NBER WORKING PAPER SERIES

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Working Paper 10880
http://www.nber.org/papers/w10880

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 2004

The author thanks Larry Goulder, Richard Newell, and Klaas-Jan Koops for helpful conversations that inspired this paper. Financial support for this work was provided by the National Science Foundation under grant number SES-0001679.

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NBER Working Paper No. 10880
October 2004
JEL No. O33, O38, O41, Q42, Q43, Q55

## ABSTRACT

Because of the long-term nature of the climate problem, technological advances are often seen as an important component of any solution. However, when considering the potential for technology to help solve the climate problem, two market failures exist which lead to underinvestment in climate-friendly R&D: environmental externalities and the public goods nature of new knowledge. As a result, government subsidies to climate-friendly R&D projects are often proposed as part of a policy solution. Using the ENTICE model, I analyze the effectiveness of such subsidies, both with and without other climate policies, such as a carbon tax. While R&D subsidies do lead to significant increases in climate-friendly R&D, this R&D has little impact on the climate itself. Subsidies address the problem of knowledge as a public good, but they do not address the environmental externality, and thus offer no additional incentive to adopt new technologies. Moreover, high opportunity costs to R&D limit the potential role that subsidies can play. While R&D subsidies can improve efficiency, policies that directly affect the environmental externality have a much larger impact on both atmospheric temperature and economic welfare.

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Politicians often propose increased R&D spending as a solution to the climate change problem. Such spending offers the political cover of doing “something” about climate change while avoiding more painful costs that may come from regulations requiring emissions reductions. For example, in his 2003 State of the Union address, President George W. Bush proposed $1.2 billion of research funding to develop vehicles powered by fuel cells. Can such policies impact the global climate? Can R&D subsidies substitute for more restrictive emissions policies? This paper addresses these questions.

Because of the long-term nature of the climate change problem, technological change is often considered a part of any policy solution. There is ample evidence that market forces such as higher prices or stringent environmental policies induce technological change. For example, Popp (2002) documents dramatic increases in patenting for renewable energy technologies during the energy crisis of the 1970s. In recent years, economic models of climate policy have paid increasing attention to the links between policy and technological change. Models that explicitly link technological progress to climate policy find that such links reduce the costs of a given policy, as policy levers serve to hasten the development of more climate-friendly technologies.

Given the importance of policy-induced technological change, as well as a political climate that favors R&D subsidies over policies to limit emissions, it is useful to consider the role that research and development (R&D) policy, by itself, might play. Such policies are of interest because, in the language of economists, markets for new knowledge are imperfect. Spillovers of knowledge make it difficult for inventors to reap the full social benefits of their innovations. As such, the incentives provided by private markets for R&D investment lead to underinvenstment in R&D. Policies addressing this, such as government-funded subsidies for

R&D, R&D tax credits, or improved intellectual property rights to help inventors capture more of the returns to innovation, lead to greater levels of R&D spending, and presumably more innovation as a result.

Recent work to consider the role of R&D policy as part of a climate policy portfolio includes Schneider and Goulder (1997), Kverndokk *et al*. (2004), and Fischer and Newell (2004). Schneider and Goulder (1997) note that even if it is desirable to postpone the bulk of emissions abatement to the future (see, for example, Wigley *et al*. 1996), short-term policies that bring about low-cost emissions reductions are desirable. One reason for this argument is that such policies spur innovation, making future emissions abatement less costly. However, they also find that simply using R&D subsidies to achieve these cost reductions is not as effective. While R&D subsidies do correct market failures that pertain to knowledge markets, they do not address environmental market failures, and thus do not encourage adoption of any newly discovered climate-friendly technologies. Kverndokk *et al*. (2004) extend this work by considering both an existing and potential new alternative energy technology. R&D subsidies increase usage of the existing alternative energy technology, but as a result delay the introduction of the newer, and possibly better, technology. Fischer and Newell (2004) compare R&D subsidies and other policies designed to reduce carbon emissions from the U.S. electricity sector. They rank R&D subsidies as the least effective for reducing emissions, but do not consider the effect of knowledge spillovers, and do not consider the use of multiple policies simultaneously.

This paper builds on this work to study the role of both carbon taxes and R&D subsidies using the ENTICE model (Popp 2004a,b), an extension of the well-known DICE model of global warming (Nordhaus 1994, Nordhaus and Boyer 2000). Like the DICE model, the ENTICE model is dynamic growth model linking economic activity and the environment. Because it explicitly models the economic impact of climate damages, the model can be used to simulate optimal policy paths that balance both the costs and benefits of climate policy. In this paper, I use the model to compare the effectiveness of R&D subsidies to policies such as a carbon tax designed to reduce emissions. Because the ENTICE model calculates the costs and benefits of each policy, I am able to build on the existing literature by calculating optimal levels of R&D subsidies. Like Schneider and Goulder, I show that these subsidies do enhance the effects of other policies, but have little impact on their own. Furthermore, by examining the change in optimal policy paths with and without R&D subsidies, I show that most of the benefits of R&D subsidies come from cost savings, as there is little change in emissions under a carbon tax with or without subsidies in place. Finally, when deciding on a level of government R&D spending, policymakers need to be aware of the opportunity costs of new R&D spending. Because R&D is performed by highly-trained personnel, some new energy R&D will likely come at the cost of other types of productive R&D. If policymakers ignore these costs, the overall macroeconomic effect of subsidies may even be negative.

## I. Theory: Market Failures Affecting Environmental R&D

While market forces will lead firms to do some research on technologies designed to reduce carbon emissions, there are two reasons to expect markets to underinvest in such R&D. These market failures provide the motivation for government policy designed to increase such research. One, of course, is the traditional problem of environmental externalities. Because carbon emissions are not priced by the market, firms and consumers have no incentive to reduce emissions without policy intervention. This reduces the market for technologies that reduce emissions, and thus reduces incentives to develop such technologies.[1]

The second market failure pertaining to R&D is the public goods nature of knowledge (see, for example, Geroski 1995). In most cases, new technologies must be made available to the public for the inventor to reap the rewards of invention. However, by making new inventions public, some (if not all) of the knowledge embodied in the invention becomes public knowledge. This public knowledge may lead to additional innovations, or even to copies of the current innovations.[2] These knowledge *spillovers* provide benefit to the public as a whole, but not to the innovator. As a result, private firms do not have incentives to provide the socially optimal level of research activity.

Much economic research has been done quantifying the effect of such spillovers. Economists studying the returns to research consistently find that knowledge spillovers result in a wedge between private and social rates return to R&D. Examples of such studies include Mansfield (1977, 1996), Pakes (1985), Jaffe (1986), Hall (1996), and Jones and Williams (1998). Typical results include marginal social rates of return between 30 and 50 percent. In comparison, estimates of private marginal rates of return on investments range from 7 to 15 percent (Bazelon and Smetters 1999, Jones and Williams 1998, Hall 1996). Since firms make investment decisions based on their private returns, the wedge between private and social rates of return suggests socially beneficial research opportunities are being ignored by firms because they are unable to fully capture the rewards of such innovations.

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[1] Note that the externality market failure need not eliminate incentives to develop such technologies completely. The market failure problem means that individuals do not consider the social benefits of using technologies that reduce emissions. However, such technologies may also come with private benefits – for example, reduced gasoline expenditures from switching to a hybrid-powered automobile.

[2] Intellectual property rights, such as patents, are designed to protect inventors from such copies. However, their effectiveness varies depending on the ease in which inventors may "invent around" the patent by making minor modifications to an invention. See, for example, Levin *et al*. (1987).

Because of knowledge spillovers, climate-friendly R&D will be underprovided by market forces even if policies to correct the environmental externalities of emissions, such as carbon taxes, are in place. Popp (2004a) finds that the welfare gains from an optimal carbon tax increase by seven percent when the tax is supplemented with R&D subsidies sufficient to support all socially-efficient research. This suggests two possible avenues through which policy can encourage the development of environmentally-friendly technologies: correcting the environmental externality and/or correcting knowledge market failures.

Not surprisingly, economic theory dictates that the socially optimal policy is to address *both* market failures. Moreover, Schneider and Goulder (1997) show that policies to address knowledge spillovers are more effective if they address all knowledge spillovers, rather than focusing on R&D pertaining to alternative energy. Nonetheless, as targeted R&D subsidies are likely to be more politically popular than either broad-based R&D measures or restrictive emissions targets, it is useful to explore the potential of each mechanism both individually and in tandem.

To address this question, I use the ENTICE-BR model of climate policy (Popp 2004b). ENTICE-BR extends the ENTICE model (Popp 2004a) to include policy-induced R&D on both energy efficiency and a carbon-free backstop energy technology source. Both ENTICE models build on the well-known DICE model of climate change (Nordhaus 1994, Nordhaus and Boyer 2000). The DICE model is a dynamic growth model of the global economy that includes links between economic activity, carbon emissions, and the climate. Because it includes both costs and benefits of climate change, it allows the modeler to simulate optimal paths for control of carbon emissions. As such, unlike the analysis by Schneider and Goulder, I am able to calculate optimal policies for both carbon taxes and R&D subsidies. Moreover, I examine how the optimal policy for each changes depending on whether the other market failure has also been addressed.

## II. The ENTICE Model

To examine R&D policies to address climate change, one must use a climate policy model that that explicitly links climate policy and innovation. Typically, these models include such links in one of two ways. *Bottom-up* models include a detailed specification of energy systems, but typically do not include detailed modeling of the overall macroeconomy. Such models usually implement induced technological change with a learning-by-doing framework, in which the costs of various technologies decrease with experience. Examples include Gerlagh and van der Zwaan (2003), Manne and Richels (2002), Grübler and Messner (1998), and Messner (1997). Because these models do not address the opportunity costs of any new research efforts, they tend to provide optimistic results concerning the potential of technological change.[3] *Top-down* models focus on the links between environmental policy and macroeconomic performance. Endogenous technological change in these models typically comes through accumulated investment in research and development (R&D). Recent models of this nature include Goulder and Schneider (1999), Nordhaus (2002), and Buonanno *et al*. (2003). However, of these models, only Goulder and Schneider include a choice of multiple energy technologies, including a carbon-free alternative.

The ENTICE-BR model belongs to this second group of models. It is a top-down model providing explicit links between economic activity and environmental damages. The model uses the basic dynamic growth model framework of the DICE model (Nordhaus 1994, Nordhaus and Boyer 2000), but includes explicit links between climate policy and climate-friendly R&D.

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[3] See Popp (2004a, 2003) for a discussion.

Climate-friendly R&D can come in one of two forms: as R&D designed to improve overall energy efficiency, or R&D that helps reduce the cost of the carbon-free energy source. The model is calibrated to a base year of 1995, and is solved in 10-year increments for a period of 350 years.[4] Figure 1 illustrates the logic of the ENTICE-BR model. Key equations pertaining to the energy research sector are presented below. Interested readers are referred to Popp (2004a,b) for more detailed presentation of the model structure.

In both the DICE and ENTICE models, the goal of the model is to maximize the present value of per capita utility, which increases along with increased per capita consumption, subject to various economic and environmental constraints. One important difference between ENTICE and the original DICE model is that energy use must enter the production function explicitly, so that the potential benefits of energy saving research can be captured. As illustrated in Figure 1, total energy services, which are defined below, are used along with capital and labor to produce output. Defining output as $Q_t$, labor as $L_t$, the physical capital stock, $K_t$, and effective energy units, $E_t$, the production function used in ENTICE-BR is:

$$(1) \qquad Q_t = A_t K_t^{\gamma} L_t^{1-\gamma-\beta} E_t^{\beta} - p_{F,t} F_t - p_{B,t} B_t$$

Note that the cost of both energy sources are subtracted from final output, and that the price of both fossil fuels and the backstop, $p_{F,t}$ and $p_{B,t}$ respectively, vary over time. The model is made dynamic by the various uses for output, which can satisfy current consumption needs, or be invested into the physical capital stock or as energy R&D.[5] Energy R&D either increases the level of energy efficiency technology or lowers the cost of the backstop technology. The

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[4] Details of the calibration can be found in Popp (2004b) and in an appendix available from the author. All results presented in this paper use the base case parameters from that paper, which assumes an initial backstop price of $1200 per carbon ton equivalent (equivalent to 7.1¢/kWh). The effect of changing the calibrated parameter values in a model with R&D subsidies is similar to the effect of such changes in the model without R&D subsidies. Sensitivity analysis in the model without R&D subsidies may be found in Popp (2004b).

[5] As in the basic DICE model, other types of R&D are treated exogenously, and simply modeled as increases in the productivity of all inputs over time.

environmental component of the ENTICE-BR model links fossil fuel usage to increases in atmospheric temperature. An associated damage function results in lower levels of output as temperature increases.

As the main difference between the DICE model and ENTICE-BR is the energy research sector, I discuss those components of the model in greater detail. Effective energy units, $E_t$, uses a nested constant elasticity of substitution (CES) framework to aggregate the contributions of fossil fuels, the backstop energy source, and knowledge pertaining to energy efficiency. The first nest, introduced in Popp (2004a), combines energy-efficiency knowledge and fuel consumption into the composite input of effective energy units. The second nest, between fossil fuels and the backstop technology, is introduced in van der Zwaan *et al*. (2002). This specification models the backstop and fossil fuels are imperfect substitutes, allowing for the possibility of "niche markets" for the backstop technology even when the price of the backstop exceeds fossil fuel prices. In each nest, the ease of substitution is represented by $\rho_i$. The case of perfect substitution is $\rho_i = 1$. The elasticity of substitution is $1/(1-\rho_i)$. Given this, effective energy units are modeled as:

$$(2) \qquad E_t = \left[ \alpha_H H_{E,t}^{\rho_H} + \left( \left( \frac{F_t}{\alpha_\Phi \Phi_t} \right)^{\rho_B} + B_t^{\rho_B} \right)^{\rho_H / \rho_B} \right]^{1/\rho_H}$$

Equation (2) states that the total energy requirements for production must be met either by the use of fossil fuel or by technological advances that substitute for fossil fuels. Note that technology affects equation (2) in one of two ways. $H_{E,t}$ represents technological advances that replace fuels in production, and can thus be thought of as improvements to energy efficiency. This stock of knowledge responds endogenously to changes in policy, through an invention possibilities frontier that is described below. $\alpha_H$ is a scaling factor that determines the level of energy savings resulting from new knowledge.[6]

In addition, technology influences the level of the backstop technology chosen by lowering the cost of this input. The backstop technology represents energy sources, such as wind or solar power, that are assumed abundant, and thus available at constant marginal cost. Currently, the high costs of these technologies limit their potential contribution to energy consumption. However, we expect that technological advances will lower their costs over time. Defining $H_{B,t}$ as the stock of knowledge pertaining to the backstop, and using $\eta$ to represent the relationship between new knowledge and prices, the backstop price at time *t* is:[7]

$$p_{B,t} = \frac{p_{B,0}}{H_{B,t}^{\eta}} \tag{3}$$

The contribution of new energy R&D to the knowledge stocks $H_{E,t}$ and $H_{B,t}$ is determined by an invention possibilities frontier, which translates R&D into new contributions to knowledge. Knowledge is cumulative, so that these contributions are added to the previous

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[6] Technology also enters exogenously through $\Phi_t$, which represents exogenous changes in the ratio of carbon emissions per unit of carbon services. Examples include changes in consumption patterns and switching to less carbon-intensive fossil fuels, such as natural gas. The role of exogenous technological change is explored more fully in Popp (2004a). This remaining technological change is retained so that emissions in the baseline (no policy) simulation with R&D replicate the results of the DICE model without R&D. The R&D modeled in the ENTICE models captures purposeful short-term efforts to improve energy efficiency or lower the costs of the backstop technology. However, such R&D is not the only way in which carbon intensity falls over time. Because the DICE model and its variants are a one-sector macroeconomic growth model, changes in consumption patterns or substitution among types of fossil fuels are not explicitly modeled. As a result, long-run emissions simulated without any exogenous decline in carbon-intensity are unrealistically high. Fortunately, Popp (2004a) shows that the percentage of exogenous technological change remaining does not affect the net economic impact of induced technological change, as it is the level of R&D induced between an exogenous and endogenous R&D simulation that is important. Changing the scaling factor only changes the *level* of emissions in each simulation, but not the *difference* between results in simulations with and without climate policy.

[7] Because differences in the costs of fossil fuels and the backstop technology will affect their relative usage, defining the costs of fossil fuels is also important. Following Nordhaus and Boyer (2000), the price of carbon is the sum of the marginal cost of carbon extraction, and a markup that captures the difference between consumer prices and the marginal costs of extraction. Defining $CumC_t$ as cumulative carbon extraction up to year *t*, and $CumC^*$ as the maximum possible extraction, the price of fossil fuels at any given time is $P_{F,t} = 276.29 + 700[CumC_t/CumC^*]^4$.
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knowledge stock. Defining $R_{i,t}$ as R&D on research for each technology at time t, the knowledge stocks are given as

$$H_{i,t} = aR_{i,t}^{b_i} H_{i,t}^{\phi} + (1-\delta_H)\cdot H_{i,t-1}, \qquad i = E,B \tag{4}$$

I assume that both $b_i$ and $\phi_i$ lie between 0 and 1. As discussed in Popp (2004a), $\phi_i < 1$ assumes there are diminishing returns to research across time. Since energy R&D is specialized within a given field, it becomes more and more difficult to find new inventions as the knowledge frontier moves out. Popp (2002) provides supporting evidence. Similarly, $b < 0$ assumes diminishing returns to research *at any given time*.

Finally, because of the public goods nature of knowledge, the role of market failures in R&D must be considered. As noted earlier, virtually all empirical studies of R&D find that the social returns to R&D are greater than the private returns to R&D. Since firms will invest until the private rates of return to R&D are equal to the rates of returns on other investments, underinvestment in R&D will occur. I model these positive externalities by constraining the private rate of return for R&D to be four times that of investment in physical capital. Removing this constraint assumes that government policies, such as R&D subsidies, are in place to correct market failures.

In addition, since empirical work suggests that at least some energy R&D will come at the expense of other forms of R&D, we need to account for the opportunity cost of R&D. Since the social rate of return on R&D is four times higher that of other investment, losing a dollar of other R&D has the same effect as losing four dollars of other investment. This is modeled by subtracting four dollars of private investment from the physical capital stock for each dollar of R&D crowded out by energy R&D, so that the net capital stock is:

$$K_t = \{I_t - 4 * crowdout * (R_{E,t} + R_{B,t})\} + (1-\delta)K_{t-1}, \tag{5}$$

where *crowdout* represents the percentage of other R&D crowded out by energy R&D, $I_t$ represents investment in physical capital, and $\delta$ is the depreciation rate of capital over time.[8]

## III. Simulations

Because the ENTICE-BR model includes environmental damages, it can be used to calculate an optimal climate policy in which marginal benefits equal marginal costs. Such a policy meets a benefit-cost criterion of maximizing total net benefits, and is equivalent to using carbon taxes to correct the environmental externality described in section I. In addition, removing the constraint that the rate of return of energy R&D be four times that of other investment is equivalent to using policy to correct market failures for R&D, such as government funded R&D that supplements private R&D effort.[9] In this section, I use the model described above to compare the effects of alleviating one or both of these market failures. I begin by summarizing the main results of using an optimal carbon tax, which corrects the environmental externality, but does not address knowledge spillovers. I then consider how the results change when R&D subsidies are used to correct the market failures resulting from knowledge spillovers. Finally, because the level of emissions reductions resulting from an optimal tax is lower than often proposed by policymakers, I also consider whether R&D subsidies affect the desirability of more restrictive emissions reduction proposals.

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[8] For this paper, I use the base case assumption of 50% crowding out, as discussed in Popp (2004a,b). These papers show that assumptions about crowding out are important, and explain much of the variation found across climate policy models that include induced technological change.

[9] Of course, the implied assumption that the social rate of return on R&D now equals that of other investments implies that the government sets subsidy levels at a socially optimal level. Thus, the results provide an upper bound for the potential of R&D subsidies. Realistically, one would expect political constraints and imperfect information to limit the government's ability to set optimal subsidies. This strengthens the results that follow, which suggest that subsidies by themselves are not nearly as effective as carbon taxes.

*A. Optimal Environmental Policy*

Popp (2004b) presents the results of a simulated optimal carbon tax without R&D subsidies. As is typical of economic models that solve for an optimal climate policy, the results recommend that climate policy proceed slowly. Because carbon emissions stay in the atmosphere for a long period of time, the marginal damage from any additional ton of emissions is low. Thus, gradually phasing in carbon reduction lowers the opportunity cost of reducing emissions without having much impact on the global climate. Figure 2 shows the carbon tax for the first 100 years. The tax starts at a value of $10.30 per ton in 2005,[10] and rises to $72.59 by 2105. To compare the magnitude of the tax to other policy goals, Nordhaus and Boyer (2000) calculate a tax of $52.48 per ton to restrict emissions to 1990 levels.

The emissions reductions resulting from this carbon tax can be found by comparing the lines for business as usual (BAU) and optimal tax in Figure 3. Compared to BAU, carbon emissions under an optimal carbon tax fall by just 3.2% in 2005, by 5.4% in 2025, and by 15.4% in 2105. As a result of this, atmospheric temperature continues to rise, although at a slightly slower pace, as shown in Figure 4. Here, and in the figures that follow, solid lines illustrate results under BAU, and dashed lines results using an optimal carbon tax only. Lines marked with additional symbols show results from a simulation also including R&D subsidies. These are discussed in subsection B.

Table 1 and Figures 5 and 6 show R&D spending on energy efficiency and the backstop technology (as well as under the R&D subsidy policy to be discussed below). In the base year (1995), there are $10 billion of energy R&D, and $1 billion of backstop energy R&D.[11] Based

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[10] All monetary figures are presented in 1990 U.S. dollars.

[11] The $10 billion figure for energy R&D represents 2% of all R&D spending by OECD countries in 1995. The $1 billion figure for backstop research represents an additional 10 percent of R&D, and comes from data in Anderson (1997).

on results from Popp (2002), the model is calibrated so that the initial elasticity of energy R&D with respect to energy prices is 0.35, and so that the elasticity falls over time due to diminishing returns to research, as discussed in section II. This results in $13 billion of energy efficiency R&D in 2005, and $1.37 billion of backstop energy R&D in 2005 under the optimal policy.

Finally, it is useful to consider the overall economic impact of the carbon tax. I calculate the *net economic impact* as the present value of consumption with policy minus the present value of consumption under BAU. Simply correcting the environmental externality through an optimal carbon tax increases welfare by $2.31 trillion.

### *B. R&D Subsidies*

The above results correct show the effects of policy designed to correct the environmental externality market failure. However, as discussed in section II, the potential of R&D to reduce the costs of complying with climate change is limited by additional market failures for R&D. Because firms cannot fully capture the social benefits of their research, they will underinvest in energy (and other) R&D. The main contribution of this paper is to ask how, if at all, the potential of R&D changes when such market failures are corrected. This section evaluates the potential of government R&D subsidies as part of a climate policy scenario.

Because two market failures, the environmental externality and knowledge spillovers, need to be corrected, there are three possible policies to consider. They differ by addressing either one or both of these two market failures. First, one could imagine a policy that simply corrects the knowledge spillover problem, but ignores the environmental externality. This would be equivalent to removing the rate of return constraint in ENTICE-BR, but not implementing a carbon tax. While such a policy corrects for knowledge spillovers, it ignores the environmental benefits that emerge from energy R&D. Second, the government could use R&D subsidies that consider both the social benefits of knowledge spillovers and the environmental benefits provided by the R&D. Such subsidies will, of course, be greater than the subsidies under the first policy option. In this case, the total level of R&D would be equivalent to the R&D under a carbon tax with the rate of return constraint removed.[12] Finally, rather than using R&D subsidies in isoloation, the government can use subsidies in tandem with an optimal carbon tax. Such a policy would be preferred to either using a carbon tax or subsidies alone, as it addresses both market failures.[13]

Table 1 and Figures 5 and 6 show the levels of both types of energy R&D under the various policy scenarios. Table 1 also shows the percentage by which R&D increases from BAU under each policy scenario.[14] In the short run, simply implementing an optimal tax increases R&D more than correcting R&D market failures. For example, compared to BAU, backstop R&D increases by 7 percent under the carbon tax (which corrects the environmental externality, but not the spillover problem), but just 4.7 percent in the BAU scenario with R&D subsidies (which corrects the spillover problem, but not the environmental externality).

However, while the percentage of R&D induced by the carbon tax remains relatively constant over time, the percentage increase induced by the subsidy grows. Each additional R&D dollar not only benefits current consumers, but also provides additional building blocks for future research. Thus, as shown in the figures, the major difference in long run R&D comes from correcting the spillover problem, rather than the environmental externality. By the middle of

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[12] Such a policy is implemented in ENTICE-BR by first solving the model with a carbon tax and no rate of return constraint. I then constrain R&D to the levels found in that run, and re-run the model without a carbon tax.

[13] Note that, unlike Schneider and Goulder (1997), I only consider the effect of correcting the knowledge market failures for energy R&D only, rather than broader policies designed to correct market failures in all R&D markets.

[14] In the table, BAU with R&D subsidies represents the first policy discussed above, in which only knowledge spillovers are considered. Optimal tax with R&D subsidies gives the level of R&D under both the second and third policies discussed above, in which subsidies address both the environmental externality and knowledge spillovers.

next century, optimal R&D subsidies increase R&D by as much as 43 percent. Furthermore, after correcting for knowledge spillovers, the additional increment to R&D from also acknowledging the environmental externality is small, as shown by the differences between the lines labeled BAU with R&D subsidies and optimal tax with R&D subsidies in Figures 5 and 6. There is a larger difference between R&D with and without subsidies under BAU (or under an optimal tax policy) than there is between R&D with and without a tax when a subsidy is in place. Thus, while climate policy will induce some increases in climate-friendly R&D, the most significant gains to R&D spending come from directly addressing the market failures resulting from knowledge spillovers.

Nonetheless, note from Figures 3 and 4 that while subsidies do increase energy R&D in the long-run, they have little impact on other important variables. Recall that, in these figures, the two solid lines show emissions under BAU and the dashed lines show emissions with the optimal carbon tax. Symbols mark the lines representing policies with R&D subsidies. These figures emphasize the importance of environmental policy for reducing emissions. While there is a significant drop in emissions between any BAU scenario versus any carbon tax scenario, there is almost no change in emissions under BAU versus BAU with R&D subsidies only. Similarly, the addition of R&D subsidies does not lead to further emissions reductions after a carbon tax is in place. Of course, similar trends hold for temperature.

Moreover, using R&D subsidies leads to virtually no change the optimal level of the carbon tax, which remains within one-half of one percent of its original level after subsidies are included. The carbon tax rate is based on the marginal damage of emissions. The marginal damage curve for carbon emissions in any given year is relatively flat, as one additional ton of carbon is just a small addition to total concentrations. While R&D allows emissions reductions to be achieved at lower cost, it does not change the marginal benefits gained from reducing emissions, which is the avoided marginal damage. A tax set at this level is still necessary to force consumers and producers to consider the environmental costs of their actions when consuming fossil fuels. While R&D subsidies can augment other environmental policy, and can help lower the costs of complying with these policies, they cannot serve as a substitute for policies designed to restrict emissions![15]

As would be expected, with such small impacts on emissions, the effects of R&D subsidies on overall economic welfare are also small. Table 2 shows the welfare gains from four separate policies: R&D subsidies only, optimal R&D subsidies only, an optimal tax only, or both an optimal tax and optimal R&D subsidies. Of course, the maximum welfare gain is achieved when policy addresses both market failures. In this case, welfare improves by $2.43 trillion. As shown in the table, most of this increase comes from the carbon tax. A carbon tax alone achieves 95% of these welfare gains. However, R&D subsidies alone achieve just 10% of the maximum welfare gain.

The above results suggest that R&D subsidies can be a useful complement to other environmental policies, but do not have the ability to address the climate change problem alone. Thus, while policymakers may find it politically expedient to fall back on proposals for increased research efforts to confront climate change, significant progress cannot be made without complementary policies in place to restrict emissions. There are two reasons for the limited potential of R&D subsidies. Most importantly, R&D subsidies address market failures in the *invention* of new technologies, but do not provide incentives to *adopt* new technologies. Consider, for example, Figure 7, which shows the percentage of energy coming from backstop

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[15] The result that the carbon tax does not change is consistent of the theoretical predictions of Goulder and Mathai's (2000) benefit-cost model, which compares optimal tax levels with and without policy-induced technological change (but ignores knowledge spillovers and R&D subsidies).

sources. Compared to BAU, this percentage increases by about five percentage points under a carbon tax. However, there is almost no change in the percentage when comparing BAU with and without R&D subsidies.

A second limitation of R&D subsidies comes from the opportunity costs of R&D. R&D is performed by highly trained scientists and engineers. Shifting more resources towards one type of research results in fewer resources available for other research opportunities. For example, Goolsbee (1998) finds that one of the chief beneficiaries of R&D tax subsidies are scientists and engineers, as increased demand for their services leads to higher wages. Similarly, in Popp (2004a), I present evidence that approximately one-half of the energy R&D spending that took place in the 1970s and 1980s came at the expense of other R&D. This lost R&D comes at a high cost. Because of market failures for knowledge, the social returns to R&D are high for *all* types of R&D, not just for energy R&D. Recall from section II that the consensus from studies on the returns to R&D is that the social rates of return are approximately four times higher than the rates of return to other investments. Thus, taking one dollar from other R&D projects has the same effect as taking four dollars from other types of investments. Indeed, the socially optimal level of R&D subsidies found by the ENTICE-BR model account for this, as the rates of return to R&D remain twice that of other investment even after the constraint requiring the returns to be four times higher is removed.[16] If the government ignores these social costs, and subsidizes energy R&D until its rate of return is equal to that of other investments, net economic welfare actually falls due to the lost value of other R&D.

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[16] The result follows from the combination of the social returns on R&D being four times that of other investments, and from the assumption that 50% of new energy R&D comes at the cost of other R&D. Thus, the total social cost of new energy R&D is twice that of other investments.

### C. Other Climate Policies

By implementing an optimal carbon tax, the above simulation shows the maximum possible gains to economic welfare from correcting the market failures concerning emissions and R&D. However, most discussions of climate policy revolve around more restrictive policies that set fixed emissions levels. Thus, I consider the interaction of R&D subsidies with two additional policies – one restricting emissions to 1995 levels, and a second mandating at least 10 percent of energy come from backstop sources.[17] The policy mandating backstop energy retains a carbon tax as well, so that climate policies are in place even after backstop prices fall to a level where a government mandate is not needed to encourage 10% market penetration.

Figure 8 compares atmospheric temperature under the BAU scenario and each of our three policy scenarios. For each policy scenario, results are presented for policies that also include R&D subsidies. As before, these subsidies have little effect on the value of variables other than R&D, so that the results without subsidies are similar. Requiring 10% of total energy to come from backstop sources slightly lowers atmospheric temperature in the short run, but has little long-term effect. As shown in Figure 9, which illustrates the percentage of energy coming from backstop sources under each policy, the mandate merely speeds up the time it takes for backstop market penetration to reach 10%. Once this occurs, the mandate has no additional effect, and usage patterns mirror those of the optimal carbon tax policy.

In contrast, restricting emissions to 1995 levels lowers atmospheric temperature nearly one degree Celsius more than either the optimal tax or backstop mandate policies. However, this drop in temperature comes at a cost. As shown in Table 2, restricting emissions to 1995 levels has a negative impact on net economic welfare – the potential benefits of reduced emissions do not justify the costs of reducing emissions quickly. Recall from Figure 3 that an optimal climate

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[17] Popp (2004b) includes a discussion of a policy restricting emissions without R&D subsidies.

policy entails a gradual emissions reduction. Acting quickly forces short-term reductions before technology has had a chance to evolve and lower the costs of action.

Turning to R&D, note that while R&D subsidies increase both backstop and energy efficiency R&D under these alternative polices, the impact of this additional R&D is generally negligible. Figures 10 and 11 show energy efficiency and backstop R&D under each policy scenario, both with and without subsidies. Not surprisingly, the restrictive policy induces the most R&D, particularly for backstop energy. As before, the biggest jumps in R&D come not from environmental policy, but from the subsidies themselves.

Nonetheless, once again R&D subsidies have little impact on emissions or temperature. In fact, under the restricted emissions case, there is no change in temperature when R&D subsidies are added to the policy, since the climate policy offers no incentives for reductions beyond what is initially mandated, even as subsidies improve the quality of technology. In this case, the only benefits from additional R&D come from cost savings. Faster development of new technologies makes meeting a fixed emissions target cheaper. As a result, the carbon tax needed to meet this goal falls by 14 percent in 2005, and by five percent in 2025. Such results are consistent with the predictions of Goulder and Mathai (2000) in the case of a cost-effective policy designed to meet a given goal at the least possible cost.

However, under both the restricted emissions and backstop mandate policies, the benefits of these cost savings are small compared to the direct effect of addressing the environmental externality through policy. In each case, R&D subsidies only improve net economic welfare by a few percentage points, as shown in Table 2. Not only do R&D subsidies not effectively address the climate change problem on their own, they also have little ability to soften the economic costs of more restrictive climate policies.

## IV. Discussion

This paper examines the potential role that subsidies for climate-friendly R&D may play in policy designed to reduce carbon emissions. Because firms are not fully compensated for the social benefits of knowledge spillovers, they perform less R&D than is socially optimal. R&D subsidies, either through direct government funding of R&D or through tax credits for private R&D activity, can help raise R&D levels to a socially desirable level. Indeed, the results show that such subsidies do have a significant effect on the long run levels of energy R&D. Moreover, in the long-run subsidies induce more R&D than a carbon tax does.

However, R&D subsidies cannot serve as a substitute for other climate policies. While R&D levels rise dramatically when subsidies are included in the policy simulations, there is little change to other variables. Most importantly, since the subsidies do not provide incentive to adopt new technologies, emissions do not fall unless subsidies are accompanied by a policy to address the environmental externality created by carbon emissions, such as a carbon tax. Moreover, for policies designed to meet a benefit-cost criterion, using subsidies does not change the optimal level of the carbon tax, as the marginal benefits of reduced emissions do not change. In contrast, under a cost-effective criterion, designed to meet a fixed emissions target at the least possible cost, R&D subsidies lower the tax level needed to achieve the desired emissions reductions. In both cases, while properly targeted R&D subsidies can lower the cost of such policies somewhat, as shown by the five percent welfare gain from the policy using both a tax and subsidies in section III B, the biggest gains to both welfare and the environment come from policies designed to target emissions directly.

Finally, when setting the level of R&D subsidies, policy makers need to consider the opportunity cost of additional R&D. Because R&D requires highly trained personnel, at least some new energy R&D efforts will come at the expense of other R&D. Just as spillovers make the social returns to energy R&D high, they also make the social returns to other types of R&D high. Thus, some of the large social benefits of additional energy R&D are offset by large opportunity costs from giving up other types of R&D spending. Ignoring the costs of reducing these R&D efforts would result in overly generous subsidies for energy R&D, and could have negative impacts on the economy as a whole.

These results have important implications for those on both sides of the policy debate. For those who advocate that climate policy should proceed slowly, the limitations of R&D suggest that technological change is unlikely to reduce the burden of costly climate policies by significant amounts. On the other hand, the results also offer support for those that argue that quick, strict emissions reductions are needed. For example, the go-slow approach suggested by the DICE model is partially a result of assumptions about the potential damages from climate emissions (see, for example, Kaufmann 1997). For those who think the damages are higher, and that strict carbon policies are justified, the results show that R&D policy alone cannot substitute for high carbon taxes or strict emissions limits if significant emissions reductions are to be achieved. In either case, while R&D subsidies can be useful to lower the cost of any given emissions target, they do not eliminate the need for such a target, nor for continued debate over the stringency that emissions limits should take.

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**Figure 1 – Schematic of the ENTICE-BR Model**

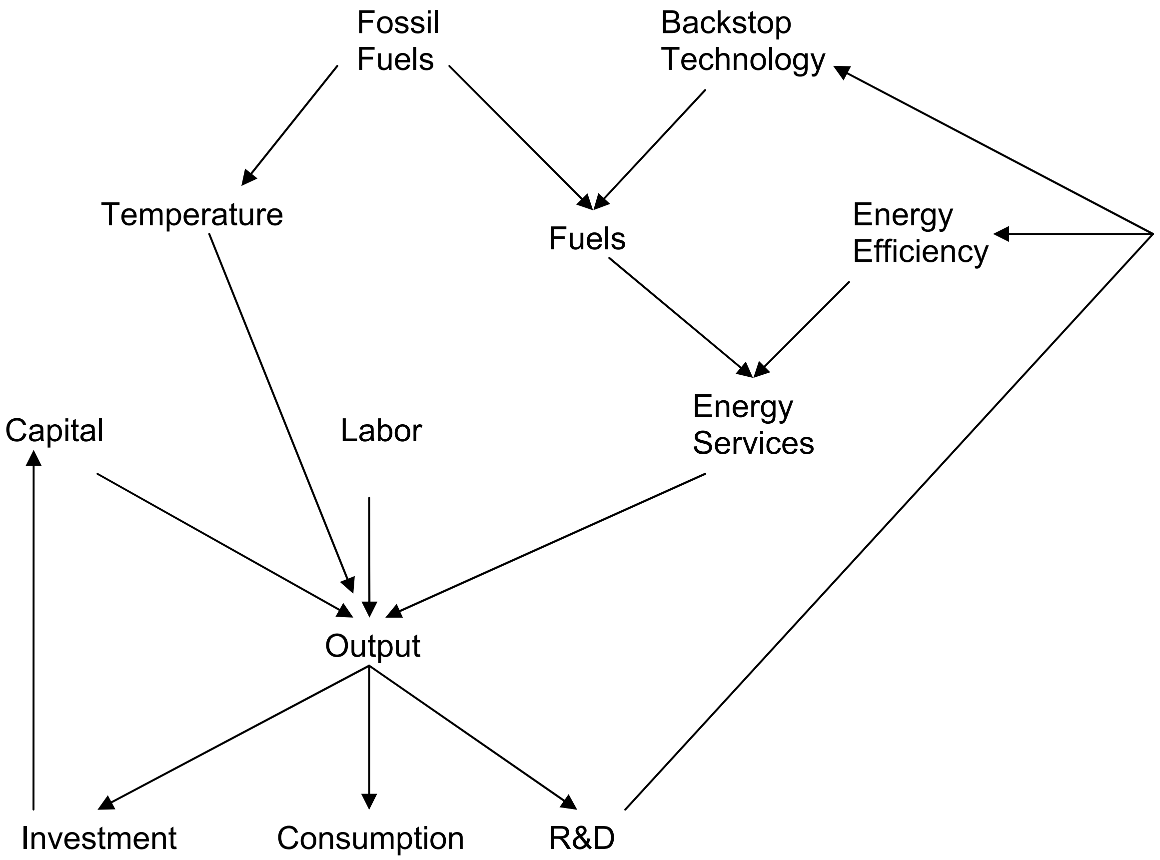


Figure 1 illustrates the logic of the ENTICE-BR model. Capital, labor and energy services are combined to produce output, which can be used for consumption, or reinvested into energy R&D or other investment. As described in the text, energy services combines two types of fuels (fossil fuels and a non-carbon backstop technology) and energy efficiency technologies. The use of fossil fuels leads to increased atmospheric temperature, which lowers output through a damage function.

## Figure 2 – Optimal Carbon Tax Rates

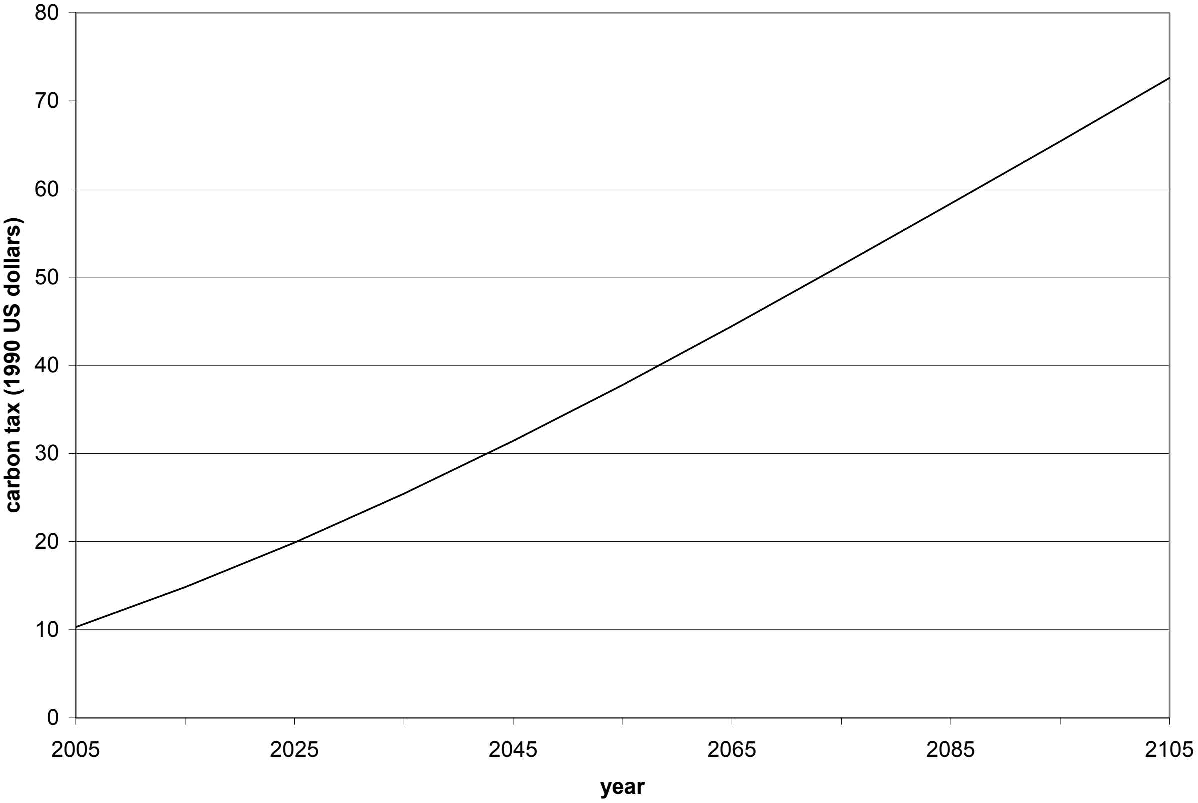
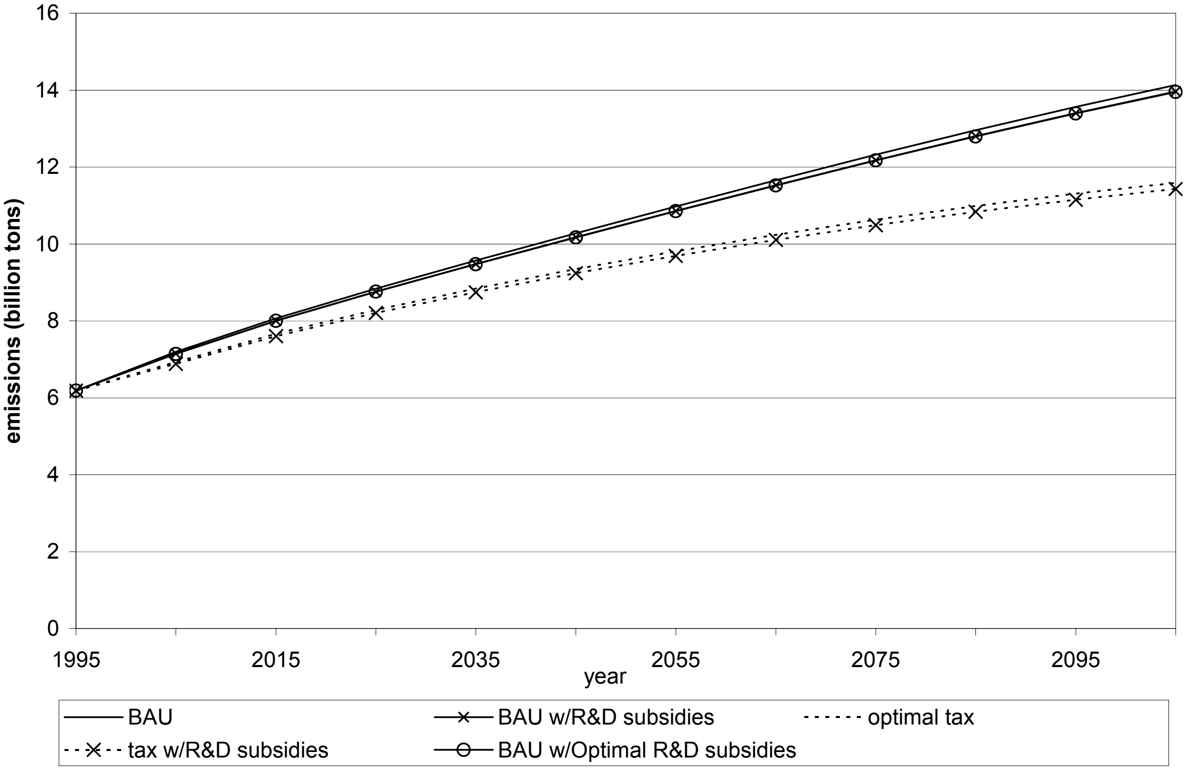
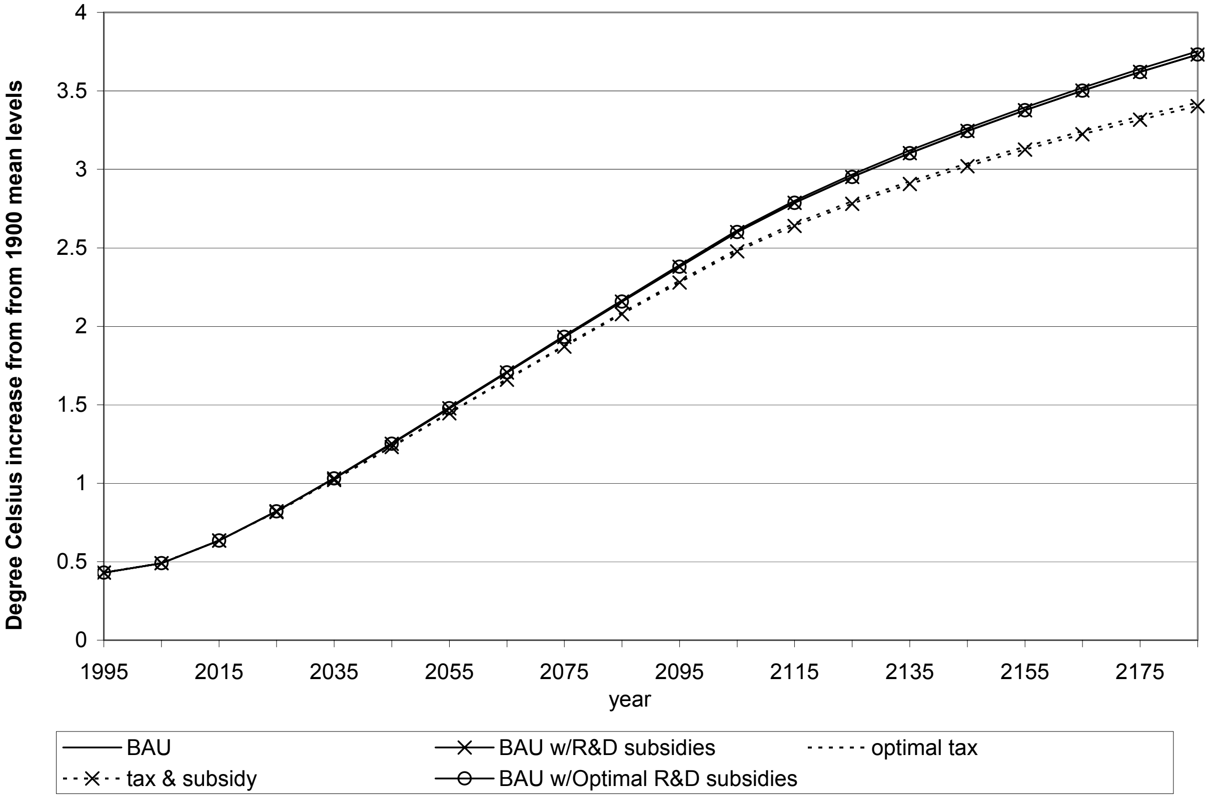


**Figure 3 – Carbon Emissions Under Optimal Climate Policies**



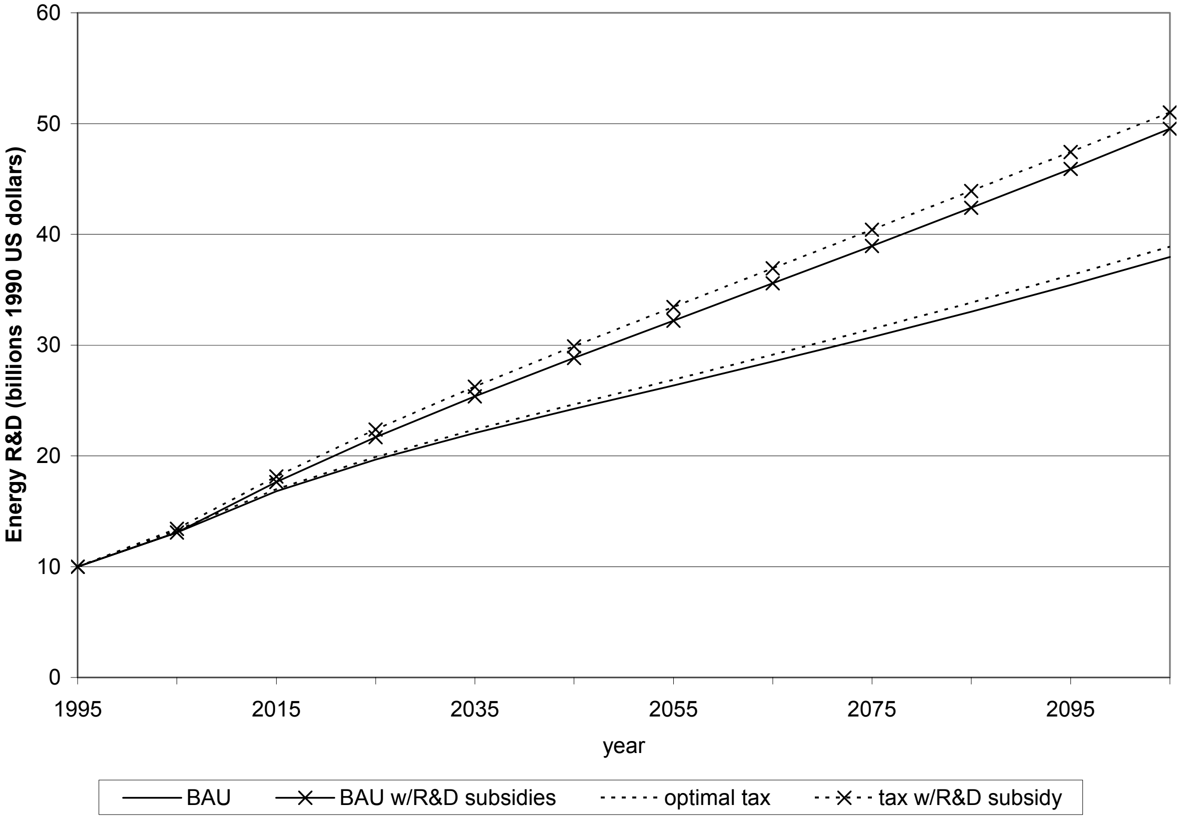
The figure shows annual carbon emissions under both business and usual (BAU) and an optimal carbon tax policy. Note that R&D subsidies, by themselves, result in very small reductions in emissions. This is true in both the BAU and optimal tax simulations. Policies aimed directly at emissions are needed to achieve reductions.

**Figure 4 – Atmospheric Temperature Under Optimal Climate Policies**



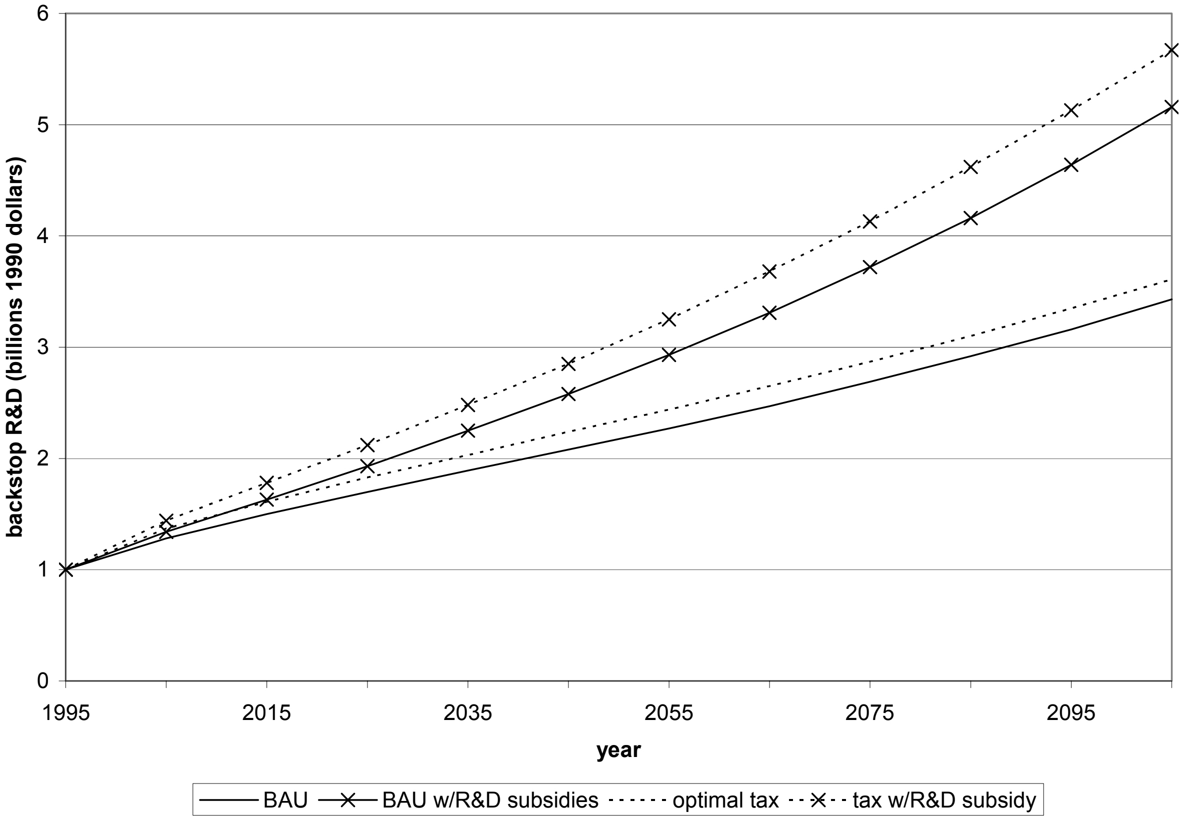
The figure shows how the departure of global mean temperature from 1990 levels, reported in degrees Celsius is affected by carbon taxes and/or R&D subsidies. As with emissions, R&D subsidies by themselves have little effect on temperature.

**Figure 5 – Energy Efficiency R&D Under Optimal Climate Policies**



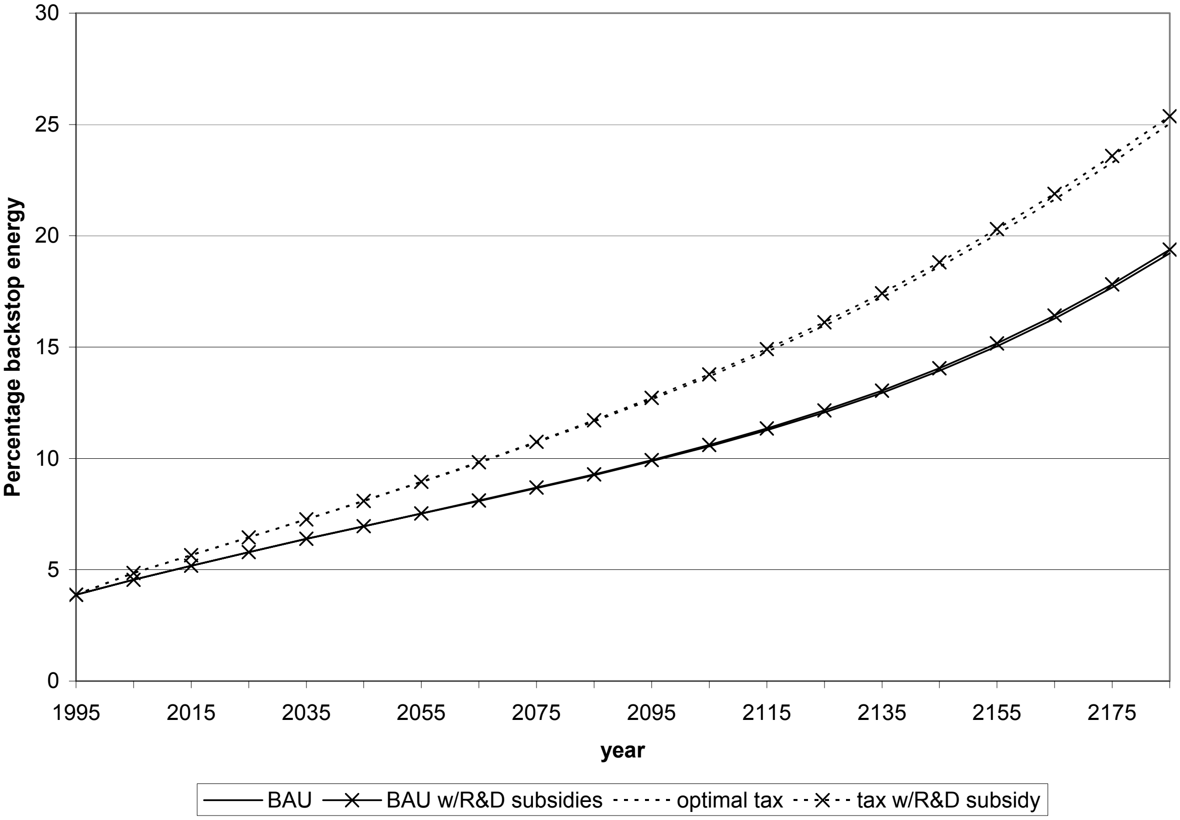
The figure shows the level of energy efficiency R&D, in billions of 1990 US dollars. As can be seen by comparing the BAU and optimal tax lines with and without subsidies, policies that correct R&D market failures induce more additional R&D than does the carbon tax itself.

# Figure 6 – Backstop Energy R&D Under Optimal Climate Policies



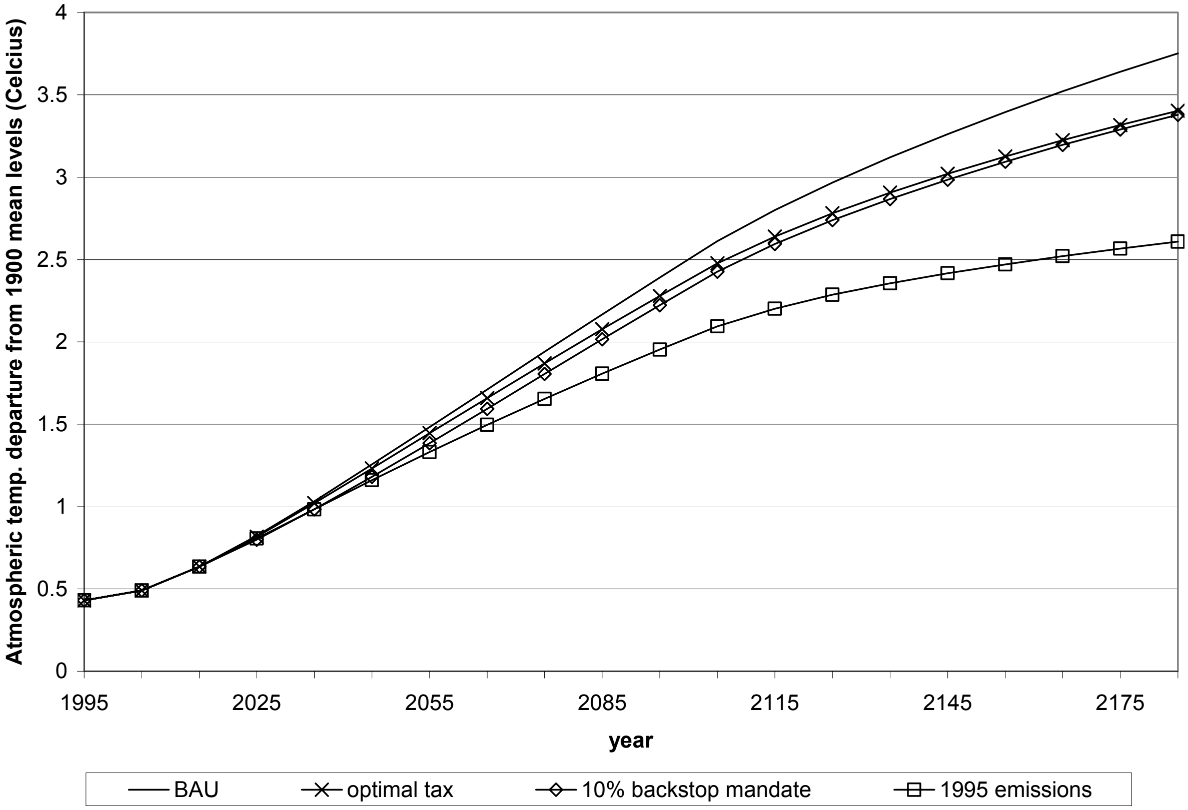
The figure shows the level of backstop energy R&D, in billions of 1990 US dollars. As can be seen by comparing the BAU and optimal tax lines with and without subsidies, policies that correct R&D market failures induce more additional R&D than does the carbon tax itself.

## Figure 7 – Percentage of Energy From Backstop Sources



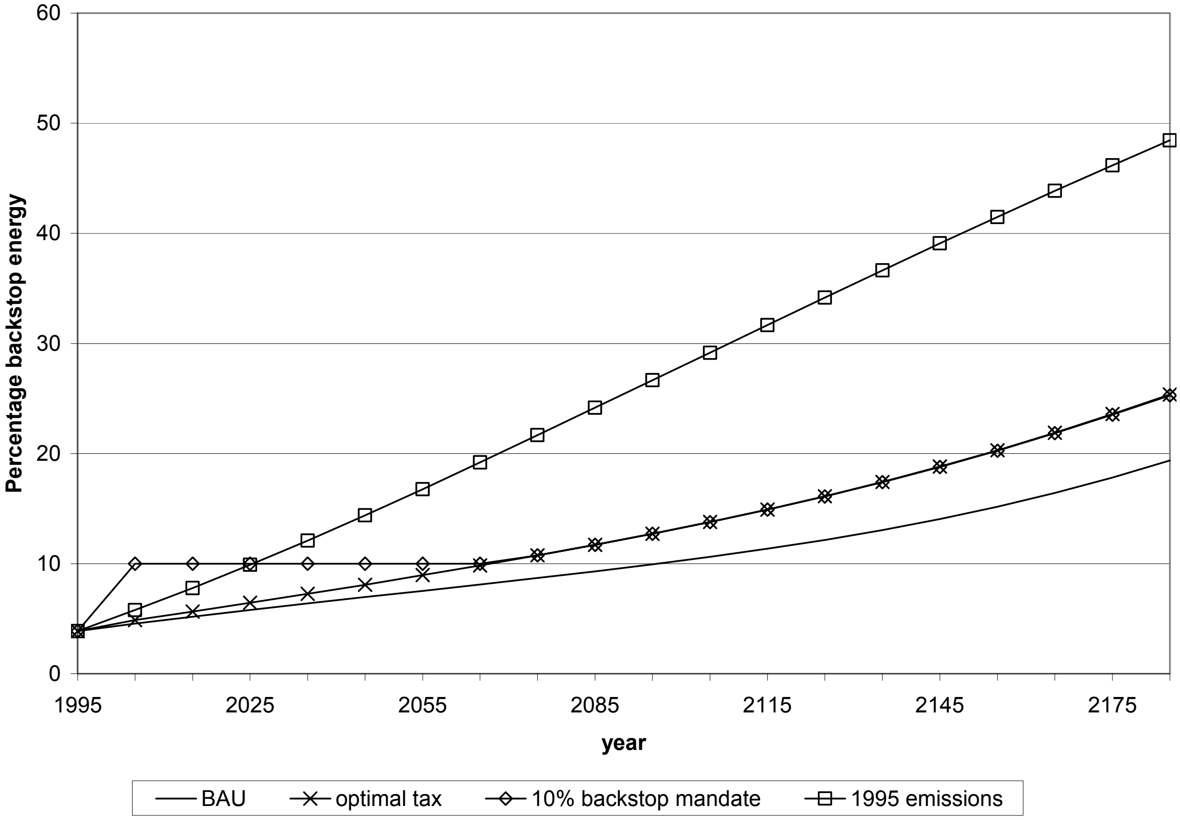
The figure shows the percentage of energy from backstop sources under BAU or an optimal carbon tax. As with emissions, a policy addressing carbon emissions directly, such as a carbon tax, is necessary to increase this percentage. There is almost no change between BAU and BAU with R&D subsidies.

**Figure 8 – Temperature Under Various Policy Scenarios**



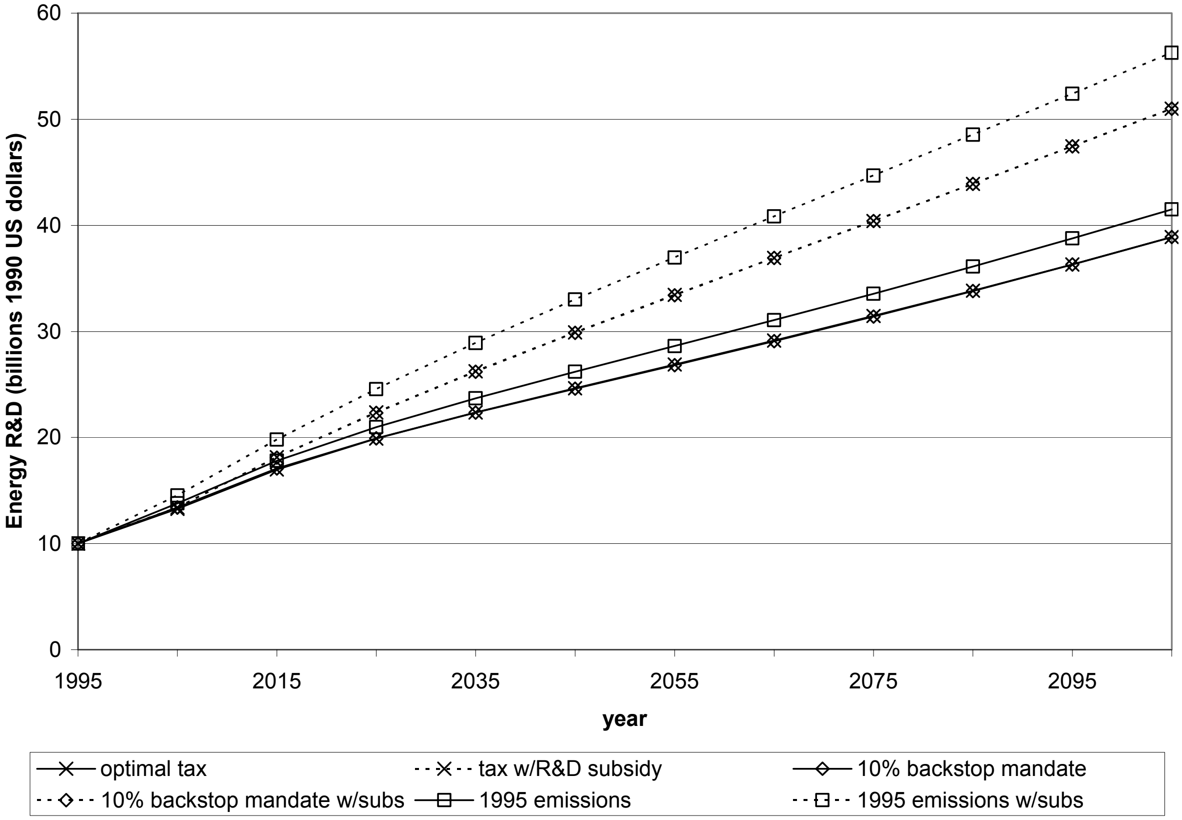
The figure shows the departure of global mean temperature from 1990 levels, reported in degrees Celsius, under various policy scenarios. In each case, both emissions reduction policies and R&D subsidies are used. While the backstop mandate has little effect on long-run atmospheric temperature, restricting emissions to 1995 levels reduces long-run temperature by over one degree Celsius compared to BAU.

**Figure 9 -- Percentage of Energy From Backstop Sources Under Various Policy Scenarios**



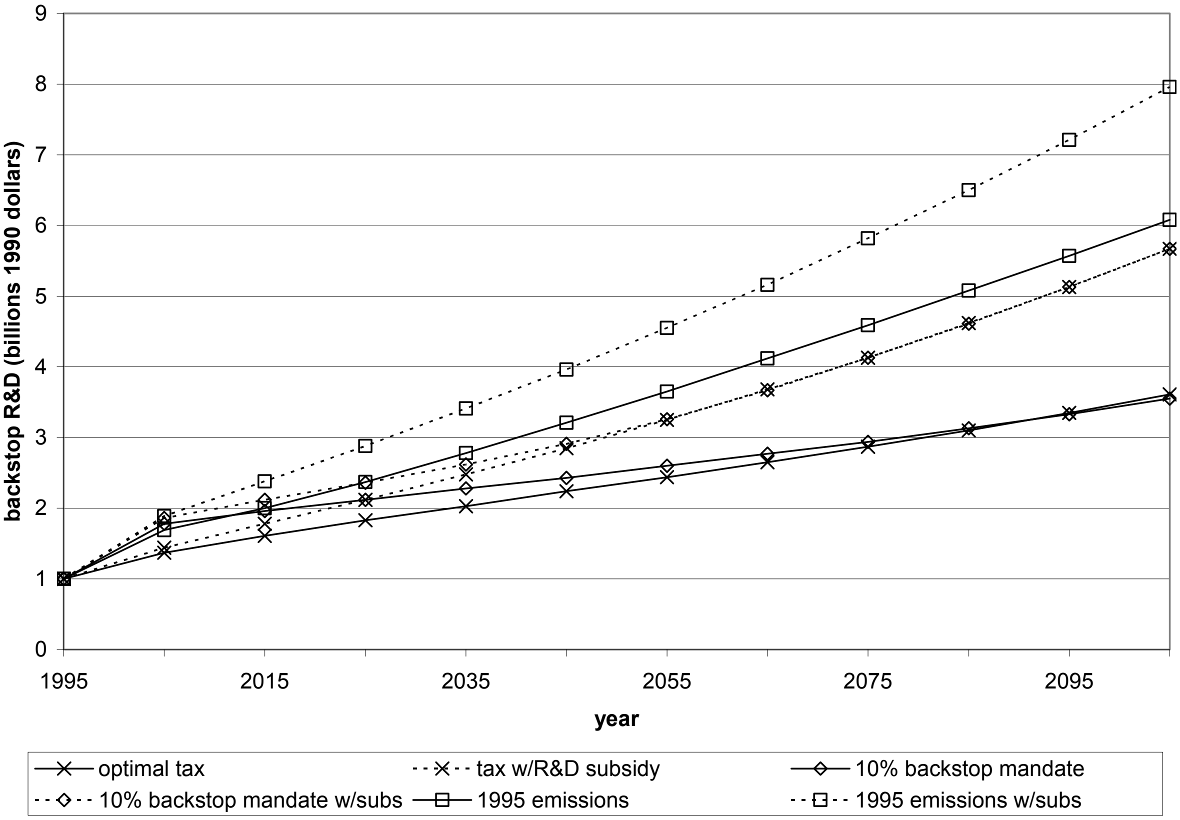
The figure shows the percentage of energy from backstop sources under various policy scenarios. Note that the backstop mandate increases backstop usage in the short-run, but has little long run effect.

**Figure 10 – Energy Efficiency R&D Under Various Policy Scenarios**



The figure shows the level of energy efficiency R&D, in billions of 1990 US dollars, under various policy scenarios. Note that the biggest increases come not from more restrictive policies, but from R&D subsidies.

## Figure 11 – Backstop Energy R&D Under Optimal Climate Policies



The figure shows the level of backstop energy R&D, in billions of 1990 US dollars, under various policy scenarios.

**Table 1 – Energy R&D Spending Over Time**

| *Energy Efficiency R&D* | **2005** | **2025** | **2055** | **2105** |
|---|---|---|---|---|
| BAU | 13.08 | 19.67 | 26.37 | 37.96 |
| w/R&D subsidies | 13.08 | 21.69 | 32.22 | 49.53 |
| optimal tax | 13.28 | 19.91 | 26.88 | 38.89 |
| w/R&D subsidies | 13.41 | 22.37 | 33.44 | 51 |

| *Backstop R&D* | **2005** | **2025** | **2055** | **2105** |
|---|---|---|---|---|
| BAU | 1.28 | 1.7 | 2.27 | 3.43 |
| w/R&D subsidies | 1.34 | 1.93 | 2.93 | 5.16 |
| optimal tax | 1.37 | 1.83 | 2.44 | 3.61 |
| w/R&D subsidies | 1.44 | 2.12 | 3.25 | 5.67 |

Percent Change from BAU

| *Energy Efficiency R&D* | **2005** | **2025** | **2055** | **2105** |
|---|---|---|---|---|
| BAU | N/A | N/A | N/A | N/A |
| w/R&D subsidies | 0.0% | 10.3% | 22.2% | 30.5% |
| optimal tax | 1.5% | 1.2% | 1.9% | 2.4% |
| w/R&D subsidies | 2.5% | 13.7% | 26.8% | 34.4% |

| *Backstop R&D* | **2005** | **2025** | **2055** | **2105** |
|---|---|---|---|---|
| BAU | N/A | N/A | N/A | N/A |
| w/R&D subsidies | 4.7% | 13.5% | 29.1% | 50.4% |
| optimal tax | 7.0% | 7.6% | 7.5% | 5.2% |
| w/R&D subsidies | 12.5% | 24.7% | 43.2% | 65.3% |

Table 1 presents levels of energy R&D spending over time, in billions of 1990 US dollars. BAU shows R&D spending under business as usual without any R&D subsidies. BAU with R&D subsidies presents the R&D levels with subsidies that address knowledge spillovers, but not the environmental externality. Optimal tax shows R&D levels under a carbon tax designed to correct the environmental externality, but without R&D policy to address knowledge spillovers. Optimal tax with R&D subsidies is the level of R&D under policies addressing both the environmental and knowledge market failures.

**Table 2 – Welfare Gains**

| | Gain from BAU | % of maximum welfare gain |
|---|---|---|
| Optimal tax & R&D subsidies | 2.43 | 100% |
| Optimal tax only | 2.31 | 95% |
| Optimal R&D subsidies only | 0.27 | 11% |
| R&D subsidies only | 0.23 | 9% |
| Restrict emissions & R&D subsidies | -3.61 | -148% |
| Restrict emissions to 1995 levels | -3.75 | -154% |
| Backstop mandate & R&D subsidies | 1.68 | 69% |
| Backstop mandate | 1.57 | 64% |

Table 2 summarizes the welfare gains under various optimal emissions policies, as well as under two alternative policies discussed in subsection C. Net economic welfare is measured as the difference in the present value of consumption between a policy and BAU simulation, and is presented in trillions of 1990 US dollars. The maximum welfare gain comes from a combination of optimal carbon taxes and R&D subsidies, as this addresses both market failures. Note that R&D subsidies themselves do not enhance welfare as much as policies that directly deal with the environmental externality from carbon emissions.