies (Jaffe et al. 2003). Empirical investigations have assessed the effects of energy price changes and regulations on innovations in energy technologies, finding support for induced innovation as well as autonomous progress (Newell et al. 1999; Popp 2002). Theoretical analyses have tended to focus on the efficacy of market-based environmental policies relative to prescriptive regulation in inducing efficient 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 (Carraro et al. 2003). While most modeling efforts assume exogenous technical change, the small number of climate-energy models that incorporate induced technological change can be roughly divided into two types (Popp 2004). 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 CO_2 taxes or tradable permits.[4] This focus is due in part to the limited ability of top-down models to represent other types of policies, which often requires greater technological detail.

In this paper, we bridge several areas in the analysis of climate policies and induced innovation. We consider a broad set of environmental policies, including indirect ones, and incorporate "knowledge investment" through 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 economic surplus. We also assess how the nature of technological progress—the degree of knowledge spillovers and the degree of innovation occurring through learning by doing or R&D-based innovation—affects the desirability of different policy measures.

Some clear principles emerge. We find that when the ultimate goal is to reduce emissions, policies that create incentives for fossil-fueled generators to reduce emissions intensity, and for consumers to conserve energy, perform better than those that rely on incentives for renewable energy producers alone. Overall, we find that the nature of knowledge accumulation is far less important than the nature of the policy incentives.[5] For the type of moderate emissions targets we explore, a renewable energy R&D subsidy turns out to be a particularly inefficient means of emissions reduction, since it postpones the vast majority of the effort to displace fossil-fueled generation until after costs are brought down. A very similar result was found by Schneider and Goulder (1997) employing a CGE approach. This requires very large R&D investments and forgoing near-term cost-effective opportunities to reduce emissions.

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[4] 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.

[5] This is consistent with the results of Parry et al. (2003), who find that the welfare gains from correcting an environmental externality are more important for policy than the gains from technological change.

While climate change is a long-term problem, the results for mid-term strategies emphasize the important role for policies that encourage abatement across all available forms and timeframes and the limitations of narrowly targeted policies, particularly those focused solely on R&D.

Nonetheless, given the presence of more than one market failure—an emissions externality and knowledge spillovers—no single policy can correct both simultaneously; each poses different trade-offs (Jaffe et al. 2005). The presence of knowledge spillovers means that separate policy instruments are necessary to optimally correct the climate externality and the externalities for both learning and R&D. In fact, we find that an optimal portfolio of policies can achieve emissions reductions at significantly lower cost than any single policy (as did Schneider and Goulder (1997)), although the reductions continue to be attributed primarily with the emissions price.

Together, these results illuminate some arguments in Montgomery and Smith (forthcoming)—that R&D is the key for dealing with climate change and that an emissions price high enough to induce the needed innovation cannot be credibly implemented. We show that an emissions price alone, although the least costly of the single policy levers, is significantly more expensive alone than when used in combination with optimal knowledge subsidy policies. Although a high future emissions price may not be credible, the required emissions price is more modest with the combination policy. However, if one believes that even a modest emissions price is not politically feasible, an R&D subsidy by itself is not the next-best policy, and the costs of that political constraint are likely to be quite large and increasing with restrictions on the remaining policy options. It should be kept in mind, however, that we focus on reductions over the near-to-mid term and incremental improvement of existing technology, rather than breakthrough technologies that might achieve deep reductions. It seems likely that policies focused on R&D have greater salience in the latter context, although this lies beyond the scope of the current paper.

1.1. *Alternative environmental and technology policies*

Among the OECD countries, policies to reduce greenhouse gas emissions and support renewable energy vary widely, both in form and in degree.[6] We distinguish six policies. First, an *emissions price on* CO_2 provides incentives to reduce CO_2 intensity and makes fossil-fueled sources relatively more expensive compared to renewables. Sweden, Denmark, Finland, and Norway have CO_2 taxes,[7] and in 2005 the European Union launched a program of tradable CO_2 emissions permits.

Second, a *tax on fossil-fueled energy* seeks to discourage use of these sources in favor of renewables. The United Kingdom, Germany, Sweden, and the Netherlands tax fossil-fueled sources, in most cases by exempting renewable sources from an energy tax. Third a *tradable emissions performance standard* sets the average emissions intensity of fossil and renewable output combined. 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.

Fourth, so-called *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 18 of the U.S. states and the District of Columbia. Fifth, a *production subsidy for renewable energy* improves the competitiveness of these sources vis-à-vis fossil fuels. The United States has the Renewable Energy Production

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[6] 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/.

[7] 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.

Incentive of 1.9 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.

Finally, *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. R&D subsidies are used to encourage both near-term improvements, as with R&D tax credits and commercialization incentives, and long-term innovations, as with targeted research programs.

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 biofuels 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.[8] The stylized model is deliberately kept simple to highlight key features. It includes two subsectors, one emitting (fossil fuels) and one nonemitting (renewables), and both are assumed to be perfectly competitive and supplying an identical product, electricity.[9] Fossil-fueled production includes a CO_2-intensive technology (coal) that operates primarily as baseload, and a lower-emitting technology (gas turbines) that dominates at the margin. To the extent that renewable energy is competitive, it displaces marginal fossil-fueled generation.[10] 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 perfect foresight 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_1 and n_2 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 within the second, longer stage by altering n_2 to reflect such discounting; in that case n_2 can be thought of as "effective" years.

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[8] 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.

[9] 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.

[10] We treat nuclear- and hydro-based generation as being fixed in response to the policies we model, a reasonable assumption based on existing detailed modeling results (see section on numerical application).

2.1. The emitting fossil-fueled sector

The emitting sector of the generation industry, denoted with superscript *F*, relies on two fossil fuels for production: coal, *x*, and natural gas, *y*. Total output from the emitting sector is $f_t = x_t + y_t$ in year *t*. Total emissions from this sector equal

$$E_t = \mu_x x_t + \mu_y y_t , \tag{1}$$

as each fuel has a fixed CO_2 intensity μ_i. Marginal production costs for natural gas- and coal-fired generation, $C_y'(y)$ and $C_x'(x)$, respectively, are assumed to be increasing in output ($C_y''(y) > 0,\ C_x''(x) > 0$). The opportunities for CO_2 abatement in electricity generation rely largely on fuel switching; although coal gasification technologies or generation efficiency improvements are options, they tend to explain little of the predicted reductions in climate policy models (see, e.g., EIA 2006).

Two policies affect the fossil-fueled 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-fueled 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. In fact, the effects of performance standards for renewables and emissions can be represented by these twin taxes.

Profits for the representative emitting firm are

$$\begin{aligned} \pi^F &= n_1\left((P_1-\phi_1)(x_1+y_1)-C_x(x_1)-C_y(y_1)-\tau_1(\mu_x x_1+\mu_y y_1)\right) \\ &\quad +\delta n_2\left((P_2-\phi_2)(x_2+y_2)-C_x(x_2)-C_y(y_2)-\tau_2(\mu_x x_2+\mu_y y_2)\right), \end{aligned} \tag{2}$$

where P_t is the price of electricity. The firm maximizes profits with respect to output from each fuel source, yielding the following first-order conditions:[11]

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[11] We assume an interior solution; although theoretically possible, no fuel will be completely driven out of the market in our scenarios.

$$\frac{\partial \pi^F}{\partial x_t} = 0: \quad P_t = C_x'(x_t) + \phi_t + \tau_t \mu_x \text{, and} \tag{3}$$

$$\frac{\partial \pi^F}{\partial y_t} = 0: \quad P_t = C_y'(y) + \phi_t + \tau_t \mu_y. \tag{4}$$

Together, equations (3) and (4) imply $C_x'(x_t) + \tau_t \mu_x = C_y'(y) + \tau_t \mu_y$, meaning that coal generation is used until its marginal costs are equalized with those of natural gas, inclusive of their respective emissions costs. The combination of these two equations means that, in the absence of an emissions price, an increase in renewables supply crowds out natural gas- and coal-fired generation in proportion to the slopes of their competing supply curves. A higher emissions price leads to a larger reduction in coal-fired production, since that is the only policy to differentiate between coal and gas.

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. 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-fueled technologies. While it is of course not strictly true that fossil-fueled 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.[12]

The knowledge stock $K(H_t, Q_t)$ is a function of cumulative knowledge from R&D, H_t, and of cumulative experience through learning by doing, Q_t, where $K_H \geq 0$ and $K_Q \geq 0$, and $K_{QH} = K_{HQ}$. Cumulative R&D-based knowledge increases in proportion to annual R&D knowledge generated in each stage, h_t, so $H_2 = H_1 + n_1 h_1$. Cumulative experience increases with total output during the first stage, so $Q_2 = Q_1 + n_1 q_1$. 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.[13] A subtle issue is whether research and experience are substitutes, in which case $K_{HQ} \leq 0$, or complements, making $K_{HQ} > 0$.

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

$$\pi^R = n_1\left((P_1 + s_1)q_1 - G(K_1, q_1) - (1-\sigma)R\left(h_1\right)\right) + \delta n_2\left((P_2 + s_2)q_2 - G(K_2, q_2)\right), \qquad (5)$$

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

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[12] An exception is room for advancement in lowering costs of cleaner generation technologies for fossil fuels, such as carbon capture and storage. Our qualitative results should carry over to policies targeting other low-carbon technologies, although the quantitative results would depend on the cost, technology, and emissions parameters particular to those other technologies.

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

Let ρ be a factor reflecting the degree of appropriability of returns from investments in R&D.[14] In the Appendix, this appropriation rate is formally derived for multiple innovating firms that derive their own benefits from knowledge and can to some degree appropriate the benefits that accrue to others as well.[15] Aggregating to our representative firm, appropriated benefits can be represented as a share of the total. Thus, $\rho = 1$ would reflect an extreme with perfect appropriability and no knowledge spillovers, while $\rho = 0$ reflects the opposite extreme of no private appropriability of knowledge investments. Similarly, $1-\rho$ reflects the degree of knowledge spillovers. We assume that all knowledge is ultimately adopted, either by imitation or licensing. Therefore, the spillover factor does not enter directly into the aggregate profit function, which reflects operating profits. Licensing revenues also do not appear because they represent transfers among firms. However, the spillover factor does enter into the first-order conditions for R&D and learning, since it determines the share of future profit changes that can be appropriated by the representative innovator. These issues are further elaborated in the Appendix.

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

$$\frac{\partial \pi^R}{\partial q_1} = n_1\left(P_1 + s_1 - G_q(K_1, q_1)\right) - \delta\rho n_2 G_K(K_2, q_2) n_1 K_Q(H_2, Q_2) = 0,$$

$$\frac{\partial \pi^R}{\partial q_2} = \delta n_2\left(P_2 + s_2 - G_q(K_2, q_2)\right) = 0, \text{ and}$$

$$\frac{\partial \pi^R}{\partial h_1} = -n_1(1-\sigma)R_h(h_1) - \delta\rho n_2 G_K(K_2, q_2) n_1 K_H(H_2, Q_2) = 0.$$

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[14] We model general knowledge as being appropriable, with no distinction according to the source of that knowledge, R&D or learning. While an empirical basis is lacking for such a distinction, one might expect that some forms of learning are less easily appropriated by other firms. We discuss the implication of relaxing this assumption in the context of the numerical simulations.

[15] With N identical firms, the appropriable share of total gains is $\rho = (1+\omega(N-1))/N$, where ω is the appropriation rate from other firms.

Rearranging, we get

$$G_q(K_1, q_1) = P_1 + s_1 - \delta\rho n_2 G_K(K_2, q_2) K_Q(H_2, Q_2), \tag{6}$$

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

$$R_h(h_1) = -\delta \frac{\rho}{(1-\sigma)} n_2 G_K(K_2, q_2) K_H(H_2, Q_2). \tag{8}$$

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 appropriable contribution of such output to future cost reduction through learning by doing (note that the last term in equation (6) is positive overall). 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 appropriated returns from R&D equal investment costs on the margin.

Note that if appropriation rates are imperfect ($\rho < 1$), from a societal perspective, firms have insufficient incentive to engage in extra production for the purpose of learning by doing. Similarly, if the R&D subsidy does not fully reflect the spillover values ($\sigma < 1 - \rho$), firms have insufficient incentive to invest in R&D. Thus, a knowledge externality accompanies the emissions externality, and both can be affected by policies that target one or the other.

2.3. Consumer demand

Renewable energy generation and fossil-fueled production are assumed to be perfect substitutes. We abstract from short-run peak-pricing variations and take a longer-term view of demand and supply curves. Let $D(P)$ be the consumer demand for electricity, a function of the price, where $D'(P) < 0$. Consumer surplus is therefore $CS = \int_{P_t}^{\infty} D(P)dP$. Thus, the change in consumer surplus due to the renewable energy policy in this partial equilibrium model is

$$\Delta CS = -n_1 \int_{P_0}^{P_1} D(P)dP - \delta n_2 \left(\int_{P_0}^{P_2} D(P)dP \right). \tag{9}$$

In equilibrium, total consumption must equal total supply, the sum of fossil-fueled and renewable energy generation:[16]

$$D(P_t) = x_t + y_t + q_t \,. \tag{10}$$

2.4. *Economic surplus*

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:

$$\Delta V = n_1\left(\phi_1 f_1 + \tau_1(\mu_x x_1 + \mu_y y_1) - s_1 q_1 - \sigma R(h_1)\right) + \delta n_2\left(\phi_2 f_2 + \tau_2(\mu_x x_2 + \mu_y y_2) - s_2 q_2\right). \tag{11}$$

Note that while we have assumed here that the emissions price results in government revenue, either through a tax or auctioned permit system, a permit system with free allocation would yield the same overall results in our model, with rents accruing to the permit holders, rather than generating government transfers. If, on the other hand, tax revenue changes were recycled by lowering more distortionary taxes in the economy, the revenue-raising policy options would perform relatively better. Incorporating such a feature would tend to widen the efficiency-cost gaps we find in our results.

Environmental benefits (i.e., reduced climate 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:

$$\Delta B = B(E_1, E_2, n_1, n_2) - B(E_0, E_0, n_1, n_2) \,. \tag{12}$$

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

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[16] Note that in the empirical application, we allow for a fixed level of nuclear and hydro generation, which are not expected to change as a function of the policies we evaluate. As a result, demand can be considered as the residual after this exogenous supply.

$$\Delta W = \Delta B + \Delta CS + \Delta \pi + \Delta V \ , \tag{13}$$

where $\Delta \pi = \Delta \pi^R + \Delta \pi^F + \Delta \pi^{Other}$, where $\Delta \pi^F = \Delta \pi^x + \Delta \pi^y$. "Other" profits represent the change in revenues for other baseload generators, as we include nuclear and hydropower in our simulations; these generators have fixed costs and capacities and profit to the extent the electricity price rises.

However, *economic surplus* 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.[17] 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 *economic surplus* within the sector will not reflect the full social impacts; still, it represents a useful baseline metric.

2.5. Comparative statics

In this section, we consider the equilibrium effect of small changes in the different taxes and subsidies; we assume, here and in our numerical simulations, that these policy prices are held constant across both periods. In the market equilibrium, we have the market-clearing condition (10), the first-order conditions for fossil-fueled generation (equations (3)–(4)) and renewable generation (equations (6)–(8)), and an equation governing knowledge accumulation. Totally differentiating these equations, and noting that $dK_2 = n_1\left(K_H dh_1 + K_Q dq_1\right)$, we derive a system of equations governing the responses to the different policy options:

$$dP_t = \left(dx_t + dy_t + dq_t\right) / D'(P_t) \ , \tag{14}$$

$$dx_t = \left(dP_t - d\phi_t - \mu_x d\tau_t\right) / C_x'' \ , \tag{15}$$

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[17] Allowing for distortionary taxes in the model is likely to widen the efficiency gap between revenue-raising policies (e.g., emissions taxes) and revenue-using policies (e.g., renewable subsidies). For a comprehensive survey of the tax interaction literature, see Goulder (2002). For a discussion of emissions leakage, see Bernard et al. (forthcoming) or Fischer and Fox (forthcoming).

$$dy_t = \left(dP_t - d\phi_t - \mu_y d\tau_t\right) / C_y'' , \tag{16}$$

$$dq_2 = \left(dP_2 + ds_t - G_{qK} dK_2\right) / G_{qq} , \tag{17}$$

$$dq_1 = \frac{dP_1 + ds_1 - \delta\rho n_2 G_{Kq} K_Q dq_2 - \delta\rho n_1 n_2 \left(G_K K_{HQ} + G_{KK} K_Q K_H\right) dh_1}{G_{qq} + \delta\rho n_1 n_2 \left(G_K K_{QQ} + G_{KK} {K_Q}^2\right)} \text{, and} \tag{18}$$

$$dh_1 = \frac{R_h d\sigma - \delta\rho n_2 \left(G_{Kq} K_H dq_2 + n_1 \left(G_K K_{HQ} + G_{KK} K_H K_Q\right) dq_1\right)}{\left((1-\sigma) R_{hh} + \delta\rho n_2 n_1 \left(G_K K_{HH} + G_{KK} {K_H}^2\right)\right)} . \tag{19}$$

The incidence of the policies in equilibrium is complicated by the incorporation of impacts on knowledge accumulation. It is therefore helpful to begin by focusing on some of the components. Substituting (15) and (16) into (14) and solving for dP_t, we derive the electricity price impacts for each period as a function of the policies affecting the fossil-fueled sector and the contemporaneous change in renewable output:

$$dP_t = \left(\left(C_y'' + C_x''\right)\left(d\phi_t + \bar{\mu}_t d\tau_t\right) - \left(C_x'' C_y''\right) dq_t\right) / \left(C_x'' + C_y'' - C_x'' C_y'' D'\right) , \tag{20}$$

where $\bar{\mu}_t = \left(C_y'' \mu_x + C_x'' \mu_y\right) / \left(C_y'' + C_x''\right)$ is an average emissions rate for the fossil-fueled sector, weighted by the slope of the supply curves. In other words, the retail price of electricity is increasing in the fossil-fueled output tax and the emissions tax and decreasing as renewable energy increases (which lowers necessary fossil-fueled supply). For additional simplification going forward, let this denominator be represented by $\chi = C_x'' + C_y'' - C_x'' C_y'' D'$.

Substituting (20) back into (15) and (16), we solve for the impacts on fossil-fueled generation:

$$dx_t = \left(C_y'' \left(D' d\phi - dq_t\right) + d\tau (\mu_y - \mu_x \left(1 - C_y'' D'\right)\right) / \chi \text{, and} \tag{21}$$

$$dy_t = \left(C_x'' \left(D' d\phi - dq_t\right) + d\tau (\mu_x - \mu_y \left(1 - C_x'' D'\right)\right) / \chi . \tag{22}$$

These expressions reveal that both fossil-fueled generation sources decline as the fossil output tax increases and as renewable generation expands. The effect of the emissions tax is twofold: (i) a direct increase in costs that reduces generation in proportion to each source’s emissions rate, and (ii) an indirect effect that increases generation as a result of price increases due to cost increases in the other fossil source. The net effect can be positive or negative for natural gas, which emits CO_2, but at about half the intensity of coal.

Substituting (18) into (20) into (17), we solve for the equilibrium impacts on future renewable electricity generation in the second period:

$$\begin{aligned} dq_2 &= \left(dP_2 + ds_2 - n_1 G_{qK} dK_2\right) / G_{qq} \\ &= \frac{\left(C_y'' + C_x''\right)\left(d\phi_2 + \bar{\mu}_2 d\tau_2\right) + \chi\left(ds_2 - n_1 G_{qK} dK_2\right)}{C_x'' C_y'' + G_{qq}\chi} . \end{aligned} \tag{23}$$

Equation (23) reveals that second-period renewable output is increasing in all of the policy levers and in knowledge.[18] Furthermore, substituting (23) into (20) and solving for dP_2, we see that the change in the second-period electricity price is a weighted sum of the tax-induced cost increases on the fossil-fueled sector, and the cost decreases due to technological change in the renewable sector:

$$dP_2 = \omega_2^F \left(d\phi_2 + \bar{\mu}_2 d\tau_2\right) - \omega_2^R \left(ds_2 - n_1 G_{qK} dK_2\right), \tag{24}$$

where

$$\omega_2^F = G_{qq}\left(C_x'' + C_y''\right) / \zeta_2 , \; \omega_2^R = C_x'' C_y'' / \zeta_2 , \text{ and}$$

$$\zeta_2 = C_x'' C_y'' + G_{qq}\left(C_x'' + C_y''\right) - G_{qq} C_x'' C_y'' D' .$$

Note that the effect of the policies on the price of electricity depends on the relative slopes of all of the supply curves, as well as that of electricity demand. The price influence of policy changes targeting fossil fuels increases with steeper renewable energy supply and flatter fossil energy supply, because the flexibility to switch toward renewables is relatively more limited in these cases. The opposite is true for the price influence of renewable sector impacts: they are stronger when the renewable energy supply curve is flatter or the fossil energy supply curves are steeper.

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[18] Knowledge is itself increasing in these policy levers, in part because it is increasing in second-period output, and because some policies directly subsidize knowledge accumulation through learning or R&D.

We see similar effects in the first period, but the incidence of the policies is complicated by the endogeneity of knowledge accumulation and second-period production. Equation (18) shows that first-period renewables output is increasing in the electricity price, the renewable subsidy, and in second-period renewable output due to learning investments. The effect of R&D (h_1) on first-period renewables output is more ambiguous: a positive R&D response will tend to temper the impact somewhat (due to diminishing returns to knowledge generation $-G_{KK}K_QK_H < 0$), but complementarity between learning and R&D could possibly reinforce it (i.e., if $K_{HQ} > 0$).

We observe a similar ambiguity from the R&D equation (19). While R&D is increasing in the R&D subsidy and in second-period renewables output, it is ambiguously related to first-period renewables output, depending on whether R&D and learning are substitutes or complements.

Substituting (18), (21), and (22), into (14) and solving for dP_1, we again find price effects are a weighted sum of the increase in the fossil-sector tax burden and the decrease in effective costs to renewable production, including the incentives from knowledge accumulation:

$$dP_1 = \omega_1^F \left(d\phi_1 + \bar{\mu}_1 d\tau_1\right) - \omega_1^R \left(ds_1 - \delta\rho n_2 \left(n_1 \left(G_K K_{QH} + G_{KK} K_Q K_H\right) dh_1 + G_{Kq} K_Q dq_2\right)\right), \quad (25)$$

where $\omega_1^F = \left(G_{qq} + \delta\rho n_1 n_2 \left(G_K K_{QQ} + G_{KK} K_Q{}^2\right)\right)\left(C_x'' + C_y''\right)/\zeta_1$, $\omega_1^R = C_x'' C_y'' / \zeta_1$, and

$\zeta_1 = C_x'' C_y'' + \chi\left(G_{qq} + \delta\rho n_1 n_2 \left(G_K K_{QQ} + G_{KK} K_Q{}^2\right)\right)$.

Again, the weights on the cost impacts targeting the fossil and renewable energy sectors depend, in ways similar to the second period, on the relative slopes of the supply curves. The difference is that in the first period, the effective supply curve for renewable energy includes the impacts on second-period costs through knowledge accumulation.

To summarize, with the exception of the R&D subsidy, the impact of a policy change on the equilibrium price in each period has two components. First is a direct effect in proportion to the policy change (tax or subsidy); second is an indirect effect due to corresponding changes in knowledge accumulation and second-period output. The R&D subsidy, on the other hand, only induces an indirect effect on prices, through its impact on second-period renewable costs and the first-period benefits to learning. In all cases, the strength of these direct and indirect effects depends on the relative slopes of the supply and demand curves, which ultimately determine the overall price impact.

2.6. Optimal policy

In weighing different policy options, it is useful to bear in mind what the efficient policy combinations would be. In this situation, three policies are needed to optimally address three externalities: emissions, R&D spillovers, and learning spillovers. An appropriate emissions price internalizes the first externality. To determine the optimal subsidies for R&D and learning, we find what is necessary to align the private first-order conditions with those of the social planner.

At the optimum, a coordinated research and learning program would yield

$$\frac{\partial \pi^R}{\partial q_1} = n_1\left(P_1 - G_q(K_1, q_1)\right) - \delta n_2 G_K(K_2, q_2) n_1 K_Q(H_2, Q_2) = 0 \text{, and} \tag{26}$$

$$\frac{\partial \pi^R}{\partial h_1} = -n_1 R_h(h_1) - \delta n_2 G_K(K_2, q_2) n_1 K_H(H_2, Q_2) = 0 . \tag{27}$$

That is, the imperfect appropriability would not influence the investment decisions. Rearranging, we get

$$G_q(K_1, q_1) = P_1 - \delta n_2 G_K(K_2, q_2) K_Q(H_2, Q_2) \text{, and} \tag{28}$$

$$R_h(h_1) = -\delta n_2 G_K(K_2, q_2) K_H(H_2, Q_2) . \tag{29}$$

Setting the right-hand sides of (28) and (6) equal to each other, as well as those of (29) and (8), we can solve for the optimal R&D and learning subsidies when spillovers are present:

$$\sigma = 1 - \rho \text{, and} \tag{30}$$

$$s_1 = -(1-\rho)\delta n_2 G_K(K_2, q_2) K_Q(H_2, Q_2) . \tag{31}$$

In other words, an R&D subsidy is needed to offset the unappropriable share of R&D returns, and a renewable generation subsidy is needed to offset the unappropriated gains from learning.

3. Policy scenarios

As developed in the modeling section, renewable energy production depends on the price received by that sector, the cost of R&D investment, and the degree of appropriability of knowledge investments. Fossil-fueled energy production and the accompanying emissions depend on the amount of renewables sector output, the after-tax price of electricity, and the price of emissions. Consumer demand depends on the price of electricity. 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 efficacy at reducing emissions. Different policies also compensate for knowledge spillovers to different degrees, also contributing to different impacts on economic surplus.

3.1. No policy

We define P_t^0 as the baseline price of electricity generation, in the absence of policy (i.e., $\phi_t = s_t = \tau_t = \sigma = 0$); the first-order conditions for production imply that output prices equal this baseline price in both markets and in each period: $P_t = P_t^R$. We assume that an interior solution exists—that is, that some renewable energy is viable without any policy. A sufficient condition would be that $G_q(K_1, 0) < P_1^0$. However, renewable energy 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. As a result, even without policy, we would expect baseline prices to decline over time, due to knowledge accumulation in the renewable energy sector.

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. All three policies increase prices for renewables, which expands production and also induces more innovation. They differ in their effects on fossil energy production and emissions reduction.

3.2.1 Emissions price

With a direct price for emissions (τ_t)—via either an emissions tax or a tradable emissions permit system—the fossil-fueled sector has an incentive to switch away from coal-fired generation. As we see in Equations (24) and (25), the market price of electricity increases in proportion to the weighted average emissions charge on fossil-fueled generation. Without other subsidies, the renewables sector receives the market price for electricity, 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. As seen in (21), the price increase does not fully compensate for the increase in the marginal costs of coal-fired generation (since $\tau_t \mu_y < \tau_t \mu_x$), resulting in less use of coal. Gas-fired generation may expand, however, if that option is more cost-effective than additional conservation or renewables on the margin.

In the absence of knowledge spillovers, the emissions price would provide efficient incentives for achieving a given emissions reduction goal, since it provides equalized incentives for emissions reduction along all three margins—reduced emissions intensity, demand conservation (via price increase), and increased renewable energy production. In the presence of spillovers, however, a price reflecting the marginal damage from emissions would not offer efficient incentives to contribute to knowledge formation. The degree of inefficiency is an empirical matter, which we explore further below.

3.2.2 Renewable power output subsidy

A renewables production subsidy (s_t) boosts the price received by the renewable energy sector and lowers its effective marginal cost relative to other sources. By putting downward pressure on the price of electricity, the renewables production subsidy crowds out fossil-fueled generation in both stages to reduce emissions. Because the market price of electricity declines, electricity use actually increases. Also, because there is no direct price on emissions, there is no discrimination between coal- and gas-fired generation in order to reduce emissions intensity.

3.2.3 Fossil power output tax

The analytic structure of a fossil-fueled production tax (ϕ_t) is similar to the renewables subsidy because it raises the price received by renewables, except that it does so through higher consumer prices for electricity, rather than a direct subsidy. Thus, both the market price and the effective price received by renewables rise in proportion to the tax. Although no incentive exists to reduce output or emissions specifically from coal relative to gas plants, to the extent that demand falls due to higher prices, fossil-fueled output and emissions will be lower than under an equivalent renewable energy subsidy.

3.2.4 R&D subsidy for renewable energy technology

Without a price on emissions or tax/subsidy on output, output prices in both markets are affected only indirectly. The primary effect of the R&D subsidy (σ) is to increase research expenditures and lower future renewables costs, crowding out fossil-fueled generation in the second stage. The R&D policy provides no incentive for energy conservation or reduction in coal relative to natural gas generation.

3.3. Rate-based policies

Two 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—sometimes called a “generation performance standard” in the context of climate policies for the electricity sector—mandates that average emissions intensity per unit of output not exceed a standard. Both policies create effective taxes on fossil-fueled 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, a given standard become less costly to meet, which is then reflected in the implicit taxes and subsidies. The question is how the renewable energy sector perceives any such price changes. Do firms in the sector recognize the impact of their innovation decisions on future 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?

A long literature recognizes that innovation incentives differ, depending on the structure of markets for output and for innovation.[19] Given our starting assumptions of a representative, perfectly competitive firm, we will proceed with the assumption that firms in the renewable energy sector have perfect foresight about price changes and take them as given. That is, each firm expects knowledge to accumulate and permit prices to respond to that accumulation; however, no individual firm expects to influence future prices by its own R&D or learning. In recognizing the equilibration of future prices, R&D incentives are diminished relative to a case of myopic expectations. If firms were to expect their own actions to further reduce those prices, the expected returns to knowledge would also fall.[20] In the numerical simulations, we assume that the rate-based targets are adjusted such that the equilibrium price premium to renewables remains constant over time. Closer examination of these issues may be of interest in future work.

3.3.1 Renewable energy portfolio standard

We model the portfolio standard as a requirement that a specific percentage of generation be from renewable energy sources in each stage. We assume that responsibility lies with the emitting industry to satisfy the portfolio constraint. Thus, the fossil-fueled producer must purchase or otherwise ensure a share of at least α_t units of renewable energy for every $(1-\alpha_t)$ units of fossil-fueled generation, or $\alpha_t/(1-\alpha_t)$ green certificates for every unit generated. Furthermore, we allow the standard to tighten over time, to allow for easier comparison with the price mechanisms and to better reflect actual policy proposals.

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[19] 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).

[20] This contrasts somewhat to the case in the previously cited studies like Fischer et al. (2003), in which innovators are permit buyers, not sellers.

In equilibrium, the incentives correspond to a combination of a fossil-fueled production tax and a renewable energy subsidy. Assuming the renewable market share 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:

$$\hat{\phi}_t = \frac{\alpha_t}{1-\alpha_t}\hat{s}_t . \tag{32}$$

The implicit tax and subsidy are determined competitively by the market to meet the portfolio constraint, as is the electricity price.

The portfolio standard provides no incentive to reduce coal reliance relative to gas, but crowds out fossil-fueled generation by implicitly taxing it and subsidizing renewables compared to the market price. Since it combines a fossil energy tax (which raises electricity prices) with a renewables subsidy (which lowers electricity prices), the portfolio standard has an ambiguous effect on consumer prices, resulting in limited energy conservation incentives, if any.[21]

Another important difference is that, for a given portfolio standard, the implicit tax and subsidy decline with reductions in renewable energy costs. 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. As a result, to maintain constant policy prices over time, the portfolio standard must become more stringent.

3.3.2 Emissions performance standard

While a portfolio standard requires a certain percentage of renewable energy, a performance standard requires a maximum average emissions intensity of fossil and renewable generation combined. With a tradable performance standard of $\bar{\mu}_t$, the emitting firm must buy

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[21] For further discussion, see Amundsen and Mortensen (2001) and Fischer (2006).

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 $\overline{\mu}_t$ permits per unit of output, which leads to an implicit subsidy of $\tilde{\tau}_t\overline{\mu}_t$ per unit of output. Thus, if the standard is binding, the fossil-fueled sector will be a net buyer of permits costing $\tilde{\tau}_t(\mu_x - \overline{\mu}_t)$ per unit of output for coal generation and $\tilde{\tau}_t(\mu_y - \overline{\mu}_t)$ for natural gas generation. (Note, however, that if the emissions intensity of gas is less than the standard $\mu_y < \overline{\mu}_t$, gas generation becomes a net seller of permits.) The renewables sector will be a seller of permits valued at $\tilde{\tau}_t\overline{\mu}_t$ 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 renewables ($\tilde{s}_t$) and fossil energy producers ($-\tilde{\phi}_t$), where

$$\tilde{s}_t = \tilde{\tau}_t\overline{\mu}_t = -\tilde{\phi}_t. \tag{33}$$

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

$$\mu_x x_t + \mu_y y_t \leq \overline{\mu}_t(q_t + f_t). \tag{34}$$

The impact of the emissions performance standard on electricity prices could be positive or negative, depending on whether the effect of the implicit tax on emissions dominates the effect of the implicit subsidy. The relative effects depend in large part on the slopes of the marginal cost curves. Because of the implicit output subsidy, conservation incentives (if any) are limited. As a consequence, compared to an equivalent pure emissions price (i.e., if $\tau_t = \tilde{\tau}_t$), total emissions are higher.

Like the portfolio standard, a fixed performance standard implies a subsidy that changes as renewable costs fall. Furthermore, an expansion of renewable energy allows fossil-fueled sector emissions to increase. Some of this will arise from greater production and some from increased emissions intensity, as the permit price falls. Thus, to maintain prices for renewables, the standard would have to tighten over time.

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.[22] 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 effects on economic surplus. 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 fuel switching among fossil sources and for raising electricity prices, which promotes 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.

The revenue and distributional implications of the different policies are also quite different. The fossil-based output tax raises revenue, as does the emissions price if it is implemented through auctioned permits or emissions taxes. Price increases are borne by producers and consumers, in relation to supply and demand elasticities. The renewables subsidy and R&D subsidy require outlays of public funds; taxpayers support the renewable energy producers, while electricity consumers and fossil producers are held harmless. The standards involve no net revenue change, implicitly earmarking the net costs of these policies back to

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[22] Goulder et al. (1999) make a related distinction among different types of emissions policies and the relative strength of incentives they provide for abatement, input substitution, and output substitution.

consumers and producers. The net effects on economic surplus depend on the magnitude of the efficiency loss in the process.

We will further demonstrate this ranking numerically as we parameterize the model in the next section. Since no one policy perfectly addresses all market failures—the emissions externality and knowledge spillovers from both R&D and learning—a clear ranking cannot be derived analytically. Each policy applies a different set of levers, for which the relative effectiveness depends on the particular parameters. For example, a tradable performance standard can reduce the emissions intensity of fossil-fueled generation and subsidize renewable energy, but it discourages conservation. Therefore, it may or may not outperform a fossil energy tax or renewable subsidy alone. Thus, we turn to a numerical application to explore both the magnitude of the efficiency cost differences and their sensitivity to specific parameter assumptions.

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 the empirical derivation of 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 sensitivity analyses that vary the relative importance of technological change through learning by doing versus R&D, the degree of knowledge appropriability, the elasticity of demand, the relative length of the two time periods, and the degree of policy stringency.

4.1. Functional form and parametric assumptions

We specify quadratic cost functions for coal-based and natural gas-based electricity generation $C_x(x_t) = c_{x0} + c_{x1}x_t + c_{x2}x_t^2/2$ and $C_y(y_t) = c_{y0} + c_{y1}y_t + c_{y2}y_t^2/2$, thereby yielding linear electricity supply curves for each fuel, $C'_x(x_t) = c_{x1} + c_{x2}x_t$ and $C'_y(y_t) = c_{y1} + c_{y2}y_t$. We also 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 calibrate the values of c_{x1}, c_{x2}, c_{y1}, and c_{y2} to a recent set of simulations of the electricity market impacts of alternative CO_2 reduction goals from the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) (EIA 2006).[23] The CO_2 intensities of coal-based and natural-gas-based electricity are set to $\mu_x = 0.96$ and $\mu_y = 0.42$ kilograms of CO_2 per kWh (kgCO_2/kWh) respectively based on the same EIA study (EIA 2006). These emissions intensities are not projected to change measurably under the climate policies modeled. The baseline price of electricity is 7.3 cents per kilowatt-hour based on projected future values of the average price of electricity (EIA 2006). See Table 2 for parameter values and other assumptions; all monetary values are inflation-adjusted to year 2004 values.

To set a value for the slope of the renewable supply function (g_2) we rely on recent studies of proposed national renewable portfolio standards (EIA 2003a, Palmer and Burtraw 2004), which suggest that a 10% renewable share would lead to a renewable credit price of about 0.03 \$/kWh. This implies a slope of the renewable supply function of $g_2 = 1.2 \times 10^{-13}$ \$/kWh^2. We solve for the intercept of the renewable supply function so that the numerical model yields baseline annual renewable generation of 1.4 x 10^{11} kWh (EIA 2006 projection for 2010), yielding $g_1 = 0.060$ \$/kWh.

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[23] This and other studies support the assumption of approximately linear marginal abatement costs over the policy range we explore.

We specify a knowledge stock having a constant elasticity relationship with respect to both the stock of experience and the stock of R&D, $K_t\left(Q_t, H_t\right)=\left(\frac{Q_t}{Q_1}\right)^{k_1}\left(\frac{H_t}{H_1}\right)^{k_2}$, implying that $K_1 = 1$. We normalize the first period R&D knowledge stock so that $H_1 = 1$. This functional form has commonly been used for this relationship, and it is empirically supported by studies of the relationship between learning by doing and product costs and the relationship between productivity and R&D. This functional form implies complementarity between R&D and learning, which is supported by the limited empirical evidence available (Lieberman 1984). We set $Q_1 = 1.4\times10^{12}$ kWh 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).

We set the values for k_1 and k_2 in our central scenario based on several pieces of evidence. Different approaches to the empirical study of technological change suggest that it is reasonable to set benchmark values of $k_1 = 0.15$ and $k_2 = 0.15$, putting their sum at about 0.3. Numerous empirical "learning curve" studies of learning by doing 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 (Argote and Epple 1990). Specifically with regard to renewable energy, the International Energy Agency (2000) suggests the learning rate for electricity from wind has also been about 0.30.

One of the reasons for the pervasive relationship between cumulative production and product cost declines is likely to be 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 tend to be reflected in the estimated learning elasticity. Thus, it is probably appropriate to view many estimated learning rates as closer to the sum of k_1 and k_2 rather than k_1 alone. The National Energy Modeling System, for example, assumes a maximum learning rate of 0.10 for renewable energy technologies within its electricity market module (EIA 2003b), but also includes other sources of technological change in the model structure.

A distinct line of research has investigated the relationship of production and cost functions and the stock of R&D knowledge, typically based on a constructed stock of R&D capital. The elasticity of R&D in these studies tends to be around 0.08 to 0.30 (Nadiri 1993), again suggesting that a value of $k_2 = 0.15$ is reasonable. Porter and Stern (2000) use a patent-based measure of the knowledge stock, finding that a doubling of the patent stock leads to about a 10% increase in total factor productivity. This is also consistent with an elasticity of $k_2 = 0.15$. Our assumptions regarding the values of k_1 and k_2 are also supported by empirical evidence from Klaassen et al. (2005) on learning in electricity production from wind.

In our sensitivity analysis, we explore different relative contributions of learning and R&D to knowledge, while holding constant the rate of technological change (i.e., decline in renewable energy costs) achieved in the central case. This reflects our sense that while there is an empirically observable overall rate of technological change, it is very difficult in practice to distinguish its underlying sources, be it learning or R&D. The level of cost reduction turns out to be 12% over the five years from the first to second stage of the model, which is reasonable given recent historical and projected future cost declines for renewable energy.

A constant elasticity R&D investment function, $R\left(h_1\right) = \gamma_0 h_1^{\gamma_1}$, has the desired properties set out above so long as $\gamma_1 > 1$. We set $\gamma_1 = 1.2$ based on a number of firm-level empirical studies of the relationship between knowledge generation, as measured by patenting, and investments in R&D.[24] Second, we assume that annual R&D spending is 3% of revenues or \$300 million in the baseline, which corresponds to the average R&D intensity of U.S. industry (NSF

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[24] In a review of the evidence on whether there are diminishing returns to R&D, Griliches (1990) suggests that for larger firms the degree of diminishing returns is only slight. In one of the most directly relevant studies in this area, Jaffe (1986) finds an elasticity of patents with respect to R&D of over 0.8 in his preferred specification. Other related studies have found a relationship of similar magnitude (Bottazzi and Peri 2003). Our model uses the inverse of this elasticity, with the comparable knowledge production to R&D elasticity being $1/1.2 = 0.83$.

2006) and is consistent with the limited information available on current private U.S. renewables R&D spending (NCEP 2004). Calibrating the model to all the other baseline assumptions yields the value $\gamma_0 = 3.9 \times 10^9$ for the central scenario.

Drawing from a sizable empirical literature estimating the private and social returns to knowledge (e.g., Griliches 1992; Nadiri 1993; and Jones and Williams 1998), we set $\rho = 0.50$, which is consistent with a social return to knowledge (i.e., including spillovers) that is roughly twice the private return.[25] We explore a range of appropriability factors from 0.25 to 1.0 in sensitivity analysis.

We assume a constant elasticity of aggregate electricity demand with respect to the price of electricity, ε, so that $D_t = D(P_0) + (P_t - P_0)dD/dP$, where $dD/dP = \varepsilon D(P_0)/P_0$. We assume ε=-0.20 based on the implied elasticity from the EIA-NEMS climate policy study discussed above. We set baseline energy demand at 4.20 x 10^{12} kWh in 2010 based on projected coal-based generation of 2.29 x 10^{12} kWh, natural gas generation of 0.67 x 10^{12} kWh, renewable generation of 0.14 x 10^{12} kWh, and nuclear and hydro generation of 1.10 x 10^{12} kWh (EIA 2006). We hold nuclear and hydro constant in the simulation as these generation sources are not expected to change in response to the policies we evaluate (EIA 2006). We consider a first stage of length $n_1 = 5$ 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 private real rate of return of 10% (so that $\delta = 0.62$), and consider a second stage of 20 years in length, whose flows we discounted back to the start of the second stage at 10% (so that $n_2 = 8.5$). Twenty years is a typical cost recovery time frame used for analysis of electricity generation technologies (EIA 2003b).

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[25] The empirical parameter values governing technological change in the central scenario of our numerical application are based on econometric and other evidence generated in the presence of existing R&D policy. The measured private versus social rate of return to R&D, and the spillover and appropriability rate implicit in this divergence, therefore incorporate preexisting corrective policies. Since social returns remain above private returns, we find a positive optimal R&D subsidy in addition to preexisting policy.

4.2. Policy simulation approach

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 $7 per ton of CO_2 in place throughout the model horizon (or about $25 per ton of carbon). 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 consequences for economic surplus 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, which is a reasonable assumption for CO_2 emissions (Newell and Pizer 2003).

For the two rate-based policies (portfolio standard and emissions performance standard), we set the rates so that the price of credits is the same in the two periods, while meeting the emissions target. As shown in Table 4, this results in an increasing stringency of the rate-based policies over time. It is worth noting that the resulting renewable portfolio standard rises from 6% in the first period to 9% in the second period, which is very close to a recent policy proposal for a national renewable portfolio standard rising from 5% by 2012 to 10% by 2020 (EIA 2003a). As the model does not permit an analytical solution, we numerically solve the nonlinear system of equations using Newton’s method.

4.3. Central scenario

In reviewing the results of the central scenario (see Table 4 and Table 5), perhaps the first point to note is that the emissions price is indeed the most efficient means of achieving a given emissions target, leading to the least cost in terms of surplus, and also requiring the least investment in renewable energy R&D. A $7 per ton of CO_2 emissions price reduces electricity emissions by 4.8% in our central scenario. In the first stage, the CO_2 price reduces coal emissions by 5.7%, encourages switching to natural gas generation (which increases by 7.6%), reduces electricity consumption by 1.0% due to a 5.3% rise in the price of electricity, and increases renewable generation by 23%, the lowest renewable increase of any of the policies. Correspondingly, less renewables R&D investment is necessary than under the other policies, with R&D rising by 75% over the baseline. As indicated by the change in consumer surplus, however, the burden on consumers may be quite large if they do not benefit from the revenue transfers.

The implicit output subsidy inherent in the tradable performance standard leads to lesser reductions coming from consumption (which actually increases slightly due to a fall in electricity prices). Consequently, more reductions must come from displacing coal and expanding renewables. The implicit emissions price inherent in the tradable performance standard is $9.5 per ton of CO_2, or 36% higher than under the explicit emissions price policy. In the first stage, natural gas and renewables are brought in to replace coal; as renewables production increases in the second stage it displaces part of this gas increase. For the renewables sector, the combination of the implicit emissions price and renewable subsidy implies a 0.6 cent/kWh increase in the price received by renewables, 0.2 cent/kWh higher than under the direct emissions price, inducing moderate expansions over that scenario. Overall, the net economic costs are 41% higher than the emissions price, making the emissions performance standard the second most cost-effective instrument. Since the standard is such that the price of electricity falls (because the emissions intensity of gas is less than the standard), consumers directly benefit in this scenario, while baseload producers lose revenues; coal producers are hit hardest, due to the higher emissions price.

The output tax of 0.8 cents/kWh, since it does not tax emissions directly, places more of the reduction burden on reducing consumption, displacing gas, and increasing renewables. This increases the overall cost of the policy by 61% relative to the emissions price. By raising electricity prices by about 75% more than the emissions price, the output tax results in a price increase for renewables of 0.7 cents/kWh, about 75% more than with the emissions price, resulting in comparable increases in renewables output and R&D investment. The fossil output tax also almost doubles the costs to consumers, while government revenues are significantly higher than under the emissions price. Profits to producers using nuclear and hydro power increase substantially, more than offsetting profit losses of producers that use coal and gas.

A renewables portfolio standard implicitly combines a nearly 0.1 cent/kWh fossil output tax with a 1.2 cent/kWh renewables production subsidy. With no conservation incentives (electricity prices actually decrease by a small amount) and no fossil-fuel-switching incentives, renewables must expand three times as much as with the emissions price to meet the target. As a result, its performance is 2.04 times as costly as the emissions price in our central scenario. Since no revenues are raised and electricity prices fall slightly, producers (in aggregate) bear the burden of the policy. Renewable electricity producers gain, while other producers lose. Consumers also gain from the price fall, which occurs when the implicit production subsidy outweighs the implicit tax on nonrenewable generation. However, the incidence of these implicit taxes depends on the relative slopes of the fossil-fueled and renewable supply curves. The electricity price would not fall if, for example, the marginal costs of gas-fired generation were sufficiently flat (Fischer 2006).

The renewables production subsidy of 1.4 cents/kWh, to generate the same emissions reductions, must be nearly twice the fossil output tax, since electricity consumption is increased, rather than reduced, due to a decrease in prices. The effects are similar to the portfolio standard, though somewhat larger, since renewables must also accommodate the increased electricity consumption. Consumers face lower electricity costs and renewable electricity producers gain, but this is more than offset by the cost to taxpayers and non-renewable electricity producers. The overall cost of the policy in achieving emissions reductions is 2.47 times that of the emissions price.

Finally, it may be of little surprise that the renewables research subsidy is by far the most costly single policy for reducing emissions, since virtually all the burden of displacing fossil output falls in the second stage. Cost-effective early emissions reductions are forgone, and all emissions reductions must be gained in the second stage by making renewables less expensive than fossil fuels in the absence of any emissions or conservation incentive. To do so without any output or emissions incentive requires costs to fall six times as much as with the emissions tax, or 25% overall. While second-stage renewable output expands by 122%, it also expands in the first stage relative to the emissions price, a result of the complementarity of learning with R&D.

4.4. Sensitivity analyses

To illustrate the importance of demand conservation responses to the different policy outcomes and to evaluate the role of the technological change process in these results, we conduct several sensitivity analyses. The results are given in Table 6, where for brevity we focus on the economic surplus of each policy relative to a \$7/tonCO_2 emissions price policy, as in the bottom row of Table 4 for our central scenario (which is repeated as the first row of Table 6 for comparison).

First we vary the elasticity of demand, making it both more elastic ($\varepsilon = –0.5$) than in the central scenario and totally inelastic ($\varepsilon = 0.0$). The main effect of a more elastic demand response is to worsen the performance of all policies except the fossil output tax relative to an emissions price. This occurs because electricity prices actually fall under the other policies, leading to increased electricity demand. More elastic demand simply worsens this counterproductive effect, while it enhances the conservation incentives of the output tax.

The scenario of totally inelastic demand illustrates certain equivalencies across different policies with respect to incentives not related to conservation, as conservation does not occur with fixed demand. As shown in Table 6, the emissions price and the performance standard—the two policies that embody incentives for reducing the emissions intensity of fossil fuels—become equivalent. This occurs because the performance standard no longer needs to rely on a higher implicit emissions price to make up for extra demand induced by the implicit output subsidy. Similarly, the output tax, the renewable portfolio standard, and the renewable production subsidy become equivalent, since these three policies each rely solely on an increase in the price received by renewables to achieve emissions reductions when no conservation is possible. This price rise occurs either through a rise in the electricity price (in the case of the output tax), a subsidy to renewable production (in the case of the production subsidy), or some of both (in the case of the renewable portfolio standard).[26]

Turning now to the sensitivity analyses focused on technological change, we explore four scenarios. In the first two, we vary the underlying source of technological change: one in which there is no learning (i.e., all technological progress derives from R&D) and another in which learning by doing is relatively more important (and R&D less so) than in our central scenario. To make these fair comparisons, we maintain the same rate of baseline technological change as in our central scenario (i.e., 12% renewable cost reduction in the no-policy case) by adjusting the relative effectiveness of learning versus R&D. When these types of sensitivity analysis have been conducted in other studies, the resulting rate of technological change has typically been altered, with results that are more-or-less predetermined. With no learning effect, $k_1 = 0.0$, so we increase the effectiveness of R&D on technological change to $k_2 = 0.19$. In the scenario with a relatively strong learning effect, $k_1 = 0.20$, we decrease the effectiveness of R&D to $k_2 = 0.13$.

As shown in Table 6, the absence of learning by doing and the strengthening of the effect of R&D to compensate make all but the R&D subsidy perform worse relative to the emissions price. Without learning by doing, additional renewables production in the first stage has no added value as an investment in knowledge, and policies that rely on expanding beyond the competitive level of production simply raise costs rather than compensate for spillovers. This negative effect is most evident for the renewable production subsidy, although the effect is not large for any of the policies. Although the performance of the R&D subsidy improves with the increase in the effectiveness of R&D, it remains by far the most costly policy. The sensitivity results for the "high learning" case are also shown in Table 6. As one might expect, the performance of policies that rely more heavily on near-term renewables expansion improve

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[26] Of course, if public funds are costly to raise, there would still be welfare differences among the three policies, due to their different revenue-raising properties.

(although only slightly) relative to the emissions tax, namely all policies but the R&D subsidy. The relative performance of the R&D subsidy worsens considerably, due to the diminished effectiveness of the R&D stock in boosting knowledge and technological change.

In two additional, closely-related scenarios, we alter the productivity of R&D-based knowledge in lowering costs (i.e., $k_2 = 0.20$ and $k_2 = 0.10$) without offsetting adjustments to the learning rate. This alters the overall rate of technological change, thereby lowering the absolute cost of all policies when R&D productivity is increased and increasing the cost of all policies when R&D productivity is decreased. The relative performance of policies is affected in a similar manner to the above scenarios holding the rate of technological change constant, with higher R&D productivity tending to improve the relative performance of all policies, particularly the R&D subsidy, relative to the emissions price. The reverse is true for the case of lower R&D productivity.

We also evaluate the effect on relative policy costs of the degree of knowledge appropriability through two additional scenarios: (1) relatively low appropriability ($\rho = 0.25$), and (2) perfect appropriability ($\rho = 1.0$). Because a lower degree of appropriability implies larger knowledge spillovers, the relative performance of any policy that directly or indirectly invests more in knowledge than the emissions price will improve as spillovers increase. Thus, with low appropriability, the costs of all the policies decrease relative to the emissions price, albeit modestly, with the R&D subsidy experiencing the largest improvement, due to its direct effect on knowledge investment. The scenario with complete appropriability eliminates the knowledge externality entirely, thereby worsening relative performance, particularly of the R&D subsidy.[27]

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[27] Although the model assumes that the appropriation rate for knowledge generated through R&D and learning is the same, the sensitivity analyses shed some light on the potential effect of relaxing this assumption. For example, if one expects learning to be more firm specific and, as a result, less likely to spill over, policies subsidizing renewables are less appropriate for compensating for the knowledge externality. They would therefore perform worse relative to the other policies. If, on the other hand, one expected learning to be more difficult to patent and appropriate the related rents, then renewable subsidy policies would be relatively more justified to internalize the knowledge externality.

In our next sensitivity analysis, we explore the effect of changing the length of time in the second stage. Shortening the number of years in the second stage from 20 to 10 lowers the weight on the second period. This worsens the performance of all policies relative to the emissions price, because there is less time in the future to benefit from the application of technological change, which is relied on more heavily in the other policies. Alternatively, increasing the weight on the second period (by quadrupling the number of years to 80) has the opposite effect of improving the performance of the other policies relative to the emissions price. In both of these sensitivity cases, however, the qualitative story remains the same and the other policies continue to be at least 35% more expensive than the emissions price in achieving CO_2 reductions.

The final sensitivity analysis examines a flat natural gas electricity supply function and illustrates the importance of the emissions intensity of the marginal fossil technology in determining the cost of renewable policies, which reduce emissions by crowding out marginal fossil generation. With a flat natural gas electricity supply function, additional renewable generation displaces only natural gas-fired generation, not the more emissions intensive coal-fired generation, making it more difficult to achieve emissions reductions.

4.5. Combination policies for addressing technology spillovers

The presence of knowledge spillovers in our model implies that separate policy instruments are necessary to optimally correct the climate externality and the externalities associated with both learning and R&D. In this section, we explore several scenarios with different policy combinations to assess empirically the theoretical findings of section 2.6, while maintaining all assumptions at their values in our central case.

We first assess a scenario with a portfolio of all three policies, with the learning and R&D subsidies set at their optimal levels and the emissions price set at a level so that the portfolio achieves the same emissions target as does a \$7/ton CO_2 price alone (i.e., 4.8% reduction). The optimal R&D subsidy of 50% is straightforward to compute from equation (30) ($\sigma = 1 - \rho = 0.5$) based on the assumed appropriability rate. The optimal first-period "learning subsidy” for renewables (s_1) depends on the future level of renewables use and other variables; it must therefore be solved numerically using equation (31) along with the other equations of the system. We find that the optimal learning subsidy is 0.3 cents/kWh, or 4% of the electricity price. While this amount of subsidy for learning may appear small, it is similar to the optimal R&D subsidy if both are expressed as a percentage of revenue. That is, the optimal R&D subsidy of 50% has a corresponding R&D level that is 12% of renewable revenue, so that the R&D subsidy is 6% of revenue. Nonetheless, this level of learning subsidy is much lower than the levels typically seen in practice, suggesting that for relatively mature renewables in particular (e.g., wind), it is difficult to rationalize large subsidies on the basis of learning.

As a result of greater cost reductions and renewables penetration with the R&D and learning subsidies, the emissions price necessary to achieve a 4.8% emissions reduction falls by 36% to \$4.5/ton CO_2 (from \$7.0/ton CO_2). Importantly, the associated cost of the policy combination becomes negative and has a slight annual surplus of \$0.04 billion. By applying the 50% R&D subsidy and 0.3 cents/kWh learning subsidy one at a time, one can see that the net surplus of the combination policy is due primarily to the R&D subsidy (\$0.20 billion surplus annually) offsetting the cost of the emissions price, rather than the learning subsidy (\$0.02 billion surplus annually). However, the optimal R&D and learning subsidies lead to emissions reductions of only 1.4% and 0.3%, respectively. These results demonstrate that the cost of emissions reductions through a combination of policies could be considerably lower than policies targeted solely at technology R&D or emissions pricing. Nonetheless, the emissions reductions associated with this policy package are due primarily to the emissions price.

Finally, we explore the potential of the emissions price to act as a second-best policy response to the knowledge externality through a scenario in which we found the level of the emissions price that minimized non-environmental costs. In our central scenario, the emissions price is the most cost-effective policy for attaining the given reduction target. The level of the chosen emissions target does, however, affect the relative importance of the environmental and knowledge externalities in determining the efficiency of different instruments. To explore this, we briefly examine the possibility of "win–win" emissions policies that in effect have zero or even negative costs due to their role in indirectly correcting the knowledge externality inherent in imperfect appropriability in our model. There is therefore a range of stringency of each of these policies that will lead to positive net benefits (i.e., negative costs), not counting environmental benefits. Under our modeling assumptions, these stringency levels are clearly less than those we explored above, which all have positive costs (not counting environmental benefits). We found that the optimal emissions price as a second-best means of correcting the knowledge externality was \$1.30/ton CO_2 in our model, leading to a 0.9% emissions reduction and an associated positive annualized economic surplus of \$0.014 billion (not including environmental benefits). We also found positive surplus associated with all the other policies set at a level to achieve the same 0.9% emissions reduction—in fact, surplus higher than that of the emissions price. For example, the 38% R&D subsidy necessary to achieve a 0.9% reduction has positive surplus of 12.3 times the emissions price, illustrating the salience of correcting R&D market failures as a "no regrets" climate policy. However, this dominance of R&D subsidies and other policies over the emissions price is limited to very low levels of targeted emissions reduction.

5. Conclusion

We assess different policy options for reducing CO_2 emissions and promoting renewable energy and evaluate their performance with respect to economic surplus, emissions reduction, renewable energy production, and R&D. We find that for anything beyond very small emissions reduction targets, the emissions price is the most efficient single policy for 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.

A renewable energy portfolio standard creates an implicit tax on fossil energy in the form of the mandate to buy green certificates, which then fund 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 cost to surplus. The performance standard, on the other hand, also provides fossil-fueled producers with the incentive to reduce their emissions intensity, which reduces the burden placed on the other margins of emissions reduction. However, the performance standard establishes an implicit fossil output subsidy, which keeps electricity prices low and reduces conservation incentives.

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, as is any incentive to reduce consumption or the emissions intensity of fossil fuels.

The underlying process of technological change, be it through learning by doing or R&D, turns out to be far less important than the incentives to use technology efficiently to reduce emissions. This case is reinforced where technology policies are directed at a small share of overall current electricity production, as are renewables. It simply becomes expensive to try to reduce overall emissions by pushing on a small piece of the electricity portfolio and without any direct incentive for reducing emissions intensity or overall energy use. Nonetheless, the nature of technological change and the degree of knowledge spillovers do have discernable effects on the relative cost of alternative policies, which have differential effects on knowledge investment and how it occurs.

Finally, we find that an optimal portfolio of policies will include an emissions price and subsidies for technology R&D and learning. In our empirical application, we find that a policy portfolio of this type can reduce emissions at significantly lower cost than any single policy alone, although the emissions reductions continue to be attributable to primarily the emissions price. Nonetheless, it seems likely that R&D focused on breakthrough technologies could have greater salience in the context of deeper long-term emissions reductions, although this lies beyond the scope of the current paper.

Appendix

An important issue in modeling technological change is the extent to which firms expect to appropriate the returns to their investments in building knowledge. In the main body of the paper, ρ represents this appropriable share for our representative firm, and we derive this parameter here from a notional model of *N* identical firms. This extends the model from Fischer et al. (2003) to *N* firms, similar to Spence (1984) but allowing for an influence of appropriability and spillovers on private R&D incentives through licensing. In contrast to Spence's (1984) model, in our model, knowledge is completely disseminated in the symmetric equilibrium, although spillovers limit the ability of innovators to appropriate all of the associated rents through royalty payments. As a result, every firm has the same cumulative investment and learning stocks, $H_2 = H_1 + \sum_{i=1}^{N} h_{1,i}$ and $Q_2 = Q_1 + \sum_{i=1}^{N} q_{1,i}$.

For an individual firm *i*, profits are

$$\pi_i^R = n_1\left((P_1+s_1)q_{1i} - G_i(K_1,q_{1i}) - (1-\sigma)R_i\left(h_{1i}\right)\right) + \delta n_2((P_2+s_2)q_{2i} - G_i(K_2,q_{2i}) + Y_i(h_{1i},q_{1i})), \quad (35)$$

where $Y(h_{1i},q_{1i})$ are royalties received from other firms, net of those paid out. In other words, $Y(h_{1i},q_{1i}) = \sum_{j\neq i} y_{ij}(h_{1i},q_{1i}) - \sum_{j\neq i} y_{ji}(h_{1j},q_{1j})$, where each royalty price y_{ij} represents the appropriable cost savings from firm *j* due to innovation by firm *i*:

$$y_{ij}(h_{1i},q_{1i}) = (G_j(K_2(H_2-\hat{\rho}h_{1i},Q_2-\hat{\rho}q_{1i}),q_{2i}) - G_j(K_2(H_2,Q_2),q_{2i})), \quad (36)$$

where $\hat{\rho}$ is the share of the innovation that cannot be imitated. In other words, the equilibrium royalty equals the cost savings to firm *j* from enjoying access to the remainder of h_{1i} that cannot be imitated.

Under these conditions, the maximum other firms will pay to license the innovation is the difference in costs between imitating the research (or learning), which has effectiveness $1-\hat{\rho}$, and costs with full access. (Note that since profits are maximized with respect to output in the second period, small changes in that variable do not affect marginal profits or marginal royalties.) Consequently, in a symmetric equilibrium with full cross-licensing,

$$\frac{\partial Y_i(h_{1i},q_{1i})}{\partial h_{1i}}=\sum_{j\neq i}((1-\hat{\rho})\frac{\partial G_j}{\partial K}\frac{\partial K_2}{\partial H}-\frac{\partial G_j}{\partial K}\frac{\partial K_2}{\partial H})\approx-\hat{\rho}(N-1)\frac{\partial G_j}{\partial K}\frac{\partial K_2}{\partial H}, \tag{37}$$

and from the individual firm's first-order conditions for learning and research, we get

$$G_{i,q}(K_1,q_{1i})=P_1+s_1-\delta n_2(1+(N-1)\hat{\rho})G_{i,K}(K_2,q_{2i})K_Q(H_2,Q_2), \text{ and} \tag{38}$$

$$(1-\sigma)R_{i,h}(h_{1i})=-\delta n_2(1+\hat{\rho}(N-1))G_{i,K}(K_2,q_{2i})K_H(H_2,Q_2). \tag{39}$$

In aggregate, royalty payments are transfers among firms, so $\sum_i Y(h_{1i},q_{1i})=0$. Furthermore, $G(K,q)=\sum_i G_i(K,q_i)$ and $q=Nq_i$, implying that $\partial G/\partial K=N\partial G_j/\partial K$. While knowledge is common across firms, research expenditures are individual, so we have $R(h_1)=R\left(\sum_i h_{1i}\right)\equiv\sum_i R_i(h_{1i})$, implying $R_h(h_1)=R_{i,h}(h_{1i})$.

Summing (38) and (39) over all firms and dividing by *N*, we have the following aggregate first-order conditions for learning and research:

$$G_q(K_1,q_1)=P_1+s_1-\delta n_2\rho G_K(K_2,q_2)K_Q(H_2,Q_2), \text{ and} \tag{6}$$

$$R_h(h_1)=-\delta\frac{\rho}{(1-\sigma)}n_2 G_K(K_2,q_2)K_H(H_2,Q_2), \tag{8}$$

where $\rho=\left(1+\hat{\rho}(N-1)\right)/N$. Due to imperfect appropriation, these results deviate from what would occur from maximizing the aggregate profit function (5) with respect to aggregate output and R&D investment in the first period (q_1 and h_1).

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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
Reduce emissions intensity of fossil fuels	Yes	Yes	No	No	No	No
Energy conservation (via electricity price increase)	Yes	It depends	Yes	It depends	No	No
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 and other assumptions

Parameter	Base Value
Baseline price of electricity	0.073 \$/kWh
Intercept of coal-based electricity supply (c_{y1})	0.023 \$/kWh
Slope of coal-based electricity supply (c_{y2})	2.2×10^{-14} \$/kWh^2
Intercept of natural gas electricity supply (c_{x1})	0.061 \$/kWh
Slope of natural gas electricity supply (c_{x2})	1.8×10^{-14} \$/kWh^2
Intercept of renewables electricity supply (g_1)	0.059 \$/kWh
Slope of renewables electricity supply (g_2)	1.2×10^{-13} \$/kWh^2
CO_2 intensity of coal-based electricity (μ_x)	0.96 kg CO_2/kWh
CO_2 intensity of natural gas-based electricity (μ_y)	0.42 kg CO_2/kWh
Electricity demand elasticity (ε)	–0.20
Learning parameter (k_1)	0.15
R&D parameter (k_2)	0.15
R&D investment cost parameter (γ_0)	3.9×10^9
R&D investment cost parameter (γ_1)	1.2
Degree of appropriability (ρ)	0.50

Table 3. Baseline results without policy

	1st stage	2nd stage
Price of electricity ($/kWh)	0.073	0.072
Electricity demand (kWh/yr)	4.20×10^{12}	4.20×10^{12}
Coal generation (kWh/yr)	2.29×10^{12}	2.27×10^{12}
Natural gas generation (kWh/yr)	0.67×10^{12}	0.64×10^{12}
Renewables generation (kWh/yr)	0.14×10^{12}	0.20×10^{12}
Nuclear and hydro generation (kWh/yr)	1.10×10^{12}	1.10×10^{12}
Renewables share of generation	3.3%	4.8%
CO_2 emissions (billion metric tons CO_2/yr)	2.48	2.44
Rate of renewables cost reduction	12%	—

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

	Emissions price ($/tCO$_2$)	Tradable emissions perform. std. (tCO$_2$/GWh)	Output tax on fossil generation (¢/kWh)	Renewables portfolio standard	Renewables production subsidy (¢/kWh)	Renewables research subsidy
Policy for 4.8% abatement	7.0	765/743	0.83	6.0%/9.6%	1.4	88%
Electricity price						
1st stage	5.3%	–1.9%	9.4%	–0.4%	–1.5%	–0.2%
2nd stage	5.0%	–2.2%	8.8%	–0.9%	–2.7%	–3.0%
CO$_2$ emissions						
1st stage	–4.2%	–3.9%	–3.7%	–2.9%	–2.9%	–0.4%
2nd stage	–5.0%	–5.1%	–5.1%	–5.3%	–5.3%	–5.9%
Renewable generation						
1st stage	26%	40%	46%	80%	86%	11%
2nd stage	33%	50%	58%	101%	109%	122%
Coal generation & emissions						
1st stage	–5.7%	–6.4%	–2.7%	–2.1%	–2.1%	–0.3%
2nd stage	–6.3%	–7.3%	–3.7%	–3.9%	–3.9%	–4.3%
Gas generation & emissions						
1st stage	7.6%	15.8%	–11.5%	–9.0%	–8.9%	–1.1%
2nd stage	5.6%	13.0%	–16.1%	–16.8%	–16.8%	–18.8%
Total electricity generation						
1st stage	–1.0%	0.4%	–1.8%	0.1%	0.3%	0.0%
2nd stage	–1.0%	0.4%	–1.7%	0.2%	0.5%	0.6%
Renewable R&D increase	75%	118%	139%	255%	277%	4043%
Additional renewables cost reduction	4%	5%	6%	10%	11%	25%
ΔConsumer surplus ($B/yr)	–15.5	6.2	–27.6	2.1	6.4	5.0
ΔProducer surplus ($B/yr)	–1.1	–6.5	4.4	–2.6	–2.2	–2.5
ΔTransfers ($B/yr)	16.4	0.0	22.8	0.0	–4.8	–5.5
ΔSurplus (excluding environ. benefits) ($B/yr)	–0.24	–0.33	–0.38	–0.48	–0.58	–2.9
ΔSurplus relative to emissions price	1.00	1.41	1.61	2.04	2.47	12.49

Table 5. Explicit and implicit taxes and subsidies of alternative policies

Policy	Explicit and implicit taxes and subsidies			Price received by renewables (¢/kWh)
	Emissions price ($/$tCO_2$)	Output tax on fossil generation (¢/kWh)	Renewables subsidy (¢/kWh)	
Fixed-price policies				
Emissions price	7.0	—	—	7.7
Output tax on fossil generation	—	0.8	—	8.0
Renewables production subsidy	—	—	1.4	8.6
Rate-based policies				
Emissions performance standard	9.5	-0.7	0.7	7.9
Renewables portfolio standard	—	0.1	1.2	8.5

Table 6. Sensitivity analyses

Δ Surplus relative to emissions price	Emissions price	Tradable emissions perform. std.	Output tax on fossil generation	Renewable portfolio standard	Renewables production subsidy	Renewables research subsidy
Central scenario	1.00	1.41	1.61	2.04	2.47	12.49
More elastic demand (ε=-0.5)	1.00	2.05	1.49	2.60	4.12	31.63
Inelastic demand (ε=0.0)	1.00	1.00	1.55	1.55	1.55	5.45
No learning/higher R&D (k_1=0.0; k_2=0.19)	1.00	1.44	1.68	2.26	2.78	4.27
High learning/lower R&D (k_1=0.2; k_2=0.13)	1.00	1.40	1.59	1.99	2.41	18.78
High R&D productivity/ baseline learning (k_1=0.15; k_2=0.20)	1.00	1.27	1.43	1.27	1.73	4.52
Low R&D productivity/ baseline learning (k_1=0.15; k_2=0.10)	1.00	1.50	1.74	2.61	3.09	44.46
Low appropriability (ρ=0.25)	1.00	1.41	1.61	1.93	2.34	3.49
High appropriability (ρ=1.0)	1.00	1.44	1.66	2.44	2.79	18.62
Shorter second stage (T=10, n_2=6.1)	1.00	1.47	1.70	2.40	2.86	19.07
Longer second stage (T=80, n_2=10.0)	1.00	1.35	1.53	1.71	2.12	7.95
Flat natural gas electricity supply (cc_2=0)	1.00	1.50	3.32	4.17	4.83	37.02