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Chapter 9

Modeling Induced Innovation in Climate Change Policy

William D. Nordhaus

9.1 Introduction

Studies of environmental and climate-change policy—indeed of virtually all aspects of economic policy—have generally sidestepped the thorny issue of induced innovation, which refers to the impact of economic activity and policy on research, development, and the diffusion of new technologies. This omission arises both because of the lack of a firm empirical understanding of the determinants of technological change and because of the inherent difficulties of economic modeling processes with externalities and increasing returns to scale. While we suspect that we know the direction of this effect—toward overestimates of the cost of emissions reductions and the trend increase in climate change—we have little sense of the magnitude of the effect or the importance of this omission. Would including induced innovation have a large or small impact on climate change and on climate-change policies? This is a major open question.

One way of remedying this omission is to draw on research in the area of induced innovation. The formal theory of induced innovation arose in the 1960s in an attempt to understand why technological change appears to have been largely labor saving (see Nelson 1959; Arrow 1962; Kennedy

1962; and von Weizsäcker 1966). More recently, theories of induced technological change have been resuscitated as the "new growth theory," pioneered by Lucas (1986) and Romer (1990).[1] The thrust of this research is to allow for investment in knowledge and human capital. Such investments improve society's technologies, and a higher level of investment in knowledge will change society's production possibilities and may improve the long-run growth rate of the economy.

Virtually all studies of induced innovation have been theoretical.[2] With few exceptions, they do not lay out a set of hypotheses that can be tested or used to model the innovation process at an industrial level.[3] The present study sets out an approach that draws on the theory of endogenous technological change as well as empirical results in this area and applies the theory to the issue of induced innovation in climate-change policy.

9.2 Theory of Induced Innovation as Applied to the Environment

It will be useful to describe the forest terrain before getting emerged in tree mathematics. This chapter presents a model of induced innovation that can describe the impact of changes in prices or regulations on the innovations in different sectors. At any given time, society has a stock of existing general and sector-specific basic knowledge and applied and engineering knowledge. By investing in improvements in the stock of knowledge, society can improve the productivity of its resources.

Inventive activity in market economies is fundamentally a private sector activity, so the decisions about the allocation of inventive activity depend on private sector incentives. The allocation to particular sectors will depend on the relative sizes of different sectors, the degree of appropriability, and the underlying "innovation-possibility frontier" (the production function for producing new knowledge). These functions are derived from or calibrated to empirical studies that analyze the inventive process. The calibrated innovation production function is then embedded into a model of the economics of global warming to determine the impact of innovation on the important variables, such as the time path of greenhouse-gas emissions and concentrations, and climate change, along with the policy variables.

The analytical background for the model is developed in detail below. The discussion in this section lays out the model of technological change to be used in the simulations that follow. In describing the analytical and modeling framework, five issues are discussed: (1) the underlying model of technology, (2) the firm's decision framework, (3) the divergence between social and private return, (4) the functional specification of the induced innovation function, and (5) the welfare implications of induced innovation.

9.2.1 The underlying model of technology

We begin with a discussion of the underlying view of technology and innovation. At any time, there is a stock of basic, applied, and engineering knowledge—both general and sector specific. The state of fundamental knowledge at each time is represented by H_t. The state of fundamental knowledge is assumed to proceed exogenously from the point of view of individual sectors.

Within an individual sector, there is a level of sector-specific technological knowledge. In each sector, new knowledge is generated by combining sector-specific research with general and sector-specific knowledge. Resources can be applied to improve the state of knowledge, and improvements in knowledge are called "innovation." These resources comprise a wide variety of activities, including basic research, applied research and development (R&D), development, and commercialization. In the discussion that follows, the inputs into the process of technological change are labeled as "research," or R_i. The outputs of research—the innovations—should be thought of in the broad sense of "new combinations" or new products, processes, or ways of doing business. $A_{i,t}$ denotes the level of technological knowledge in sector i in year t. Hence, technological change (i.e., changes in $A_{i,t}$) is denoted by $\partial A_{i,t}/\partial t = \dot{A}_{i,t}$, where a dot over a variable represents the time derivative of that variable, or as $\Delta A_{i,t}/A_{i,t-1}$ in a discrete, period model.

Production in sector i is given by $X_{i,t} = A_{i,t} f_i()$, where $f_i()$ is a function of inputs of capital, labor, etc. Useful new innovations increase technology, as represented by the following *innovation-possibility frontier*:

$$\dot{A}_{i,t}/A_{i,t} = \phi_1(R_{i,t}, H_t) \; , \tag{9.1}$$

where $\dot{A}_{i,t}/A_{i,t}$ is the rate of technological change (either discrete or continuous depending on the context).

9.2.2 The firm's decision framework

Although research takes place in a wide variety of institutions, we examine research that takes place in profit-oriented enterprises. For this purpose, we assume that research is an investment activity that is pursued for commercial purposes and has well-determined private and social returns. This assumption allows us to model induced innovation in a conventional economic framework once we take into account the externalities of research.

This basic framework contains two major assumptions. The first is that inventive activity is undertaken with an eye to increasing profits rather than for prestige, Nobel prizes, not-for-profit altruism, or curiosity. While much academic and government research does not fit this pattern, the focus here is on the profit-oriented activity in firms that is directed to improving energy and environmental production technology. The second major assumption is that the innovation-possibility schedule is deterministic. This could easily be modified to include a risk component to inventive activity as long as the risks were independent and reasonably nicely distributed. This second assumption is worrisome because of the evidence that the distribution of returns to inventive activity is highly skewed. [4]

To understand the allocation of research, we need to examine the way innovation affects profitability of *private* individual agents. This can be treated in a number of ways, but the following is consistent with current findings in the industrial organization literature. [5]

We view the production process as consisting of a large number of elemental goods and production processes (e.g., sending bits of information, producing Barbie dolls, lighting rooms, or producing a kilowatt-hour of electricity). For simplicity, we assume that these elemental processes have constant returns to scale. At any time, there is a dominant technology for each process. The dominant technology in one period becomes widely available in the next period and sets the upper limit on prices. In the model, the period is a decade and represents the effective life of a new invention. In the preceding period, this dominant technology costs $C_{i,t-1}$ and has a market price of $P_{i,t-1} = C_{i,t-1}$. A single new innovation in period t then lowers the cost to $C_{i,t} < C_{i,t-1}$. We assume that the inventor can appropriate the fraction α of the cost savings from the innovation. Then (for "run-of-the-mill" innovations), the inventor maximizes profit by setting the price at $C_{i,t} + \alpha[C_{i,t-1} - C_{i,t}]$.[6]

Inventive activity in a sector leads to an improvement of the basic technology, increasing the level of productivity, $A_{i,t}$. The improvement reduces the cost of production from $C_{i,t-1}$ in the preceding period to $C_{i,t}$ in the current period. The inventor captures the fraction α of the innovation (this being the appropriability ratio). Figure 9.1 shows the initial competitive price, new cost, and new price under these assumptions. The shaded profit region is "Schumpeterian" or innovational profits. As is shown in the figure, the current period price (P_1) therefore lies between the competitive cost of the old technology (C_0) and the new, lower cost of the innovation

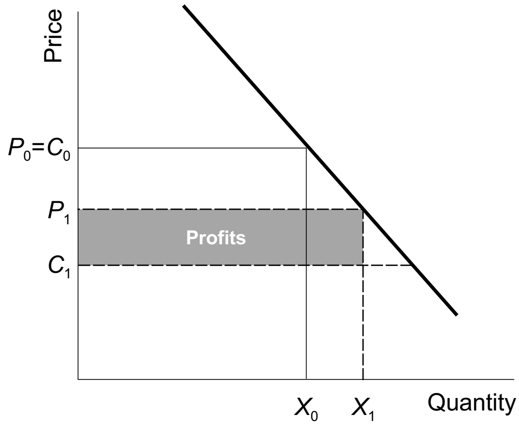

Figure 9.1. Impact of Innovation on Price, Cost, and Profits.

(C_1). The extent to which the current price is above the cost depends on the appropriability ratio.

The inventor's profits are equal to $(P_1 - C_1)X_1$, which can be approximated by $\alpha(C_0 - C_1)X_0 = \alpha[(C_0 - C_1)/C_0](P_0X_0) = \alpha[\Delta A_1/A_0](P_0X_0)$. In other words, the value of the innovation is approximately equal to the appropriability ratio times the improvement in technology times the value of output.

The firm's decision is then to determine the profit-maximizing amount of research given all the parameters and constraints of the market. The major parameters are the degree of appropriability, the form of the innovation-possibility function, the size of the market, and the cost of research.

9.2.3 The divergence between social and private return

A major issue raised by the presence of technological change is the likelihood that invention involves external economies or, more precisely, that R&D has a social rate of return that greatly exceeds the private rate of return on those investments. This is of course the primary economic justification for government intervention in the allocation of research funds. The divergence between social and private return also poses thorny problems for economic modeling. If research had equal private and social returns, it could be treated as simply another investment.

While estimates differ from sector to sector, there is a substantial body of evidence that, for the United States, research has a social return of 30 to 70 percent per annum, versus private returns on capital in the 6 to 15 percent range.[7] A government summary of the literature stated that "The benefits to industries which purchase new or improved products from innovating firms [have] rates of return . . . estimated to range from 20 to 80 percent" (National Science Board 1977:126). A summary by the leading practitioner in this area, Edwin Mansfield, stated that "practically all of the studies carried out to date indicate that the average social rate of return from industrial R&D is very high. Moreover, the marginal social rate of return also seems high, generally in the neighborhood of 30 to 50 percent" (Mansfield 1996:191).

An alternative approach would be to assume that all residual economic growth is determined by "human ingenuity." This approach would imply a social rate of return of around 150 percent per annum rather than 50 percent per annum. This calculation assumes that about 1 percent of output is devoted to the "human ingenuity sector" and that the rate of total factor productivity after removing all other inputs is 1.5 percent per annum.

9.2.4 Functional specification of the induced innovation function

Given these background observations, we now discuss the specification of the induced innovation function employed in the present study. We assume that production takes place with fixed proportions. Under this view, substitution itself is a costly process, and research and engineering costs must be devoted to employing knowledge to develop and deploy new techniques.

In the specific application, we investigate the role of "carbon-energy-saving technological change," or CESTC. The model used here simulates the energy system by defining a new input into production called "carbon energy." Carbon energy is the carbon equivalent of energy consumption and is measured in carbon units. Carbon energy is one of the inputs (along with capital and labor) used to produce output. Carbon dioxide (CO_2) emissions and output are therefore a joint product of using inputs of carbon energy. This can be interpreted as a world in which energy is produced either by pure carbon or by substitutes that are some blend of pure carbon and capital and labor.

Technological change takes two forms: economy-wide technological change and CESTC. Economy-wide technological change is Hicks neutral, while CESTC reduces the carbon energy coefficient of the fixed-proportions production function. In other words, CESTC reduces the amount of carbon emissions per unit output at given input prices.

The next step is to find an appropriate functional form for the innovation-possibility function in Equation (9.1). For this purpose, we concentrate only on the CESTC and assume that the Hicks-neutral component of technological change is exogenous. We further assume that there are diminishing returns to research, so that there is an interior solution to the representative firm's profit-maximizing decision. Moreover, we allow for depreciation of knowledge, either because of economic obsolescence (as new products replace old ones) or because of natural factors (such as adaptive pests) that reduce the value of the innovation over time.

In this spirit, it will be convenient to assume that the innovation-possibility frontier is generated as a constant-elasticity function of the level of research in the sector:

$$\dot{A}_{i,t}/A_{i,t} = \phi_i(R_{i,t}, H_t) = \kappa_i R_{i,t}^{\beta_i} - \delta_i \,, \tag{9.2}$$

where the Roman-letter variables are as defined in Equation (9.1) and the Greek letters are parameters. Equation (9.2) is a standard approach to modeling the economic impact of inventive activity (see, e.g., Griliches 1998).

There is one assumption that is hidden in the specification in Equation (9.2), concerning the "recharge" of the innovational potential. This question involves how rapidly the pool of potential innovations is recharged or replenished. There are two interesting polar cases. The first, which we follow, is the "building-on-shoulders" model of innovation, in which current innovations build on past innovations. As modeled in Equation (9.2), there are diminishing returns to inventive activity in any particular period, but in the next period the innovation possibilities are replenished. This implies that a high rate of innovation in one period leads to a larger stock of knowledge in the next period, and innovation in the next period builds on the "shoulders" of the larger stock of knowledge. Hence, in the building-on-shoulders approach, high innovation in one period leads to automatic recharge of the pool of potential innovations in the next period. This approach leads to technological drift in which the long-run level of technology depends on the past intensity of research.

An alternative approach, called the "depletable-pool" approach, is one in which the stock of potential innovations is an exogenous pool that is determined by activities outside the sector. In this approach, potential innovations are like a pool of fish that breed at a given rate so that heavy research fishing today reduces the number of invention-fish available in the next period. In other words, the stock of innovations is exogenously given, so more rapid innovation today leads to depleted opportunities tomorrow. The maximum level of technology in this approach is essentially exogenous, although a sector can be closer to or farther from the frontier; research can move the industry closer to the exogenous frontier but it does not advance the frontier.

It would seem appropriate to use the building-on-shoulders model when the relevant technology is largely self-contained and the research process is intrinsically cumulative. The depletable-pool model would be appropriate for processes like diffusion, or when the sector is small and much of the relevant technology is determined outside the sector.

9.2.5 The welfare implications of induced innovation

The present study does not consider the general-equilibrium impacts of induced innovation through its impact on other sectors. In the modeling of induced innovation presented below, aggregate output, labor, capital, and factor prices are taken as given. However, a few observations about the welfare impacts of induced innovation are in order.

In considering the impact of induced innovation in the carbon-energy sector, we must consider the possibility that higher inventive activity in one sector will reduce inventive activity in other sectors. That is, as research is reallocated from other areas to the carbon-energy sector, there may be more rapid technological change in the climate-change sector and less rapid technological change in other sectors.

In analyzing the welfare impact of changing conventional inputs, we generally put a social price tag of US$1 on inputs that cost US$1. For research, this would be appropriate if the higher research spending simply required more bricks and scribes without diminishing research in other sectors. For inventive activity, however, the higher inventive activity in the carbon-energy sector may reduce inventive activity in other sectors. This would occur under either of two conditions. First, under the commercial view described in the last section, increasing inventive incentives in one sector reduces incentives in others. The decline in other sectors occurs because the increased market value of output in the carbon-energy sector through carbon taxes or emissions constraints raises the relative cost of production in the carbon-energy sector and lowers the relative cost of production in other sectors, both of which tend to raise returns and reallocate inventive activity to the now-larger sector. Hence, if total output is unchanged, and if the technological parameters of the innovation-possibility frontiers in different industries are similar, a unit increase in research in the carbon-energy sector would accompany a unit decrease of research in the rest of the economy.

The second condition under which the social opportunity cost of reduced research in other sectors would be more than US$1 would be where the supply of research is less than perfectly elastic. For example, consider the case where there is a fixed stock of researchers (e.g., a fixed stock of people who are inclined to tinker, invent, and try new combinations). As some of the tinkerers are attracted to the carbon-energy sector to try to solve the world's environmental problems, they will pay less attention to unsolved problems in other sectors. If John von Neumann had been attracted to solving problems of the environment rather than those of computers, the cost to society would have been much more than a fractional lifetime of labor inputs into computation.

From a modeling perspective, we handle this issue by assuming that the opportunity cost of higher research in the carbon-energy sector is a multiple of its dollar costs; for the numerical calculations we take this multiple to be four. This assumption implies that the social return to research is four times the private return and is a convenient way of handling the externality of research discussed in Section 9.2.3.[8] In other words, this assumption implies that the present-value opportunity cost of research is US$4 of output per US$1 of research, so that when we calculate the social costs of increasing the research in the environmental sectors, we must reckon the loss in research outputs in the non-environmental sectors. It seems likely that the first of these assumptions is well supported by existing evidence. The second is more speculative, but it is important only for the welfare implications and not for the findings about the dynamics of technological change or the impact of induced innovation on the energy sector.

9.3 Application in the R&DICE Model

Here, we estimate the impact of induced innovation by putting the model of technological change described in the previous section in a new version of the globally aggregated DICE model, referred to here as the R&DICE model.[9] This section provides a brief description of the DICE-99 model and then describes the modifications that are incorporated for the R&DICE model.

9.3.1 The DICE-99 model

The version of the model used for this study is the DICE-99 model, a globally aggregated model of the economics of global warming that includes the economy, carbon cycle, climate science, and impacts. This highly aggregated model allows a weighing of the costs and benefits of taking steps to slow greenhouse warming.

The latest versions are the RICE-99 and DICE-99 models. The RICE-99 model is an eight-region model of the world economy with a climate module. The DICE-99 model is a globally aggregated version of the RICE-99 model calibrated to match the major features of the larger model. While losing the regional detail of the RICE-99 model, the DICE-99 model has several advantages. It is more useful for understanding the basic structure of economic policy issues posed by greenhouse warming because it is small enough that researchers can understand the individual linkages in an intuitive way. It is more easily modified because the number of parameters is much smaller. It is much faster, so that alternative experiments can be tested more easily. In addition, it is available in a spreadsheet format, which can be more easily understood and manipulated by researchers.

The basic approach in the DICE model is to consider the trade-off between consumption today and consumption in the future. By taking steps to slow emissions of greenhouse gases (GHGs) today, the economy reduces the amount of output that can be devoted to consumption and productive investment. The return for this "climate investment" is reduced damages and therefore higher consumption in the future.

The DICE-99 model has an objective function which is the discounted utility of consumption. More precisely, the objective function to be maximized is the sum across periods of the discounted utilities, where the utility function is the population times the logarithm of per capita consumption. This objective function is maximized subject to a number of economic and geophysical constraints. The decision variables that are available to the economy are consumption, the rate of investment in tangible capital, and the climate investments, primarily reductions of GHG emissions.

The model contains both a traditional economic sector found in many economic models and a climate sector designed for climate-change modeling. In the economic sector there is a single commodity, which can be used for either consumption or investment. The world is endowed with an initial stock of capital and labor and an initial level of technology.

The environmental part of the model contains a number of geophysical relationships that link together the different forces affecting climate change. This part contains a carbon cycle, a radiative forcing equation, climate-change equations, and a climate-damage relationship. In DICE-99, endogenous emissions are limited to industrial CO_2, which is a joint product of carbon energy. Other contributions to global warming are taken as exogenous. DICE-99 contains a new structural approach to carbon-cycle modeling that uses a three-reservoir model calibrated to existing carbon-cycle models. Climate change is represented by global mean surface temperature, and the relationship uses the consensus of climate modelers and a lag derived from coupled ocean-atmospheric models. The

DICE-99 model also contains new estimates of the damage function from climate change.

The major equations of the model along with modifications (discussed in the next section) are provided in Appendices 9.A and 9.B.

9.3.2 Modifications for the R&DICE-99 model

In the basic DICE model, carbon intensity is affected by *substitution* of capital and labor for carbon energy. The economic mechanism at work is substitution in that increases in the price of carbon energy relative to other inputs induce users to purchase more fuel-efficient equipment or employ less energy-intensive products and services. In the Cobb-Douglas production function, for example, a 10 percent increase in the price of carbon energy relative to other prices, when markups and other factors are taken into account, will lower the carbon/output ratio by approximately 4 percent.

In the R&DICE model, carbon intensity is affected by *technological change*. Here, the mechanism at work is induced innovation, which works in a manner quite different from substitution. A rise in the price of carbon energy will give an inducement to firms to develop new processes and products that are less carbon intensive than existing products. They therefore invest in new knowledge— through research, development, and informal investments. The new knowledge produces new processes and products, which lower the carbon intensity of output. To simplify the analysis, we have removed the processes of substitution from the R&DICE model to focus the analysis on the induced-innovation mechanism.

The difference between the standard substitution approach and the induced-innovation approach is illustrated in Figures 9.2 and 9.3. Figure 9.2 illustrates how an increase in the relative price of carbon energy would induce substitution from point A to point B. By contrast, in the R&DICE model, an investment in research leads to purely carbon-saving technological change, moving the technique from point A to point C (see Figure 9.3).

Analytical Changes

More precisely, the implementation of the R&DICE model takes the following steps:

- We begin with the DICE-99 model as described above and shown in Appendices 9.A and 9.B.
- We then take the capital, labor, and interest rate variables from the DICE model and set these as exogenous. This gives the exogenously

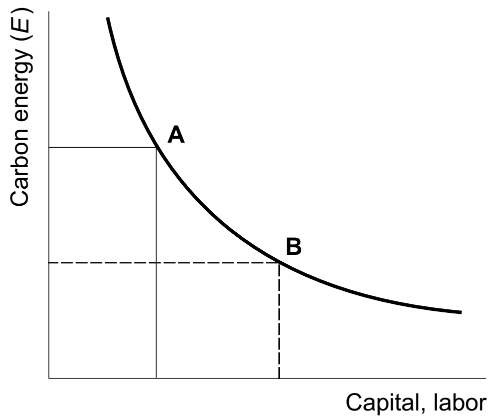

Figure 9.2. Substitution Approach.
In the standard substitution approach, an increase in the price of carbon energy leads to a substitution of capital and labor for carbon energy, moving along the production isoquant from A to B. In the usual approach, substitution is costless and reversible.

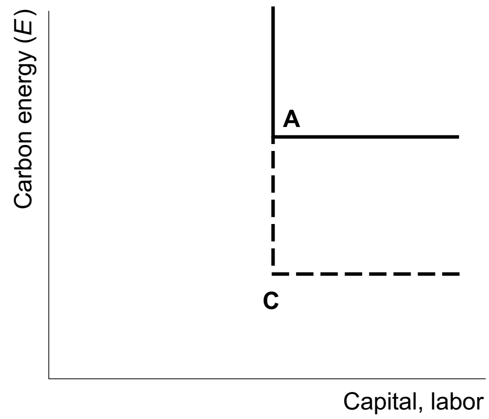

Figure 9.3. Induced-Innovation Approach.
In the induced-innovation approach, we assume that there is no costless substitution. Initially, the economy is at point A. After an investment in research, a new technique is developed with the same output as at A but with inputs shown by point C. We assume that technological change takes place in the baseline solution, and the R&DICE model investigates the role of carbon-saving technological change. The primary difference between this and the substitution approach is that the movement from A to C is both costly and irreversible.

determined level of output, $Q^*(t)$ in Equation (1-R&DICE) in Appendix 9.B.

- We then adjust the output balance equation in equation (2-R&DICE) by making two further corrections. First, we subtract the cost of carbon energy from output to reflect the fixed-proportions assumption. Second, because research is now an endogenous variable, we subtract the cost of research. Note that the cost of research is multiplied by the factor of 4 to reflect the divergence of social and private costs discussed in Section 9.2.

- We next adjust the emissions equation to reflect the assumption that all changes in carbon intensity occur through induced innovation rather than substitution. In the standard DICE model, shown in equation (4-DICE), substitution is reflected in the parameter μ. This is removed in equation (4-R&DICE), and industrial carbon emissions are a function only of output and the endogenous carbon intensity, $\sigma(t)$.

- The final change comes in determining the carbon intensity. In the DICE model, the no-controls carbon intensity (i.e., the carbon intensity with no climate-change policy in the form of regulations or carbon taxes) is determined by estimates of technological trends. In the R&DICE model, we assume that the carbon intensity is endogenous and determined by the equation for induced innovation described in Section 9.2 and shown as equation (5-R&DICE). In this specification, the change in the carbon intensity is a function of research spending on carbon-saving technological change.

Equations (6) through (11) in Appendix 9.B are identical in the DICE and R&DICE models.

Calibration

The final issue is the calibration of the parameters of the R&DICE model. More precisely, we need to specify the parameters of the induced-innovation function in equation (5-R&DICE). Given the functional form, there are three parameters to estimate: Ψ_1, the productivity of research; Ψ_2, the elasticity of technology with respect to research; and Ψ_3, the depreciation rate of technology.

There is a great deal of research in the existing literature on both the elasticity and the depreciation rate. The elasticity has been estimated to lie in the range of 0.05 to 0.20 depending on the specification, industry,

Table 9.1. R&D and Output for Fossil Fuels, United States (Billions of Dollars per Year).

	1987	1988	1989	1990	1991
Gross output, fossil fuels	77.0	86.9	83.3	99.6	87.8
R&D, fossil fuels	1.5	1.6	1.6	1.8	2.0
R&D/output (percent)	2.0	1.8	1.9	1.8	2.3

Source: Bureau of Economic Analysis and National Science Foundation.

and time period. The deprecation rate is variously estimated at between 1 and 10 percent per year depending on the specific technology and the time period. We use these broad bounds to ensure that the actual calibration produces sensible estimates.

Within these broad ranges, the model produces three variables that can be used for calibration:

- *Criterion 1*. The first calibrating variable is the rate of return on R&D. From earlier discussion, we determined that a major feature of induced innovation is the divergence between social and private return. On the basis of existing studies, we impose a ratio of social to private return of 4.

- *Criterion 2*. The second calibrating variable is the trend in the carbon intensity of production. We assume that at the level of privately optimized R&D that occurs with *no climate damages*, the trend of carbon intensity would be as close as possible to the baseline (zero-carbon-tax) emissions path of the DICE-99 model. The numerical criterion to be minimized is the sum through 2150 of the squared deviations between the baseline projections of carbon intensity of the DICE-99 model and the baseline carbon intensity projected by the R&DICE model.

- *Criterion 3*. The final calibration is optimized R&D. Table 9.1 shows recent data for the United States on energy R&D for fossil fuels along with total gross output originating in the oil, gas, and coal industries. The data indicate that this industry has had a ratio of R&D to output of about 2 percent of sales in recent years. We therefore assume that R&D for carbon energy is 2 percent of output at the optimized level. For the calibration, we assume that the R&D/output ratio is constant for the entire period.

We then select the three parameters of the model so that they meet the calibration targets. The actual procedure is as follows: First, the level of R&D is optimized for an initial set of parameters $[\Psi_1^{(i)},\ \Psi_2^{(i)},\ \Psi_3^{(i)}]$. The calibration criterion 1 is automatically met through this optimization. We then adjust the parameter values so as to meet calibration criterion 3 exactly. We then set the parameters so that criterion 2 is best achieved (in the sense that the sum of the squared deviations of the carbon/output ratio from its target is minimized). In summary, we set the parameters so that the depreciation rate and the R&D/output ratio are exactly equal to their estimated values, while the remaining parameters are set to fit the path of the estimated CO_2 output trajectory. In these estimates, calibration criterion 2 has a standard deviation of 15 percent.

The actual form of the calibrated equation is

$$[\sigma(t) - \sigma(t-1)]/\sigma(t-1) = .415R(t)^{0.139} - 0.20\ , \tag{9.3}$$

where $\sigma(t)$ is global industrial CO_2 emissions per unit of world output and where the time period t is 10 years.

The DICE and R&DICE model runs are calculated for 40 periods (400 years). The optimization in the R&DICE model estimates the optimal research inputs for the first 10 periods, but for the subsequent periods the ratio of research spending to spending on carbon energy is assumed to be constant for computational simplicity.

Model Runs

We will analyze three simulations:

- *Case A: No controls*. In the market run, there is no climate-change policy. Carbon-energy research is determined endogenously to maximize global income according to the procedure described above.

- *Case B: Climate policy with substitution but exogenous technology*. In the second experiment, we determine the optimal policy with an exogenous technology but with price-induced substitution. The mechanism is a carbon tax (determined by the discounted value of the marginal damages from emissions) that induces substitution away from carbon energy. This is estimated using the DICE model with adjustments for the baseline technology so that the base conforms to case A.

- *Case C: Climate policy with endogenous technology but no substitution*. In the third experiment, there is induced innovation but no substitution. Here, carbon taxes are again determined by the marginal damages from climate change, and the carbon tax induces research

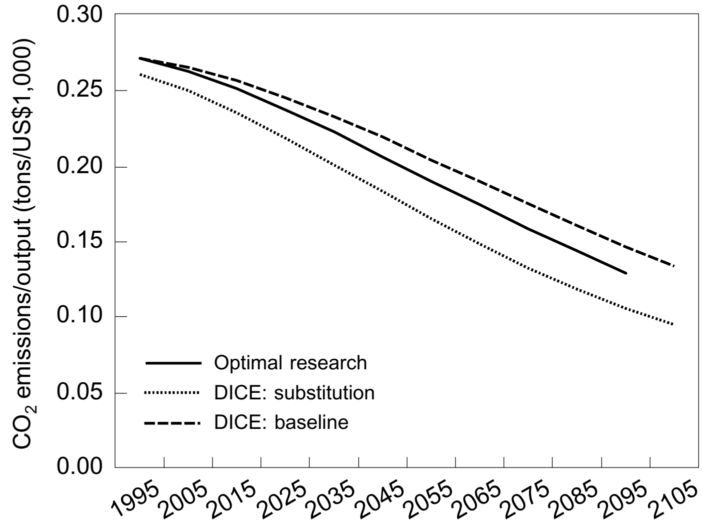

Figure 9.4. Carbon Intensity of Output under Different Approaches.

and technological change. Research is determined according to the criterion that the social rate of return is four times the private rate of return.

9.4 Results

9.4.1 Overall trends

One of the major issues is the impact of induced innovation on carbon intensity. We would expect that induced innovation would lead to a slower initial reduction in carbon intensity than would substitution, but the cumulative reduction in carbon intensity might well be larger in the long run. Figure 9.4 shows the carbon intensities of the baseline, substitution, and optimal-research (or induced-innovation) scenarios. Figure 9.5 shows the percentage reduction in emissions for the two policy scenarios. The first important conclusion is that the reduction in carbon intensity in the induced-innovation strategy is quite modest in the early decades. The reduction in emissions from induced innovation is about 6 percent over the first half century and about 12 percent after a century.

Second, it is interesting to note that the reduction in emissions from substitution is substantially larger than the reduction from induced innovation at the beginning (see Figure 9.5). The reduction in emissions from substitution is 12 percent by 2050 and 22 percent by 2100. The reductions

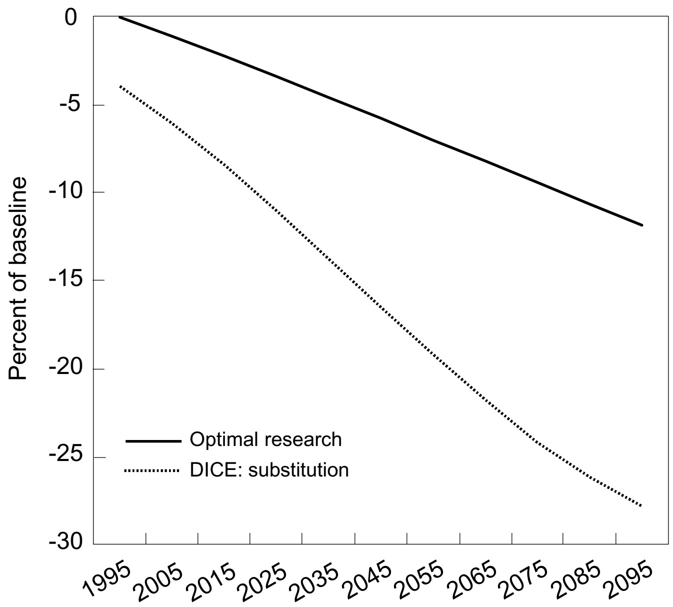

Figure 9.5. Emissions Relative to Baseline under Different Approaches.

from substitution are larger than those from induced innovation through the twenty-second century. Indeed the "crossover point" between induced innovation and substitution does not come until about 2230—although the exact timing is sensitive to the specification. This is perhaps the greatest surprise of the present study. We might have thought that allowing induced innovation with the supernormal rates of return would have led to quite rapid reductions in carbon intensities, but this proved not to be the case. We discuss the reasons for this result below.

Figure 9.6 shows the impact of optimizing emissions of industrial CO_2 in both the baseline and substitution and optimal-research cases of the standard DICE model and in the case of induced innovation in the R&DICE model. Figure 9.7 shows the impact on projected global mean temperature. Induced innovation produces more emissions and less temperature reduction than does substitution. After two centuries, induced innovation reduces global mean temperature by 0.25°C while substitution reduces global mean temperature by 0.54°C. The crossover point where induced innovation beats out substitution is not reached at any point in the entire simulation period, although the crossover point for CO_2 concentrations is reached after about four centuries.

We next turn to the impact on research. Global R&D on carbon energy in 1995 in the baseline R&DICE run is US$11 billion in 1990 prices.

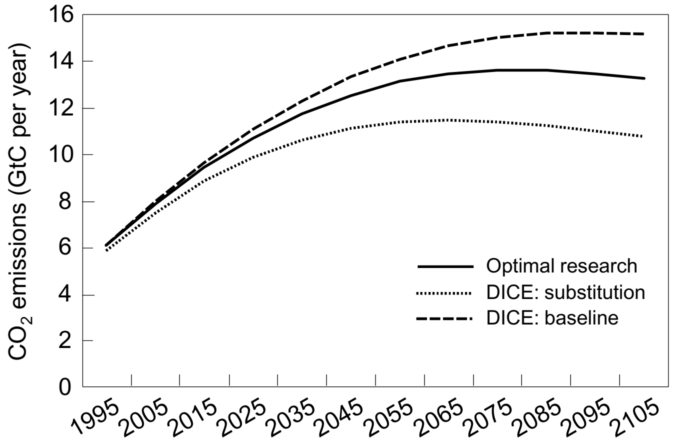

Figure 9.6. Industrial CO_2 Emissions under Different Approaches.

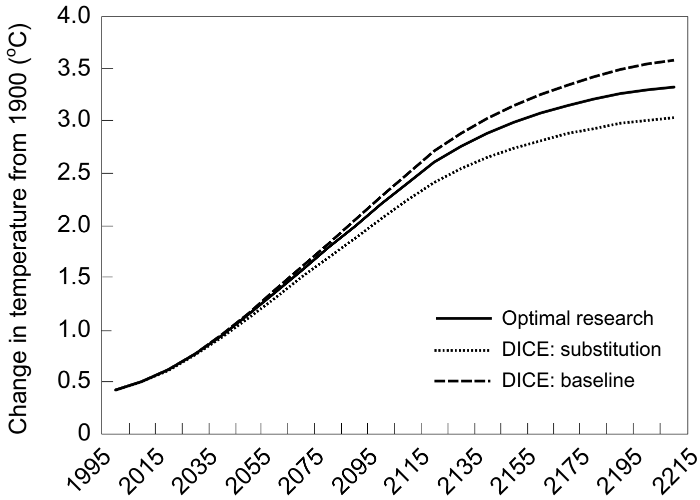

Figure 9.7. Global Temperature Change under Different Approaches.

This compares with estimates of US$2 billion in 1991 for the United States alone. There are no comparable data for most other countries, but we can extrapolate to determine whether the numbers in the R&DICE model are reasonable. The United States accounted for 23 percent of carbon use; with growth in the economy and the same ratio of R&D to output for the world, this would yield a global R&D total of US$10 billion in 1995. This probably overstates the actual world total given the higher research intensity in high-income countries, but the numbers are close enough to allow us to conclude that the model captures the basic numbers accurately.

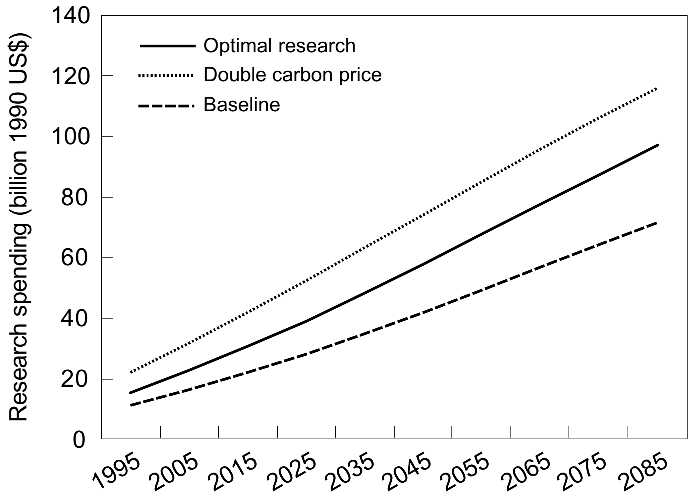

Figure 9.8. Research and Development on Carbon Energy under Different Scenarios.

The impact of induced innovation on research is shown in Figure 9.8. Total research spending increases by 40 percent when the climate externality is internalized through appropriate pricing. For this graph, we also show the impact on R&D spending of a doubling of carbon prices: a doubling of carbon energy prices leads to an increase in R&D spending of 80 percent in the model. The elasticity of research with respect to the price of carbon energy is therefore around 80 percent, which is consistent with existing studies (see Popp 1997).

As Figure 9.9 shows, the optimal carbon taxes for both the induced-innovation (R&DICE) and the substitution (DICE) cases are virtually identical. The reason they are so similar is that the optimal carbon tax equals the present discounted value of the damage from emissions. The optimal carbon tax is basically the same in the two approaches because there is so little impact on the path of climate change.

The welfare impacts of the two policies are shown in Table 9.2. As noted above, the welfare interpretation in the R&DICE model is somewhat tricky because of the externality. In calculating the welfare gains, we have assumed that the research reallocated to the carbon-energy sector has an offset in other sectors that just balances the externality. That is, a US$1 increase in research in the energy sector leads to a US$4 increase in the value of production in the energy sector (in present value terms); but the increase in value in the energy sector is just offset by a US$4 decrease in the value of research in the non-energy sector. This would be the case

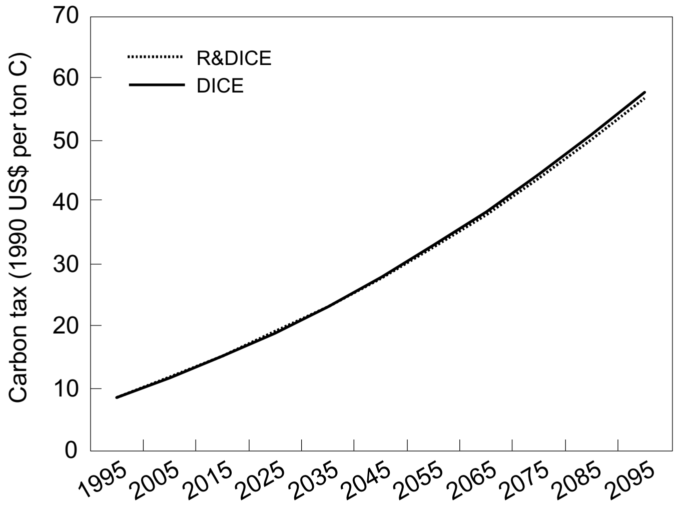

Figure 9.9. Optimal Carbon Taxes in DICE and R&DICE Models.

Table 9.2. Welfare Implications of Alternative Models.

	Difference from no controls (billions of 1990 US$)
DICE	
No controls	0
Optimal controls	585
R&DICE	
No induced innovation	0
Induced innovation	238

either if the total stock of research is fixed or if the gap between social and private returns is the same in different sectors and the induced effect in other sectors is equal and opposite to the induced effect in the carbon-energy sector.

Under these assumptions, the introduction of induced innovation increases the discounted value of world consumption by US$238 billion. This is about 40 percent of the welfare gain from substitution policies, which is $585 billion (1990 US dollars). Basically, induced innovation has less welfare potential because the quantitative impact on research is smaller than that on substitution.

9.4.2 Discussion

A major surprise of the present study is how little impact induced innovation has in the near term. A simple example illustrates why this outcome is, on reflection, quite sensible. For this calculation, we take 10 periods (100 years) starting in the year 2000. We calculate that the optimized level of R&D on carbon energy with no climate-change policies would average about 2 percent of total expenditures on carbon energy. This would average about US$30 billion per year.

If we internalize climate damages into carbon-energy prices, the wholesale carbon price (including the carbon tax) would increase about US$22 per ton on average, an increase of 24 percent. Firms operating in the energy sector would see the cost of their energy fuels rise under a carbon tax and would increase their carbon-energy R&D. Suppose that the R&D/output ratio remains constant. Assuming for simplicity that output is unchanged, a 24 percent increase in the price would therefore induce a 24 percent increase in R&D. (The actual result over the first 10 periods is 37 percent, which is above the static calculation because the carbon tax is rising.) This would lead to an increase in R&D of US$7.7 billion per year on average.

Next consider the returns on this investment. For this calculation, we ignore depreciation. The return on this investment is 14.2 percent per year in carbon emissions savings (four times the rate of return on capital). The annual costs of carbon energy during the first 10 periods are US$1,490 billion per year. With these costs and an average increase of US$7.7 billion in R&D, a 14.2 annual percent rate of return would lead to a decline in the carbon/output ratio of 0.142 $\times$ US$7.7/$1,490 = 0.073 percent per year.

The decline in the carbon/output ratio over these 10 decades induced by the higher carbon-energy prices in the R&DICE model is 0.126 percent per year. The divergence between the simple calculation (0.073) and the R&DICE model (0.126) arises because the estimated R&DICE elasticity of research with respect to carbon prices is 1.5 rather than 1.0. With this correction, the simple example in the last paragraph yields an estimated decline of 0.109 percent per year. The small remaining difference between the simple example and the R&DICE model results from depreciation of technology and timing factors.

9.4.3 Sensitivity analysis

One of the difficulties with using complex numerical methods like the R&DICE model is that it is always difficult to know how sensitive the conclusions are to alternative specifications or alternative values of the key

Table 9.3. Sensitivity Analysis for Major Parameters: Impact upon Emissions Decline Rate (Percent per Year, First 10 Periods).

	R&D/sales ratio (percent)			
	1	2	3	
Externality factor				
2	–0.03	–0.06	–0.09	
4	–0.06	–0.13	–0.19	
8	–0.13	–0.25	–0.38	
Decline rate:				
In baseline:				–0.62
Necessary to stabilize emissions from 2000 to 2100				–0.91

parameters. We have undertaken extensive sensitivity analyses in previous studies and limit the analysis here to asking how sensitive the key results are to alternative parameter values. Some preliminary tests indicated that the key important parameters are the baseline level of R&D and the externality factor (e.g., the ratio of social to private returns to research).

Table 9.3 shows the impact of alternative specifications of these two key parameters on the rate of decline in the emissions/output ratio. For these calculations, we have used a reduced-form model rather than the full model because of the complexity of reestimating the parameters and rerunning the model. The central case is shown in the middle of the three-by-three matrix of numbers. It states that under the central assumptions, the decline in the emissions/output ratio from induced innovation is 0.13 percent per year over the first 10 periods. Looking at the columns to the left and right, we see what the impact of a higher or lower R&D/sales ratio is. If we have underestimated the current level of R&D on energy by 50 percent, then the impact of induced innovation will be to reduce the emissions rate by 0.19 rather than 0.13 percent per year. Reading vertically, we see that if the externality factor is 8 rather than 4, then the induced decline rate is 0.25 percent rather than 0.13 percent. Neither of these seems particularly likely. There is no evidence that the externality ratio is a factor of 8, and we believe that the R&D/output ratio of 2 percent is likely to be high when developing countries are included.

The last two lines of Table 9.3 put these sensitivity analyses into perspective. The first shows the projected decline in the baseline emissions/output ratio. The last line shows our estimate of the required *further* reduction in the emissions/output ratio necessary to stabilize emissions over the 21st century. According to our estimates, in the central case, induced innovation is likely to reduce emissions about one-eighth of the amount necessary to stabilize emissions. Even in the most optimistic case at the lower right, induced innovation will produce less than half of the amount required to stabilize emissions.

9.5 The US Program to Promote Climate-Friendly Technologies

9.5.1 The US program for induced innovation

In response to the Kyoto Protocol, the United States, under the Clinton administration, proposed both an undefined future program for emissions limitations and a current technological initiative to improve the carbon efficiency of energy use. The rationale of the program was described in the 1999 *Economic Report of the President*, which stated:

> [A]chieving climate change policy goals will require improving the energy efficiency of the economy. In addition to policies affecting energy prices directly, the Administration believes that a strong argument can be made for policies to stimulate innovation and diffusion through R&D and appropriate fiscal incentives. (Council of Economic Advisers 1999:206)

The administration's budget for fiscal year 2000 included US$4 billion in a Climate Change Technology Initiative (CCTI). This program was designed to provide fiscal incentives "offsetting in part the appropriability problems associated with [climate change] R&D" (Council of Economic Advisers 1999:207).

The CCTI for 2000 contained two kinds of programs:

- *Tax credits for low-carbon energy and energy efficiency* amounting to US$3.6 billion (although only US$0.4 billion is actually in the budget proposal). These credits are for fuel-efficient vehicles, solar equipment, energy-efficient building equipment and homes, biomass, and other similar investments.

- *R&D investments* for the major sectors (buildings, industry, transportation, and electric power) totaling US$1.4 billion.

These programs are not currently under consideration by the George W. Bush administration, but given the propensity of governments to propose these kinds of measures, it will be useful to analyze their impacts.

9.5.2 Analysis

It is difficult to analyze the CCTI because of the lack of programmatic detail and because we know relatively little about the rate of return on federal investments in this area. We will estimate the impact based on the following assumptions:

- The tax credits are generally ones to promote energy saving rather than carbon saving. We therefore assume that they reduce the energy/output ratio rather than the carbon/output ratio. For this purpose, we assume that one-half of the expenditures go to reducing carbon and one-half go to reducing capital and labor.
- The tax credits are assumed to have an impact of US$1 of increased investment per US$1 of federal outlay. This is a common finding in studies of the impact of investment tax credits. For modeling purposes, these are assumed to have no impact on induced innovation.
- Expenditures on federal R&D are assumed to have a social rate of return that is one-half that of the return on private R&D. While there is no firm evidence on this issue, the rationale for this assumption is that there is no "bottom line" check on federal research and that there are many examples of persistent waste in federal programs. Even with this assumption, the overall social rate of return is well above that of conventional investment.
- We assume that the investments continue at the same real level indefinitely.

9.5.3 Results

We have analyzed the CCTI by augmenting the baseline investment and R&D expenditures in the R&DICE model according to the assumptions made above. The investments are assumed to be carbon reducing with a normal rate of return, while the R&D component is assumed to be carbon saving with a rate of return one-half that of private R&D. We then solve the model with the augmented R&D expenditures.

The first result is that the US technology program is unlikely to have a major impact on emissions. According to our estimates, the program will reduce emissions by about 30 million tons per year over the next half century. The emissions reduction is far less than would be induced by optimal substitution or induced innovation (see Figure 9.10).

Figure 9.11 compares the impact on emissions from the US technology program with the emissions reductions called for under the Kyoto

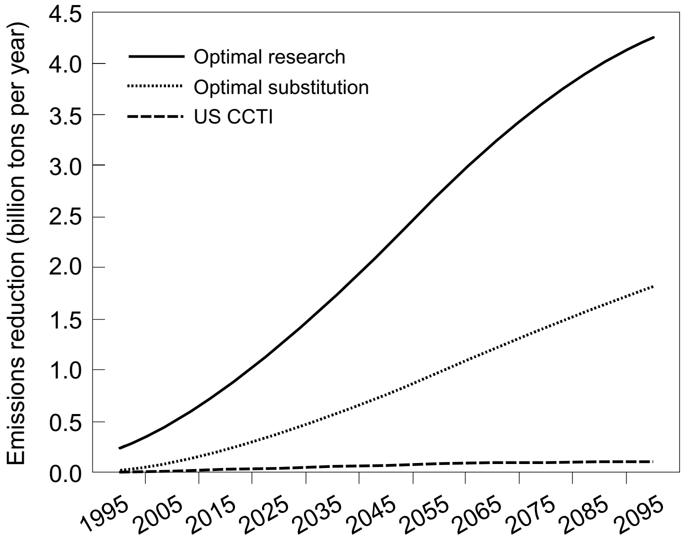

Figure 9.10. Comparison of Impact of US Technology Program with that of Other Policies on Global Emissions.

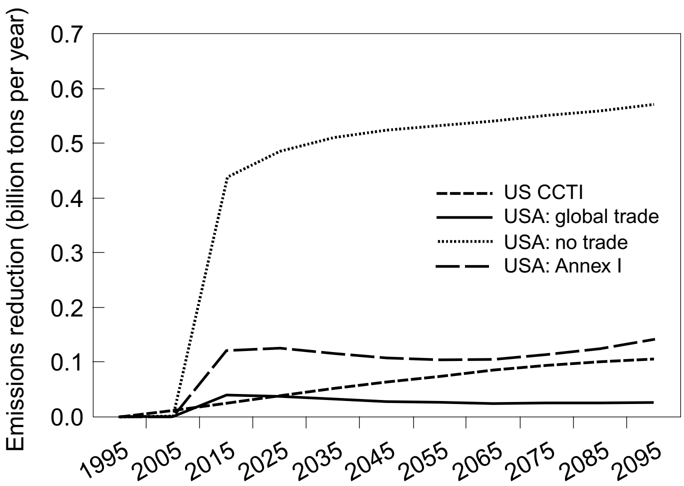

Figure 9.11. Comparison of Impact of US Technology Program with Emissions Reductions for the United States under the Kyoto Protocol.

Protocol.[10] The total emissions reductions (which would be required were there no emissions trading) is given by the upper line in Figure 9.11, while the lower two trading lines show the estimated US emissions reductions with Annex I trading and with global trading. The US technology program would lead to only a small fraction of the total US emissions reductions called for under the Kyoto Protocol—around 10 percent of scheduled total emissions reductions over the next century. However, the technology program is approximately the same order of magnitude as the emissions reductions under the trading programs. The reduction in global temperature from the CCTI after a century is estimated to be 0.006°C.

We should emphasize that these estimates are highly speculative and are likely to be quite optimistic. They rely on the assumption that the technology program would be effective in promoting efficient investments in low-carbon energy and technologies and in energy efficiency. Should the program turn out to be a wasteful pork-barrel program or become hung up on exotic pet projects, the emissions reductions would be much smaller or even negligible.

One final point is that the technology initiative is a relatively high-cost program. The discounted cost is US$150 per discounted ton of carbon (in 1990 prices), whereas we estimate that the same carbon benefits can be attained with an average cost of less than US$10 per ton carbon. This figure overestimates the costs, however, because approximately one-half of the benefits would come in reducing non-carbon inputs.

9.6 Conclusions

The primary conclusion of the present study is that induced innovation is likely to be a less powerful factor in implementing climate-change policies than substitution. A rough calculation is that the reductions in CO_2 concentrations and in global mean temperature resulting from induced innovation are approximately one-half those resulting from substitution.

All of this is a major surprise, at least to this author. But in hindsight, the results are intuitive. The primary reason for the small impact of induced innovation on the overall path of climate change is that the investments in inventive activity are too small to make a major difference unless the social returns to R&D are much larger than the already-supernormal returns. R&D is about 2 percent of output in the energy sector, while conventional investment is close to 30 percent of output. Even with supernormal returns, the small fraction devoted to research is unlikely to outweigh other investments.

What are the likely shortcomings in the model? One issue comes from the assumption of no substitution. If in fact substitution occurs, this would tend to reduce the value of induced innovation because the value of induced innovation would decline as non-carbon energy is substituted for carbon energy. A second issue lies in the oversimplified specification of the underlying technology. The R&DICE model assumes that carbon emissions and carbon energy are joint products, with no alternative fuels available. Hence, the possibility of using low-carbon fuels instead of high-carbon fuels is omitted. A richer specification of the technology would allow induced innovation in technologies that lower the carbon intensity of carbon-energy fuels. The difficulties of modeling this richer technology set are formidable, however, because of the lack of any data on which to base the innovation-possibility function. It is difficult to guess at the potential bias here, as the impact of induced innovation in this broader set of fuels could go either way.

If these results are confirmed for other models, they suggest our climate-change problem is unlikely to be solved by induced innovation. The interpretation is tricky, however. It definitely does not say that technology is unimportant. A technological miracle of a low-cost and environmentally benign backstop technology may indeed by just around the corner and put the climate-change worrywarts out of business. Rather, the proper interpretation is that we should not look to regulatory stringency or high emissions taxes as a way of forcing inventors to solve our global environmental problems. Necessity may indeed by the mother of invention, but there is limited payoff in inducing the delivery through regulations or high taxes.

Acknowledgments

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Notes

1. See also the extensive survey in Jorgenson (1996).

2. For a recent overview, see Ruttan (2001) as well as the related chapters in this volume.

3. One example of incorporating technological change in policy analysis is the work of Jorgenson and his colleagues; see, for example, Jorgenson and Wilcoxen (1991). See also Goulder and Schneider (1996) and Goulder and Mathai (1997). This literature is surveyed by Weyant and Olavson (1999) and by Clarke and Weyant (Chapter 3 in this volume). A major problem with current approaches is that in these models there is no

explicit linkage between innovation or technological change and inventive inputs.

4. For a discussion of this point and its implications, see Nordhaus (1984).

5. This approach is inspired by Arrow (1962).

6. Run-of-the-mill innovations are those that are sufficiently small that the price of the innovation is determined by the limit price rather than the monopoly price.

7. There is an extensive literature on this subject. In particular, Nelson (1959); Griliches (1973); Mansfield *et al*. (1975, 1977); National Science Board (1977); Nathan Associates (1978); Mansfield (1980, 1985); Pakes (1985); Jaffe (1986); Levin *et al*. (1987); Jaffe *et al*. (1993); and Hall (1995).

8. Strictly speaking, the two assumptions are equivalent if the rate of return is constant and if there is no depreciation of knowledge. Given the actual data and assumptions in the DICE model, using the precisely correct shadow price would lead to a time-varying factor between three and four. However, it does not seem fruitful to calculate the exact time-varying factor for the different depreciation rates.

9. Full documentation of the RICE-99 and DICE-99 models is provided in Nordhaus and Boyer (2000). The spreadsheet version of the model available on the Internet at http: //www.econ.yale.edu/∼nordhaus/home page/dicemodels.htm.

10. The estimates for the impact from the Kyoto Protocol are from Nordhaus and Boyer (1999).

Appendix 9.A
Definition of Variables for R&DICE Model

The variables are defined as follows. We have omitted certain obvious equations such as the capital balance equation and the definition of per capita consumption. In the listing, t always refers to time (t = 1990, 2000, ...).

Exogenous variables

$A(t)$ = level of technology
$E^L(t)$ = land-use CO_2 emissions
$L(t)$ = population at time t, also equal to labor inputs
$O(t)$ = radiative forcings of exogenous greenhouse gases
$Q^*(t)$ = gross world output
t = time

Parameters

β = marginal atmospheric retention ratio of CO_2 emissions
γ = elasticity of output with respect to capital
δ_K = rate of depreciation of the capital stock
λ = feedback parameter in climate model (inversely related to temperature-sensitivity coefficient)
$\rho(t)$ = pure rate of social time preference
θ_i = parameters of climate damage function
Ψ_i = parameters of innovation-possibility function
η_i = parameters of climate system
ϕ_i = parameters of carbon cycle

Endogenous variables

$C(t)$ = total consumption
$c(t)$ = per capita consumption
$D(t)$ = damage from greenhouse warming
$E(t)$ = carbon-energy inputs, also equal to industrial CO_2 emissions
$F(t)$ = radiative forcing from all greenhouse gas concentrations
$I(t)$ = investment
$K(t)$ = capital stock
$M_{AT}(t)$ = mass of CO_2 in atmosphere (deviation from pre-industrial level)
$M_{UP}(t)$ = mass of CO_2 in upper reservoir (deviation from pre-industrial level)
$M_{LO}(t)$ = mass of CO_2 in lower ocean (deviation from pre-industrial level)
$Q(t)$ = gross world product
$T_{UP}(t)$ = atmospheric temperature relative to base period
$T_{LO}(t)$ = deep ocean temperature relative to base period
$U(t) = U[c(t), L(t)]$ = utility of consumption
$\sigma(t)$ = industrial carbon/output ratio
$\Omega(t)$ = output scaling factor due to damages from climate change

Policy variables

$R(t)$ = R&D inputs into the carbon-energy sector (in induced-innovation approach)
$\mu(t)$ = control rate (in substitution approach)

Appendix 9.B
Equations of DICE-99 and R&DICE model

Objective function

$$\max_{\{c(t)\}} = \sum_t U[c(t), L(t)]\rho(t) = \sum_t L(t)\{\log[c(t)]\}\rho(t) \quad (0)$$

Production function

$$Q(t) = \Omega(t)A(t)K(t)^\gamma L(t)^{1-\gamma} \quad \text{(1-DICE)}$$
$$Q(t) = \Omega(t)Q^*(t) \quad \text{(1-R\&DICE)}$$

Consumption equals output less investment and production costs

$$C(t) = Q(t) - I(t) \quad \text{(2-DICE)}$$
$$C(t) = Q(t) - I(t) - 4R(t) - p(t)E(t) \quad \text{(2-R\&DICE)}$$

Capital accumulation

$$K(t) = (1 - \delta_K)K(t-1) + 10I(t-1) \quad \text{(3-DICE)}$$
$$K(t) \text{ exogenous} \quad \text{(3-DICE)}$$

Emissions

$$E(t) = [1 - \mu(t)]\sigma(t)A(t)K(t)^\gamma L(t)^{1-\gamma} + E^L(t) \quad \text{(4-DICE)}$$
$$E(t) = \sigma(t)Q^*(t) + E^L(t) \quad \text{(4-R\&DICE)}$$

Carbon intensity

$$\sigma(t) = \sigma(0)\exp(-\upsilon t) \quad \text{(5-DICE)}$$
$$[d\sigma(t)/dt]/\sigma(t) = \Psi_1 R(t)^{\Psi_2} - \Psi_3 \quad \text{(5-R\&DICE)}$$

Per capita consumption

$$c(t) = C(t)/L(t) \quad (6)$$

Carbon cycle

$$M_{AT}(t) = 10 \times E(t) + \phi_{11}M_{AT}(t-1) - \phi_{12}M_{AT}(t-1) + \phi_{21}M_{UP}(t-1) \quad \text{(7a)}$$
$$M_{UP}(t) = \phi_{22}M_{UP}(t-1) + \phi_{12}M_{AT}(t-1) - \phi_{21}M_{UP}(t-1) + \phi_{32}M_{LO}(t-1) - \phi_{23}M_{UP}(t-1) \quad \text{(7b)}$$
$$M_{LO}(t) = \phi_{33}M_{LO}(t-1) - \phi_{32}M_{LO}(t-1) + \phi_{23}M_{UP}(t-1) \quad \text{(7c)}$$

Radiative forcings

$$F(t) = \eta\{\log[M_{AT}(t)/M^*_{AT}]/\log(2)\} + O(t) \quad (8)$$

Climate equations

$$T_{UP}(t) = T_{UP}(t-1) + \eta_1\{F(t) - \lambda T_{UP}(t-1) - \eta_2[T_{UP}(t-1) - T_{LO}(t-1)]\} \quad \text{(9a)}$$
$$T_{LO}(t) = T_{LO}(t-1) + \eta_3[T_{UP}(t-1) - T_{LO}(t-1)] \quad \text{(9b)}$$

Damage equation

$$D(t) = \theta_1 T(t) + \theta_2 T(t)^2 \quad (10)$$

Damage parameter

$$\Omega(t) = [1 - b_1\mu(t)^2]/[1 + D(t)] \quad (11)$$

For those familiar with the DICE model, the major changes are in Equations (B.2), (B.5), (B.11), and (B.12) of the original model (see Nordhaus 1994).

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