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The effects of economic and policy incentives on carbon mitigation technologies

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Abstract

The ability to estimate the likely effects of potential climate change policies on energy use and greenhouse gas (GHG) emissions requires an improved understanding of the relationship between different policy alternatives and energy-saving and GHG-reducing changes in technology. A particularly important and understudied aspect of this set of issues is the conceptual and empirical modeling of how the various stages of technological change are interrelated, how they unfold over time in response to market forces, and the differential impact of various policies (for example, R&D subsidies, environmental taxes, information programs). We summarize several contributions to this literature and suggest promising areas for continued research on empirical analysis and modeling of induced technological change.

Keywords: Carbon dioxide; Emission reduction; Incentives; Technology; Policy

1. Introduction

Serious consideration is currently being given to a range of international and domestic policy actions to reduce carbon dioxide emissions due to their potentially damaging effects on the climate. Changes in carbon emissions can be driven by a number of factors, including changes in economic activity, energy use per unit of economic activity (energy efficiency), and the carbon intensity of energy used (carbon efficiency). Obviously, limiting economic activity as a means of reducing

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carbon emissions has scant political appeal for rich countries, let alone poor ones. Technological improvements that generate enhanced energy and carbon efficiency have therefore been the principal means discussed for addressing climate change. Recent policy proposals have included R&D funding, tax credits for the purchase of energy-efficient equipment, public–private partnerships aimed at developing and deploying energy-efficient technologies, carbon cap-and-trade systems, renewable-energy performance standards for electricity generation, and energy-efficiency standards for products. Broader policies under discussion–including a tradable carbon permit system or carbon emission fees–could have even greater effects on energy-related technologies.

An improved understanding of the relationships between market incentives, government policies, and technological change is therefore crucial for forecasting the baseline level of technology, its associated carbon emissions, and the likely magnitude, cost, and timing of emission reductions associated with alternative policies. In fact, different assumptions about baseline improvements in energy efficiency are often the single largest source of difference in predictions about the cost of achieving given climate policy objectives (Gaskins and Weyant, 1996).

In addition, public policies themselves can affect the rate and/or direction of technological change: by directly mandating characteristics of products that can be offered for sale (for example, through appliance efficiency standards) or that can be purchased and installed (local zoning requirements); by directly carrying out research and development activities at government laboratories or sponsoring them in the private sector; or by providing economic incentives through taxes, tradable permits, and other instruments that indirectly encourage the development and use of technologies with specific characteristics. In the present context, this last option refers to the possibility that higher (expected) energy prices will lead to the development and adoption of energy-consuming capital goods that are less energy-intensive in their use, a notion that is directly related to Hicks' (1932) induced innovation hypothesis.[1]

Economists who have studied technological change agree that the rate and direction of innovation is affected both by *exogenous* "technological opportunity" and by the *endogenous* expected rate of return to particular innovations (Schmookler, 1966; Rosenberg, 1982; Jaffe, 1988).[2] In the climate change context, much analysis of these issues has revolved around the extent to which changes in energy efficiency are induced by energy prices, and the extent to which energy efficiency improves "autonomously", or purely as a function of time.[3]

One can distinguish three steps or stages in the process by which a new, superior technology permeates the marketplace. *Invention* constitutes the first development of a scientifically or technically new product or process. Inventions may be patented, though many are not. Either way, most inventions never actually develop into an *innovation*, which is accomplished only when the

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[1] Discussions regarding global climate change policy reinforce the importance of the relationship between public policy and technological change. In U.S. Senate testimony, Janet Yellen, then Chair of the Council of Economic Advisers, commented on the difficulty of carrying out economic analysis of the Kyoto Protocol: "One area in which the uncertainty is particularly large is the pace of technological progress–including diffusion of existing energy-efficient technologies, as well as research and development of new technologies–and the extent to which the pace will accelerate in response to government programs" (Yellen, 1998).

[2] In some cases, the non-endogenous component of technological change has been characterized as an "autonomous" component. See, for example, Manne and Richels (1992).

[3] There has been much debate regarding the rate of "autonomous energy efficiency improvement" or AEEI (Manne and Richels, 1992) in integrated assessment models of climate change. The AEEI is measured as a residual; that is, it is defined to be the rate of improvement in energy efficiency that is not explained by other factors contained within a given model. Hence, the magnitude of the AEEI should be, by definition, a function of the particular model being employed. As several authors have noted, the results produced by integrated assessment models tend to be highly sensitive to the magnitude of the assumed AEEI (Gaskins and Weyant, 1996).

new product or process is commercialized, that is, made available on the market. A firm can innovate without ever inventing, if it identifies a previously existing technical idea that was never commercialized, and brings a product or process based on that idea to market. The invention and innovation stages are carried out primarily in private firms through a process that is broadly characterized as "research and development" (R&D). A successful innovation gradually earns a significant share of the purchases of firms or individuals, a process labeled *diffusion*. The cumulative economic or environmental impact of new technology results from all three of these stages, which we refer to collectively as the process of technological change.

For the purpose of modeling the interaction of energy use and climate change, however, there are two additional steps that mediate the impact of technological change on emission of greenhouse gases. If sales of new equipment were increasingly dominated by more efficient models, this would gradually increase the efficiency of the stock of equipment in use, a process we label *stock turnover*.[4] Finally, the efficiency of the stock of equipment in use will in turn affect how intensely people utilize the equipment. The (greenhouse-gas) efficiency of the existing stock, combined with the intensity with which it is used, determines the emissions of greenhouse gases.

Each of the elements of this process is limited by steps further back in the chain of technological change and also subject to technical limitations. Current greenhouse-gas efficiency is to a great extent constrained by the efficiency of the existing stock of equipment, subject to the level of utilization.[5] The efficiency of this year's stock is significantly determined by the efficiency of last year's stock, and only gradually affected by changes in the efficiency of new models being purchased. Diffusion of more efficient equipment into the sales of new models is limited by the menu of available products from which purchasers can chose. Innovation can change these offerings, but innovation is in turn limited by the feasible set of product models (that is, characteristics bundles) given by invention at a point in time. Invention is in turn limited by invention possibilities based on the costs of research and development, the availability of technical knowledge, and technical constraints such as physical limits to energy efficiency. Table 1 provides an overview of these relationships.

As an example, consider tradable carbon permits or taxes on carbon content which raise the price of fossil fuels.[6] Over a sufficiently long time horizon, such policies may be anticipated to have a number of effects. First, for any given stock of equipment or technologies, they may cause less energy to be consumed. Second, among the menu of equipment that is available, such policies will cause more efficient technologies (capital) to be chosen. Third, it is also possible that sufficiently strong carbon policies would induce greater investment of resources into the research and design of efficient machines, so that the efficiency of the *menu* of options from which people can choose in the market place is improved. These last two linkages refer to the potential endogeneity of technological change, and over the course of several decades or more, these invention, innovation, and diffusion effects are likely to dwarf any utilization effects.[7]

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[4] In many studies of technology diffusion, the word "diffusion" is used to encompass both the increasing sales of the new technology (what we have labeled diffusion), and its increasing share of equipment in use (what we have labeled stock turnover). This approach makes sense if the new technology is so superior to existing equipment that its availability causes many users to scrap existing equipment sooner than they otherwise would have and replace it with new equipment. In the case of much energy-using equipment, it seems more plausible that more efficient models will gradually replace existing models as those older models wear out and are eventually replaced.

[5] Short-run price elasticities of demand for energy are typically quite low, being estimated at about -0.1 to -0.2 (Bohi, 1981).

[6] See, for example, Nordhaus (1991), Jorgenson and Wilcoxen (1992), Goulder (1995), and Pizer (1999).

[7] Hogan and Jorgenson (1991) provide evidence that technological change could indeed overwhelm short-run substitution effects, even over the span of a few years.

Table 1
Interrelationships among technological change stages and incentives

Stage and key decision maker	Key influences	Taken as given	How measured?
Invention (inventing firm)	R&D costs, expected revenues, market share, royalties, non-pecuniary rewards	Invention/innovation possibilities and tradeoffs; expected diffusion	Patents, patent citations, characteristics of available products, tradeoffs among characteristics
Innovation (commercializing firm)	R&D costs, manufacturing costs, expected revenues, market share		
Diffusion (purchases) (user)	Capital and operating costs, product characteristics, exogenous "environmental" variables	Menu of available products, their characteristics, and tradeoffs; expected usage	Average characteristicsof new purchases, number or proportion of adopters
Stock turnover (user)	Growth in demand for energy services; depreciation of existing equipment	Distribution of characteristics in new purchases; previous stock	Average characteristics of stock of equipment, number or proportion of stock that incorporates new technology
Use (user)	Energy price, weather, final product demand	Characteristics of equipment stock	Units of energy use (e.g., hours, kW)

Large-scale simulation models used to model energy and carbon policies do not adequately treat the potential for endogenous energy-saving technological change. Rather, technological change is typically treated simply as a function of calendar time, which–assuming that the direction of technological change may in fact be price-responsive–makes the estimation results from such models sensitive to the time period studied, among other potential problems. As a result, policy-analytic forecasts from models that do not properly treat endogenous technological change are likely to misestimate the timing, cost, and extent of energy and carbon reductions associated with various public policies such as carbon taxes or tradable carbon permits (Popp, 2003).

The purpose of this paper is to summarize some recent research on the effects of government policies and economic incentives on the invention, innovation, and diffusion of mitigation technologies. In Section 2 we review empirical research on the influence of energy prices and regulatory policies on energy-efficient innovation. In Section 3 we summarize research on the influence of market and policy incentives on technology diffusion. Section 4 reviews the prospects for and integrated assessment modeling results regarding carbon capture and storage technologies. Section 5 offers some concluding remarks and suggestions for future research.

2. Price- and policy-induced innovation

A natural way to model induced technical change at the microeconomic level is to recognize that energy-saving technological change comes about largely through the introduction of new capital goods that embody improved energy efficiency, or energy input per unit of output. Energy efficiency can then be thought of as an attribute or characteristic of the capital goods. Newell (1997) and Newell, Jaffe, and Stavins (1999) examined the extent to which the energy efficiency of the menu of home appliances available for sale changed in response to energy prices between 1958 and 1993, using a model of induced innovation as changing characteristics of capital goods. Data were for hundreds of product models from the Sears catalogue and other publicly available data sources. Hicks formulated the induced innovation hypothesis in terms of factor prices. Newell et al. (1999) generalized this concept to include inducement by regulatory standards, such as labeling requirements that might increase the value of certain product characteristics by making consumers more aware of them. More generally, non-price regulatory constraints can fit within the inducement framework if they can be modeled as changing the shadow or implicit price that firms face in emitting pollutants. In their framework, the existing technology for making a given type of equipment at a point in time is identified in terms of vectors of characteristics (including cost of manufacture) that are feasible. The process of invention makes it possible to manufacture "models" (characteristics vectors) that were previously infeasible. Innovation means the offering for commercial sale of a model that was not previously offered for sale. Induced innovation is then represented as movements in the frontier of feasible models that reduce the cost of energy efficiency in terms of other attributes, as shown in Fig. 1.

By constructing a series of dynamic simulations, they examined the effects of energy price changes and efficiency standards on average efficiency of the menu of products over time. They found that a substantial amount of the improvement was what may be described as autonomous (that is, associated with the passage of time), but significant amounts of innovation were also due to changes in energy prices and changes in energy-efficiency standards. They found that technological change in air conditioners was actually biased against energy efficiency in the 1960s (when real energy prices were falling), but that this bias was reversed after the two energy shocks of the 1970s. In terms of the efficiency of the average model offered, they found that energy efficiency in 1993 would have been about one-quarter to one-half lower in air conditioners and gas water heaters, if energy prices had stayed at their 1973 levels, rather than following their historical path. Most of the response to energy price changes came within less than 5 years of those changes.

Newell, Jaffe, and Stavins have applied the same approach to investigate innovation in other important energy-using technologies, including farm tractors, which are representative of the general purpose internal combustion engine, and jet aircraft. There is an exceptionally rich array of data for

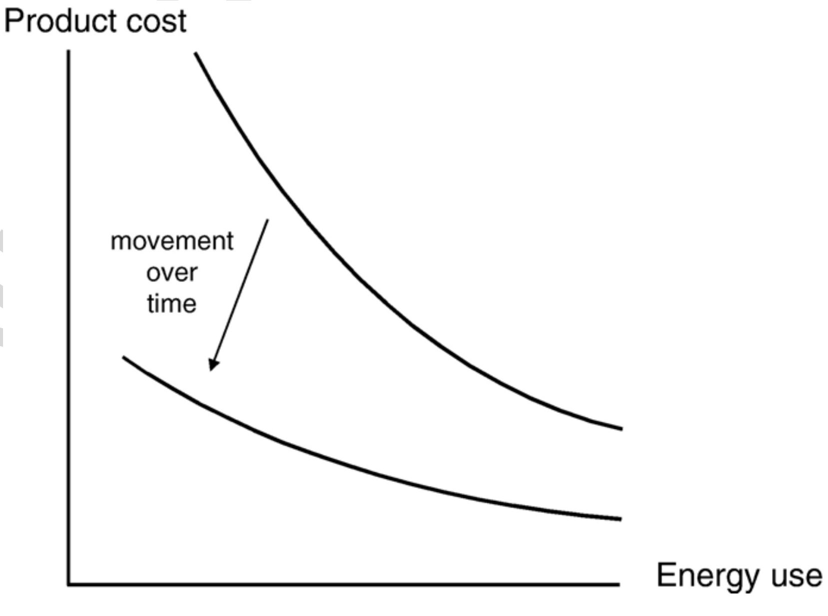

Fig. 1. Innovation in product characteristics.

farm tractors that spans over 80 years and across thousands of different product models and dozens of manufacturers. In prior research we found that the key information requirements for an investigation of induced energy-saving product innovation are data on product characteristics (e.g., horsepower and energy efficiency), purchase price, production costs, product output, and characteristics "prices" such as the price of energy (for energy efficiency) and the wage rate (for horsepower).

For the case of farm tractors, we constructed a database on product characteristics from the Nebraska Tractor Test Data reports (1920–1996), which have been conducted by the University of Nebraska for virtually every tractor model sold in the U.S. since 1920. The data set contains 1631 different models of wheel tractors from seven major manufacturers (Allis Chalmers, Case, Deere, Ford, International Harvester, Massie Ferguson, and White) and several other minor manufacturers spanning 78 years (1918–1995). The full data set has 5724 complete observations, with information on each tractor's test number, year tested, make, model, fuel type, energy efficiency, horsepower, and whether the tractor had a cab or four-wheel drive. We also employed data on the cost of tractor production, product output, energy prices, and farm wages.

Overall, the results are consistent with the economic interpretation of the parameters. The estimated elasticities for the various characteristics all have the expected signs and reasonable magnitudes; and the coefficient on cumulative production is negative, indicating positive technological change. The results confirm that the cost of durable goods increases with increasing energy efficiency, capacity, and other desirable characteristics, and that the cost of producing a given bundle of characteristics tends to fall with increased cumulative production experience as a result of technological change in production techniques and product design.

In addition, we found support for induced innovation in the tradeoffs between product cost, energy efficiency, and horsepower. That is, the slope of the technological frontier with respect to fuel efficiency was less negative during periods of higher energy prices, meaning that the elasticity of product cost with respect to energy flow is lower, or, equivalently, that the tradeoff at a point in time between production cost and energy efficiency has shifted so that energy efficiency is less expensive on the margin. The same was found to be true for horsepower with respect to changes in the real farm wage.

In addition, we found support for the existence of a "learning curve" in tractor production, as represented by a strong positive relationship between product cost reductions and cumulative output. Specifically, a 10% increase in cumulative production was associated with about a 7% decrease in quality-adjusted product cost. In fact, cumulative output proved to bear a clearer relationship to product cost reductions than did time, which is typically employed in analyses of technological change. Given the pervasive association between production experience and product costs found in the empirical literature, an important area of further research is the possible incorporation of learning effects into aggregate modeling efforts. This raises significant analytical and empirical challenges.

3. The influence of market and policy incentives on technology diffusion

3.1. Technology information programs

As policies that would entail significant energy price increases are unlikely to be politically attractive in the near term, the near-term focus in the United States has been on the development and diffusion of technology through other means. Thus, policy proposals have tended to emphasize programs that foster research, development, and deployment of technologies, government-industry partnerships, tax credits and other financial incentives, minimum appliance efficiency standards, voluntary agreements, and information programs.

Information programs, which seek to encourage energy efficiency by increasing awareness of conservation opportunities and offering technical assistance with their implementation, are an important element of this energy-efficiency policy portfolio. These programs take a variety of forms, including educational workshops and training programs for professionals, advertising, product labeling, and energy audits of manufacturing plants. In addition to alerting firms to profitable conservation opportunities, access to more accurate performance information can reduce the uncertainty and risk associated with adopting technologies that are new, or that receive differing reviews from equipment vendors, utilities, or consultants. The economic rationale for these programs lies primarily in public good aspects of knowledge and information provision. Although these public information programs are not free, the cumulative benefit of educating many users with similar information can greatly exceed the costs. Such information, however, tends to be under-provided by the private sector. Concerns about environmental externalities associated with energy production and use provide additional justification for these programs.

Despite the role that information programs play in existing and proposed energy-efficiency policy portfolios, surprisingly little is known about how participants respond to such programs. Although a reasonably large literature surveys various potential market barriers and market failures in energy-efficiency investment, few analyses have focused specifically on information programs. This is in part due to a lack of adequate data for analysis. One exception is Morgenstern and Al-Jurf (1999), who analyze data from the Department of Energy's 1992 Commercial Buildings Energy Consumption Survey. They find that information provided through demand-side-management utility programs appears to make a significant contribution to the diffusion of high-efficiency lighting in commercial buildings. Although not the focus of their examination of energy-saving product innovation, Newell et al. (1999) find that the responsiveness of energy-efficient innovation in home appliances to energy price changes increased substantially during the period after energy-efficiency product labeling was required.

Anderson and Newell (2004) focused on actions taken by manufacturing plants in response to energy audits offered through the U.S. Department of Energy's Industrial Assessment Centers (IAC) program, which has been providing energy assessments at no financial cost to small- and medium-sized manufacturers since 1976. This program is of interest for several reasons. First, significant opportunities to conserve energy may exist in the industrial sector, which represents 37% of total national energy consumption. Second, the opportunity to focus on the behavior of small- and medium-sized firms is rare due to data constraints, even though these firms represent over 98% of all manufacturing firms and more than 42% of total manufacturing energy consumption. This focus is particularly appropriate given that smaller firms are more likely to benefit from access to information and expertise, which tend to be more readily available to larger firms. Finally, the IAC program has generated an unusually extensive set of data on the characteristics of conservation opportunities identified and actions taken under the program. One attractive aspect of these data is that there are multiple observations available for each firm, allowing the use of a fixed effects model to control for unobserved differences in firms' propensities to adopt technology.

Because of their detail, these data provide a unique opportunity to quantify the factors that encourage small- and medium-sized industrial firms to invest in energy-conserving technologies. After summarizing the general character of projects adopted under the IAC program, Anderson and Newell (2004) explore the influence of technology costs, expected energy savings, and individual firm characteristics on the likelihood of adopting projects. They employ models of varying flexibility to examine and compare the degree of response to differences in capital costs and operating cost savings, as well as the energy price and quantity differences that underlie savings. The results strengthen our understanding of how certain factors influence technology adoption decisions, and whether this behavior is consistent with economic expectations. In addition, the results offer evidence on the likely relative effectiveness of policies aimed at increasing energy efficiency, such as energy or carbon price increases, technology subsidies, and policies that directly alter the energy use of technologies.

Another important aspect of this type of investment decision-making is the “payback cutoff,” “hurdle rate,” or other discounting factor that firms employ when measuring current costs against future benefits. The rate of discount used for climate policy analysis has huge implications on the results. There is a substantial literature that suggests that “implicit discount rates,” which one can calculate based on the capital cost versus operating cost savings of various implemented and unimplemented projects, can in practice be quite high relative to market interest rates (Hausman, 1979; Train, 1985). A related literature further contends that these high implicit discount rates are attributable to various market barriers and market failures–including information problems–and that these problems can be ameliorated by appropriate policies (Ruderman et al., 1987; also see Jaffe and Stavins, 1994).

Accordingly, several analyses of carbon mitigation costs have modeled the effect of information programs and other policies by significantly lowering the discount rate used for energy conservation decisions. The Clean Energy Futures study (Brown et al., 2001; Interlaboratory Working Group, 2000), for example, lowered investment hurdle rates to 15% in the industrial sector (and 7% in the residential sector) to capture the effect of information programs and other energy conservation policies. Such lowering of hurdle rates has the intended effect of decreasing estimated energy use in the model, but modeling the effect of information programs in this way also leads to a number of side effects. Lower hurdle rates also increase the rate at which energy use declines in response to energy price increases resulting, for example, from a carbon permit system or carbon tax. This implies a reduction in the cost of carbon mitigation efforts through carbon price policies.

By expanding the perceived range of investment opportunities available to firms, information programs may indeed lead to the adoption of profitable but previously unimplemented technologies, associated energy use reduction, and lower observed *implied* hurdle rates. But this does not imply an across-the-board reduction in the *actual* investment hurdle rate, which is unobserved and could remain at pre-policy levels. In other words, it is entirely possible that managers continue to apply hurdle rates well above market interest rates to the new set of possibilities brought forth by an information program. On the other hand, it is possible that information programs actually do significantly alter the way in which firms trade off the current costs and future benefits of all energy conservation opportunities, for example, by educating managers to focus more on the operating cost savings of projects.

Anderson and Newell explore these issues by examining the rates of return for potential projects faced by firms that participated in the IAC program to determine whether the level of implicit discounting used by plants that received information assistance may have decreased to levels that some studies suggest. Finally, they analyze the reasons given by firms for not adopting recommended projects in order to determine whether this decision is due to the economic undesirability of the projects, or to some remaining type of market barrier or failure.

They find that about half of the projects recommended by energy assessment teams are actually adopted by the plants receiving these recommendations, although they cannot say how many of these projects might have been adopted in the absence of the energy audit. They find that that firms respond as expected to marginal changes in the financial characteristics of projects (i.e., technology costs, energy prices, the quantity of energy saved, energy operating cost savings, and the payback period) (Fig. 2). Firms are about 40% more responsive to investment costs than to energy savings, suggesting that policies to reduce implementation costs may be somewhat more

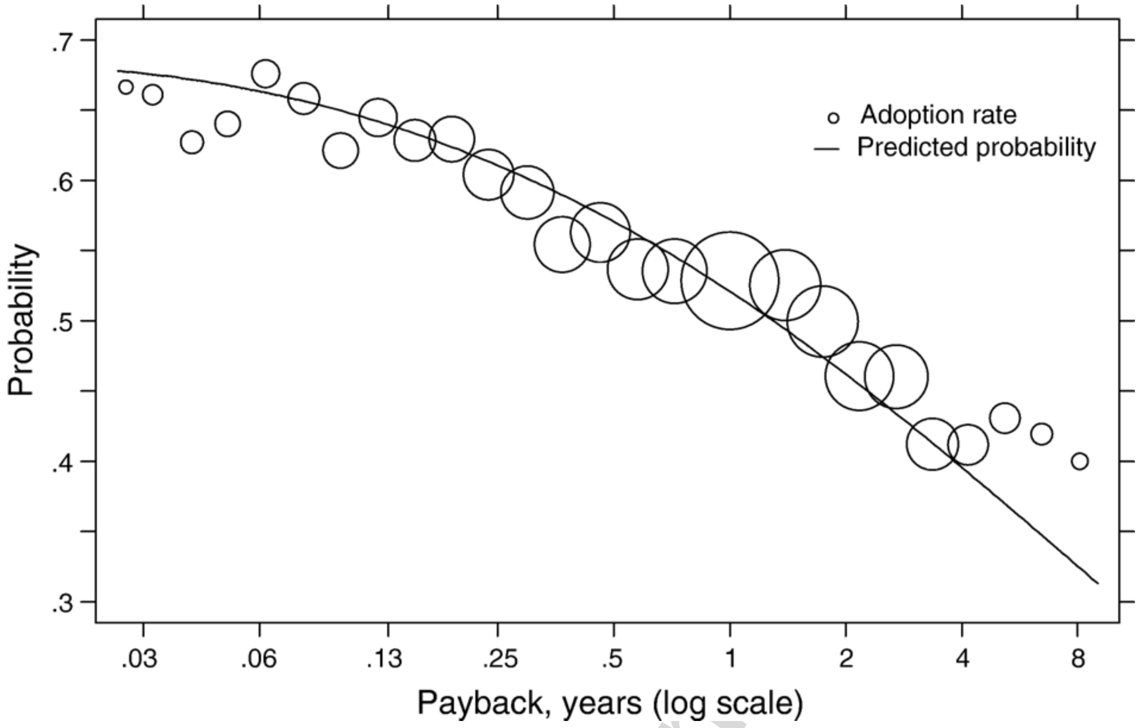

Fig. 2. Probability of adoption of energy efficient technologies versus payback. See Anderson and Newell (2004). Circles represent the observed adoption rates for fixed intervals of payback in log scale. The areas of the circles are proportional to the number of observations in each interval. The solid line is the predicted probability of adoption for estimated econometric model.

effective than various mechanisms that raise energy prices. Although the financial characteristics of projects are clearly important, there also appear to be other, unmeasured project-specific factors (e.g., individual project lifetimes, unmeasured costs and benefits, uncertainty regarding costs and benefits, or project complexity and risks) that influence the investment decision.

Anderson and Newell estimate that the investment threshold typically used by the plants in evaluating which energy audit recommendations to adopt was about a 1 to 2-year payback, which corresponds to an implicit hurdle rate of 50% to 100% for projects lasting 10 years or more. Although they are unable to determine whether participation in the IAC program actually lowered investment hurdle rates, these payback thresholds are consistent with what many surveys of plant managers suggest that they deliberately use for many types of investments, including those for energy conservation. In any event, these hurdle rates are many times higher than those assumed in many analyses of the effects of various climate policies.

Finally, the reasons given by program participants for not adopting certain project recommendations suggest that most of these disregarded projects may have been economically undesirable. Many of these reasons hint at various unmeasured costs, project risks, and uncertainty that are unlikely to be reflected in estimated implementation costs and projected annual savings. On the other hand, many projects were likely rejected because of institutional or bureaucratic barriers within firms, and most of the reasons are sufficiently vague that they cannot rule them out as indicative of institutional or bureaucratic barriers.

Overall, Anderson and Newell (2004) found that one can view the glass as either half full or half empty. Although the results suggest that the IAC program has led to the adoption of many financially attractive energy conservation projects, plants found about half of the projects recommended by assessment teams to be unattractive. This suggests that other, more costly policies targeted at increasing the financial attractiveness of these projects (e.g., energy/carbon taxes, or tax breaks/

subsidies for implementation) may be needed to further promote energy efficiency in these firms. Furthermore, it would seem that policies that could lengthen the short paybacks that firms routinely demand from all types of projects (not just those for energy efficiency) would have implications that extend well beyond the realm of energy and climate policy.

3.2. The influence of alternative policy instruments on technology diffusion

The theoretical literature has long recognized that alternative types of policy instruments can have significantly different effects on the rate and direction of technological change, typically finding that economic incentive-based instruments (e.g., pollution taxes and tradable pollution permits) can provide more efficient incentives for technology adoption than conventional regulations (e.g., technology and performance standards). Despite a reasonable amount of theoretical attention, little empirical evidence exists on the dynamic effects of environmental regulation, particularly with respect to the relative effects of alternative policy instruments. Kerr and Newell (2004) provide some of the first such evidence.

That paper reports a detailed empirical study of these issues for an important industry undergoing technological responses to a dramatic decrease in allowed pollution levels. While many are familiar with the success of the tradable permit system for sulfur dioxide, the phasedown of lead in gasoline by U.S. petroleum refineries during the 1970s and 1980s was the first major success in implementing a market-based environmental policy. Historically, lead was added to gasoline to inexpensively boost octane levels, but it also has serious side effects on human health. They assess the pattern of technology adoption by refineries during the lead phasedown, both across refineries and across time, with the intent of understanding how various economic incentives, market factors, and the stringency and form of regulation influenced this process.

Toward this end, Kerr and Newell (2004) develop a model of the technology adoption decision in the presence of regulation and derive an econometrically testable duration model. Their econometric approach is related to that taken by several applied industrial organization studies of technology adoption, although those studies do not assess the influence of regulation on the process of technological change. The model suggests that firms will gradually adopt the technology as its costs fall and increased regulatory stringency increases the value of adoption; firms with lower benefits or higher costs will adopt more slowly. They also test the proposition that there will be a divergence in the adoption propensities of low versus high compliance cost plants during periods with a tradable permit system versus an individually binding performance standard (Malueg, 1989). Plants with relatively low costs of compliance (i.e., sellers in a permit market) will have greater incentives for cost-saving technology adoption within a trading regime. At the same time, relatively high-cost plants (i.e., permit buyers) will have decreased adoption incentives under the permit system.

The intuition behind this latter proposition is that the tradable permit system encourages all plants to take action until their marginal cost of pollutant reduction equals the permit price, while the individual standard forces all plants to attain a fixed target. Sellers' incentives to adopt are higher under the permit system because they can undertake additional reductions and get extra profits by selling permits. The incentives to adopt would be lower for buyers under the permit system, however, since they can buy permits rather than being forced to self-comply with relatively expensive reductions. Thus, the tradable permit system provides incentives for *more efficient* adoption, but it can lower adoption incentives for some plants with high compliance costs. Under a nontradable performance standard, such opportunities for flexibility do not exist to the same degree. If plants face individually binding standards, they will be forced to take individual action–such as technology adoption–regardless of the cost, with the resultant inefficiency reflected in a divergence across plants in the marginal costs of pollution control.

They employ a unique panel data set on petroleum refineries covering the full period of the U.S. lead phasedown, which began with a requirement that new cars after 1974 use unleaded gasoline. This was followed by performance standards on lead in gasoline, a tradable permit market controlling the lead in leaded gasoline (1983–1987), ending with a more stringent performance standard and ultimately a ban in 1996. The adoption of pentane–hexane isomerization technology–a substitute for lead as a source of octane–was one of the major responses to the increased severity of regulation.

Kerr and Newell (2004) find that increased regulatory stringency (which raised the effective price of lead) encouraged greater adoption of lead-reducing technology. They also show that larger and more technically sophisticated refineries were more likely to adopt the new technology. Importantly, they further find that the tradable permit system provided incentives for more efficient technology adoption decisions. The relative adoption propensity of refineries with low versus high compliance costs was significantly greater under the tradable permit regime than under a nontradable performance standard.

4. Invention and innovation of unconventional technologies: the case of carbon capture and storage

Energy efficiency and low-carbon or renewable energy sources were once seen as the only realistic means to reduce carbon dioxide (CO_2) emissions. In recent years, however, analysts and policymakers have begun to recognize the potential for a third option. Carbon capture and storage (CCS) technologies would remove CO_2 emissions from large, stationary sources (e.g., power plant flue gases). Captured emissions would then be compressed and transported for storage in geologic reservoirs (e.g., saline aquifers or depleted oil wells) or the deep ocean. In contrast to indirect forms of sequestration (e.g., forestation or enhanced ocean uptake of CO_2), which absorb CO_2 from the atmosphere, CCS seeks to avoid atmospheric emissions altogether.

Recognizing this, policymakers have recently begun to view the potential for CCS with increased seriousness. For instance, the budget devoted by the U.S. Department of Energy to CCS research has increased from about $1 million in 1998 to $44 million in 2003, just 5 years later. Internationally, the IPCC recently convened a group of policymakers and experts to outline the structure of a future IPCC special report on CCS technologies. And just this February, the U.S. Department of Energy announced plans for FutureGen, a $1 billion project to build a prototype power plant that integrates hydrogen and electricity production from gasified coal with geologic storage of captured CO_2 emissions.

In a review of CCS technologies and related modeling results, Anderson and Newell (2004) examine the prospects for CCS in terms of its technical feasibility, cost, timing, ancillary environmental effects, and potential contribution to an overall climate policy portfolio. Given current experience with these technologies in the oil, gas, and other industries, they find that their application to carbon mitigation is already technically feasible. Experience with these technologies in the oil, gas, and other niche industries shows that their application to carbon mitigation is technically feasible.

The existing evidence also suggests that these technologies could be economically attractive, given sufficiently stringent climate policies. Niche industries such as natural gas and hydrogen production already produce pure streams of CO_2, which could be compressed and diverted to storage sites at relatively low costs (i.e., under $50/t C). In fact, natural gas production is the only known case in which CCS technologies have been applied for the sole purpose of emissions reduction. This and similar opportunities are, however, quite small. Recent estimates suggest that the application of CCS in the electric power and industrial sectors could significantly reduce total U.S. emissions at a current cost of about \$200/t C to \$250/t C avoided. This is within the range of estimated costs for domestic U.S. compliance with the Kyoto Protocol, and many expect that these costs could fall substantially with time and technological development. In addition, a rise in natural gas prices–as would likely occur with the onset of a price on carbon emissions–could also lower the carbon price at which CCS technologies become competitive.

Although CCS may be economic under stringent climate policies, a number of technical, environmental, and political issues arise with regard to transportation and storage of captured CO_2. Despite significant experience with storage of CO_2 and other substances in underground reservoirs, there is substantial uncertainty regarding how much CO_2 such reservoirs can hold, how long injected CO_2 would remain trapped, and whether injected CO_2 would escape from storage reservoirs to other formations. The effects of ocean storage are even more uncertain, raise additional environmental concerns, and are more likely to generate controversy. Storage of CO_2 as carbonates could lessen many of the concerns related to ocean storage but would generate other environmental concerns and would entail substantially higher storage costs. Finally, leakage from storage facilities would weaken CCS as a source of permanent emissions reductions, though CCS could still provide valuable temporary storage while less costly permanent means of mitigation are being developed (e.g., renewable energy sources).

Recent modeling efforts at MIT (McFarland et al., 2004), Carnegie Mellon University (Johnson and Keith, 2004), and Pacific Northwest National Laboratory (Edmonds et al., 2002) have examined the role of CCS technologies under various carbon policies. Although these models differ significantly in methodology and geographic scope, their CCS results are fairly consistent. CCS technologies are typically found to enter into significant use after 20 to 35 years at carbon prices of \$50/t C to \$100/t C (see Table 2). Also notable is the finding that IGCC (Integrated Gasification Combined Cycle) plants with CCS are surprisingly competitive in these models, eventually surpassing NGCC (Natural Gas Combined Cycle) as the dominant fossil fuel technology. These results appear to differ markedly from those presented above, which indicate that when NGCC plants without CCS are the relevant reference technology, CCS plants only become competitive at \$200/t C or higher.

There are two primary sources of this apparent inconsistency. First, these models assume that technological change will lower the cost of CCS by as much as one-third compared with our estimates above (David and Herzog, 2000). Second, and more importantly, these models all

Table 2
Key results for CCS costs in electricity sector from integrated modeling studies

Study, scenario, and timeframe	CCS technology	CCS price (\$/t C)	CCS entry year	Max share of electricity production, year
EPPA, global price of \$50/t C in 2010, rising to \$200/t C by 2040, 1995–2095	NGCC	100	2020	16%, 2040
	IGCC	100	2020	50%, 2100
CMU, \$150/t C applied across MAAC region, 2000–2040	NGCC	175	–	–
	IGCC	75	Immediate	35%, 2040
	PC retrofit	50	Immediate	10%, 2040
MiniCAM, stabilization at 550 ppmv, 1995–2095	NGCC	90	2020–2035	15%, 2095
	New PC	90	2020–2035	6%, 2095

MIT Emissions Prediction and Policy Analysis (EPPA) results are from McFarland et al. (2004). Carnegie Mellon University (CMU) results are from Johnson and Keith (2004). MiniCAM results from Pacific Northwest National Laboratory are from Edmonds et al. (2002). The \$175/t C entry price for NGCC plants in the CMU results represents the level at which NGCC would penetrate, where the 2000–2040 tax is higher than \$150/t C.

predict–either through endogenous modeling or exogenous assumptions–that gas prices will rise relative to coal during this century. As we discuss above, if the price of gas rises sufficiently, the relevant reference technology actually shifts from NGCC plants without capture to IGCC plants without capture, leading to a drop in the carbon price at which CCS technologies for IGCC plants become competitive.

Overall, the results of these studies suggest that fuel switching from coal to natural gas and energy efficiency improvements would provide the least costly options for moderate reductions in carbon emissions. Given sufficiently stringent carbon reduction targets, however, CCS technologies could play an important role in lowering mitigation costs. By allowing for the continued use of cheap coal at low effective rates of emissions, CCS technologies would provide a competitive alternative to costly renewable energy sources and fuel switching in the face of rising gas prices. Finally, CCS could capture significant quantities of CO_2 without exceeding most current estimates of probable storage capacity.

Several integrated assessment modeling studies suggest that CCS could play an important role in mitigating carbon emissions, conditional on policies that impose a sufficiently high implicit or explicit price on such emissions. The results indicate that fuel switching from coal to natural gas and energy efficiency improvements would be the least costly options for moderate reductions in emissions. For larger reductions and higher carbon prices, however, CCS substantially lowers mitigation costs. Assuming no barriers to implementation other than cost (i.e., ignoring political and environmental issues) and given certain assumptions (e.g., regarding fuel prices and energy demand), these studies suggest that a significant number of new plants with CCS would enter the power supply sector within the next few decades, though CCS retrofits could enter in just a few years given a sufficiently high price on emissions. The availability and use of CCS technologies would decrease reliance on renewable energy sources while encouraging electricity production to shift from natural gas to coal power. CCS would significantly reduce the present value of the cost of mitigation over time. Finally, CCS would result in the capture of significant quantities of CO_2 without exceeding most current storage capacity estimates.

5. Concluding remarks

An understanding of the process of technological change is important for economic analysis of climate change policy for two broad reasons. First, the environmental impact of social and economic activity is greatly affected by the rate and direction of technological change. This linkage occurs because new technologies may either create or mitigate pollution, and because many environmental problems and policy responses are evaluated over timeframes in which the cumulative impact of technological changes is likely to be large.

The importance of the first link is manifest in determining the economic and environmental "baseline" against which to measure the impacts of proposed policies. That is, before we can discuss what we should or should not do about some environmental problem, we need to forecast how severe the problem will be in the absence of any action. Such forecasts are always based, in some way, on extrapolation of historical experience. Within that historical experience, the processes of technological change have been operating, often with significant consequences for the severity of environmental impacts. Forecasts for the future based on this historical experience depend profoundly on the relative magnitude of the effects of price-induced technological change, learning-by-doing and learning-by-using, public sector R&D, and exogenous technical progress. Sorting out these influences with respect to environmentally relevant technologies and sectors poses a major modeling and empirical challenge.

A particularly important and understudied aspect of this set of issues is the conceptual and empirical modeling of how the various stages of technological change are interrelated, how they unfold over time, and the differential impact that various policies (for example, public-sector R&D, R&D subsidies to the private sector, environmental taxes, information programs) may have on each phase of technological change. There has been relatively little empirical analysis of these policy options directed specifically at the development of environmentally beneficial technology.

Looking forward, there are several promising areas for continued research on the modeling of induced technological change in CGE models:

- Further empirical analysis of the effects of alternative policy instruments on technological change, including non-carbon-price policies such as subsidies for technology adoption, R&D funding and tax incentives, information programs, renewable portfolio standards, and energy efficiency standards.
- Improved ability of assessment models to assess the effects of both price and non-price technology policies. This may require relaxing assumptions that the only relevant market failure is that related to the climate externality. In this regard, attention to knowledge spillovers and informational market failures may be necessary.
- Critical assessment and synthesis of the existing empirical literature on learning curves in energy technologies and new empirical research to avoid any pitfalls of previous studies and that can potentially be incorporated into computational models including those of an aggregate nature.
- Improved ability of assessment models to incorporate learning effects in an economically coherent manner.
- Empirical research on the degree of knowledge spillovers across different sectors and across national boundaries.
- Improved treatment by assessment models of technology spillovers and the opportunity cost of R&D directed toward carbon mitigation technology.
- Empirical research and improved incorporation into aggregate model of "nonconventional" mitigation technologies such as carbon capture and storage and renewable energy technologies.
- Empirical, analytical and numerical research on the treatment of long-term discounting in assessment models and its influence on technological change.

The potential long-run consequences of today's policy choices create a high priority for broadening and deepening our understanding of the effects of environmental policy on innovation and diffusion of new technology. Unfortunately, these issues cannot be resolved at a purely theoretical level, or on the basis of aggregate empirical analyses. For both benefit-cost and cost-effectiveness analysis, we need to know the *magnitudes* of these effects, and these magnitudes are likely to differ across markets, technologies, and institutional settings. Thus, taking seriously the notion of induced technological change and its consequences for environmental policy requires going beyond demonstration studies that test whether or not such effects exist, to carry out detailed analyses in a variety of sectors in order to understand the circumstances under which they are large or small. This will require significant research attention from multiple methodological viewpoints over an extended period of time. But the alternative is continuing to formulate public policies with significant economic and environmental consequences without being able to take into account what is going on "inside the black box" of technological change.

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