Issues in modeling induced technological change in energy, environmental, and climate policy

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This paper addresses the objective of including Induced Technological Change (ITC) in research and policy models of energy, environment, and climate change. Theoretical foundations, fundamentals, and current methodologies for ITC models are reviewed. In addition, limitations and possible extensions to ITC models are explored. Current approaches to energy–environmental modeling that neglect technological characteristics such as heterogeneity, uncertainty, and path-dependence are likely to underestimate both the impact and the lags in the effectiveness of policy options.

Keywords: climate policy, technological change, spillovers, innovation theory

1. Introduction

This paper addresses the objective of including endogenous technological change in research and policy models of energy, environment, and climate change. Almost everyone, researchers and policy makers alike, agrees that the response of technology to economic incentives over the coming decades may be crucially important in the design of appropriate energy and environmental policies. Unlike policy instruments alone that affect inputs, technology has the potential to change the underlying dynamics of the climate change system. Understanding endogenous technological change is important because policies will tend to affect the evolution of technologies and therefore the costs and benefits of policies and outcomes. Current approaches to energy–environmental modeling are likely to underestimate both the impact and the lags in the effectiveness of policy options.

Thus, questions about the optimal timing and stringency of greenhouse gas abatement policies have become more concerned with assumptions about exogenous technological change in the economic models. In addressing questions about the optimal timing of carbon abatement, Grubb et al. helped focus attention on the need to fully endogenize the rate and direction of technical change [16]. Since then, Goulder and Mathai, Goulder and Schneider, and Nordhaus have constructed climate policy models to examine the effects of including technological change endogenously [10,11,32].

The purpose of this paper is not to critically evaluate particular model findings or draw policy conclusions from them. Rather, it is to examine the methodology by which Induced Technological Change (ITC) is modeled and find both inherent modeling limitations and opportunities for improvement, drawing on insights from innovation and new growth literature. We do not attempt a comprehensive review of innovation literature – only a selective review to highlight relevant ideas and present distinctions important to ITC modeling. (A broader and more comprehensive survey of innovation literature relevant to ITC is given by Weyant; Carraro also reviews aspects of ITC modeling, particularly with regard to strategic gaming and geographic effects [5,44].) Since ITC modeling is at an early stage in development, this paper places emphasis on qualitative insights. A critical question concerns how much confidence we can expect to place in models of long-term technological change, and how much of the analysis should rest on the qualitative insights of policy and decision makers. The paper should be of interest both to integrated climate change and ITC modelers, as well as those drawing policy conclusions from these models.

The paper begins with a brief review of innovation literature to explore the context in which ITC models have been developed. Two elements make up the heart of models of innovation: (1) private investment incentives, and (2) spillovers from R&D. Particular attention is devoted to reviewing the notion of spillovers from R&D and distinguishing it from private investment incentives. Then, prominent examples of the state-of-the-art ITC models are reviewed, and generalizations are made about fundamental aspects common to all of them. The final section is devoted to exploring limitations and possible extensions to ITC models, such as complementary sources of technical change, heterogeneity of innovators, uncertainty in returns from R&D, and path-dependence and inertia. Besides suggesting possibilities for improvement, one of the key insights here is that induced change, as well as policy lags, may be much more significant if extensions from the conventional economic frameworks are considered. It is important to recognize, though, that the extensions are general improvements to exogenous models of technological change, and do not require a focus on ITC to be considered.

2. Theoretical background

The literature on innovation seeks to answer two questions. First, what are the nature and sources of innovation opportunities? Secondly, how do markets allocate resources to innovation opportunities, leading to new products and market structures? These questions are fundamental in endogenizing technical change. In addressing the questions, much of the theoretical literature focuses on the role of knowledge in innovation, particularly the appropriability of investment in knowledge and the subsequent spillovers. Sectoral studies and "appreciative" theory tend to focus more on institutional and environmental factors in innovation, which are central themes in section 6.

Conventional theoretical approaches to technological innovation may be broadly categorized into two types. First, we will refer to "innovation theory" as the general study of industrial innovation using standard economic concepts. Innovation theory studies how firms make profitable use of opportunities for technological change. The primary focus is on investment incentives leading up to innovation and the expected appropriability of innovations. The second category of conventional economic theorizing about technical change concerns growth at the macro level. Endogenous growth theory, or "new" growth theory, borrows insights from innovation theory, but its principal concern is with the spillovers following upon innovations and their potential to provide a source of long-term growth for the economy. The new growth theory models of technical change are farther abstractions from firm behavior than innovation theory, but they are more easily amenable to representing endogenous technical change in climate policy models.

2.1. Innovation theory

The main contributions of innovation theory have been to emphasize the private profit incentive as a key source of innovation and to draw attention to the complex and imperfect competition from which innovations arise. The origins of innovation theory, however, included Arrow's description of the primary resource for invention as technological information, which he characterized as freely available and generally applicable [2]. From Arrow's work emerged a consensus that basic science provides the technological paradigms or raw material for major cycles of innovation. Information about these major innovations is generally a public good, implying that the private sector will underinvest in this type of basic research. However, the innovation literature makes a useful distinction between technological breakthroughs and the resulting incremental product and process improvements. Since Arrow's early work, most innovation literature has focused on this second stage of the innovation process. Economic models of individual firms capture the second stage of incremental innovations. Innovation theory's principal concern has been to analyze the efforts of individual firms to develop and appropriate product technologies and to define markets for these products in order to maximize profits, rather than maximizing the rate or scope of innovation.

There evolved several notions of how firms allocated resources to innovation. The market pull theory of innovation, developed in Schmookler's 1966 work, hypothesized that major innovations created a new product frontier that was common knowledge [41]. Schmookler assumed that identifying and bringing to market innovative products under the new paradigm was straightforward, and the challenge to entrepreneurs was gauging and responding to market needs. Alternatively, the technology-push theory of innovation, stated formally and clearly by Rosenberg in 1976, hypothesized that production capacity evolves over time as the result of unpredictable product and process innovations [35]. This theory emphasized the uncertainty involved in innovation, though innovation activity was still represented exogenously and the focus was still on incremental improvements. By the 1980s the insights of Arrow, Schmookler, and Rosenberg had been digested. Economists confronted analytical barriers in trying to incorporate uncertainty in both market and technology, and shifted their focus to empirical work, defining what may be referred to as the market-definition or technology-appropriation theory of innovation. The primary new result of this generation of empirical work was the identification of the surprisingly large degree of appropriability of many product and process innovations. Instead of patents, the most commonly cited method of protecting innovations was reported to be a combination of learning curves, lead-time effects, and trade secrets.

Innovation theory, then, tells us that profit incentives account for a major source of innovative activity, largely because knowledge and technology are appropriable. Knowledge becomes embedded in people, capital, and organizations and thereby creates the profit incentive. However, appropriability also implies entry barriers and market inefficiencies from monopolistic behavior.

2.2. Endogenous growth theory

Endogenous growth theory has absorbed lessons from innovation theory about the appropriability of technology and knowledge. Traditional growth models expanded their scope from labor and capital to include human capital and technology. Innovation theory suggested both that technology could not be treated as a strictly public good and that human capital could not be treated as a strictly private one. Both had private aspects that created private incentives for their development and public aspects that generated positive externalities.

The new growth models, reviewed by Romer, Grossman and Helpman, and Jorgenson [14,20,34], no longer assume perfect competition or technology as a perfect public good. Purposive, profit-seeking investments in knowledge play a critical role in the long-run growth process. In particular, the non-appropriable aspects of the technology created by the profit-seeking firms, in the form of specialized human or physical capital, creates spillovers, or positive externalities. Positive externalities of this kind create increasing returns to scale and the prospect for steady long-run economic growth.

Because endogenous growth theory is still in a state of development, computable models based on it are not presently available. Still, the theory emphasizes the importance of spillovers in modeling technological change. From the premise that spillovers are a fundamental source of economic growth, it follows that any models of long-term technological change need to include spillovers as a fundamental ingredient.

3. Spillovers and ITC

While spillovers are generally recognized as a fundamental aspect of technological change and economic growth, they are talked about and measured in many different contexts. This section seeks to provide some clarity in discussions about spillovers and their incorporation in ITC modeling, beginning with a review of some empirical evidence for spillovers.

3.1. Spillovers and returns to R&D: Empirical evidence

Spillovers have been heralded as the key to answering whether new growth theories will allow the economy to escape the fate of diminishing returns, and any long-run model of ITC is incomplete without them. Empirical studies show that spillovers are significant in magnitude though difficult to measure and confined to sectors or regions. The precise definition of a spillover is also sometimes a source of difficulty, and more will be said on this later in this section.

Since spillovers are generally accepted as simply a positive externality from research and investment in knowledge, measurement has been problematic and varied. The type of spillover investigated is one source of difference. Some studies make the distinction between embodied R&D, where spillovers occur through intermediate or investment goods, but most studies focus on disembodied, knowledge spillovers. With knowledge spillovers, firms are typically modeled as having knowledge capital or “R&D capital” that is freely augmented by research from other firms. Empirical research can also be classified by which channels or mechanisms it assumes that R&D knowledge will “spill over”, and this is the major source of measurement difficulty. Spillovers may be assumed to be an unweighted function of other firm or industry R&D. More commonly, spillovers are modeled as weighted sums of other R&D by various means of measuring “distance” from the source to the recipient of the spillover. The major research questions remain measurement questions: how to measure output, whether the measures capture the contribution of R&D, and how “R&D capital” is constructed.

While outlining the measurement difficulties, Griliches still concludes that the studies do point to some general conclusions: R&D spillovers are present, may be quite large, with social rates significantly above private rates [12]. Sakurai et al. report that most spillover studies indicate private returns of 10–20% [40]. Looking at the different studies that have included outside R&D as a variable, Mohnen comes up with an average estimate of the excess of the social rate over the private rate of approximately 50–100% [25]. Interestingly, some studies find that the rate of return from outside R&D is higher than within industry R&D. This indicates that spillovers do not necessarily require the “first-order” assumption that the externality is larger in the home industry.

Empirical studies also suggest significant regional and sectoral variations in technological progress and how spillover externalities are distributed. A study by Kim and Lau indicates that technical progress (increased efficiency) has accounted for only a small part of economic growth in newly industrialized Asian “dragon” nations, but has been the most important factor in OECD countries’ recent growth [22]. Confirming this national variation, the Sakurai study finds that the average return to direct R&D is 15%, but the return varies greatly by country, with some as high as 40 and 50% in 1970s and 1980s. As far as the distribution of spillover externalities, there is some evidence for international spillovers, but smaller industrialized countries typically benefit most from international spillovers. Also, spillovers differ by sector. The Sakurai study found that embodied R&D was not important to TFP growth in manufacturing, but it had high social returns (130–190%) in the information and computer technology sector [40].

3.2. Different frameworks for thinking about spillovers

Beyond the measurement difficulties, spillovers are also difficult to grasp because innovation theory and endogenous growth theory approach the concept from different perspectives. Growth theory observes the economy at the macro-level, developing models to account for growth seen in the economy as a *consequence* of firm innovation. Fundamental to this accounting in the growth models is the notion of spillovers as strict positive externalities. As models develop more rigor, they are more explicit in modeling individual investment incentives of firms and how innovation come about, but the primary focus is still on spillovers as positive externalities. Innovation theory, on the other hand, begins with an examination of the firm at the micro-level, trying to capture its true behavior in a descriptive manner. The primary focus is on the appropriability of technology and knowledge and its implications for investment incentives *prior* to innovation. Spillovers are touched upon, but only insofar as they affect investment incentives. In innovation theory, spillovers may be said to raise investment incentives by providing more equal access to knowledge and lowering entry barriers, but they are also said to lower investment incentives since innovations are not fully appropriable. In this sense, the spillover is no longer a strictly positive externality. The different starting points for talking about spillovers can cause difficulties and misunderstandings when trying to model technological change in an integrated framework.

3.3. Spillovers as a heuristic modeling tool: A definition

It is our belief that the definition of spillovers in the ITC context should be kept plain and simple, in the style in which endogenous growth theory begins: *spillovers are any positive externality that results from purposeful investment in technological innovation or development*. The notion of spillovers, at least until empirical work sheds more light on the principles at work and more precisely defines the matter, principally concerns an observation of the consequences of innovation. In the current state-of-the-art, spillovers are a modeling and accounting convention describing macro-level observations, rather than a description of underlying mechanisms in innovation. Until empirical work has more to say about spillovers, we should accept such a broad and vague definition, and accept an artificial distinction between appropriability and spillovers. Models of firm behavior should focus on the expected appropriability of technology and knowledge in investment incentives. Spillovers can then be overlaid on models of investment behavior as “add-on”, strictly positive externality features. Thus, while it may be a worthy goal to explicitly model firm investment behavior with appropriability in mind, spillovers should still be modeled in a stylized, heuristic manner.

It is tempting to bridge the related notions of appropriability and spillovers as complementary pieces of the same pie, so that knowledge is either appropriated or “spilled over”. For example, Carraro discusses spillovers as having a direct effect of lowering marginal gains from innovations (reducing appropriability), and an indirect effect of a collective positive externality from private research. He discusses the difficulty of finding the net “sign” of the effect of the spillover parameter on R&D [5].

However, with our currently limited understanding of spillovers and consequently our broad and artificial definition, we suggest that bridging spillovers and appropriability in a model of innovation may add to confusion rather than clarity on the issue. First, the mechanisms behind spillovers are not observable; spillovers are after-the-fact measures in which we need somewhat artificial and subjective metrics. As such, spillovers are limited to aggregate level models of the innovation process. This is in contrast to investment incentives, which are based on more clearly observable and understandable mechanisms at the level of the firm. Secondly, the apportionment of knowledge ownership is not a zero sum game. Since there are many levels and mechanisms through which firms can benefit from the knowledge spilled over from others, models would be too restrictive if they strictly tied spillovers to appropriability. It is true that the magnitude of spillover externalities is influenced by the appropriability of the innovation, but their influence is not strictly limited by appropriability. Even the complete appropriation of an innovation may still result in positive externalities by expanding related markets or creating new innovation possibilities for other firms. For example, the development of increasingly complex and higher speed microprocessors by the semi-conductor industry has had a profound impact on the types of products offered by the telecommunications and computer industries. Thus, modelers should consider spillovers as different ways in which innovation and growth is accelerated – a catalyst added to the innovation process that is originally defined by investment incentives.

We are not saying that the ideas represented by spillovers are not relevant innovation incentives. On the contrary, past spillovers lower entry barriers and help establish firms’ positions within industries, and the prospect of certain types of spillovers related to appropriability may lower the incentive to invest. What we are saying is that, given the current state-of-the-art about knowledge spillovers, we should invoke spillovers as strictly positive externalities that result *from* previous investment decisions. The relevance of spillovers to making investment decisions should be accounted for by considering the firm’s innovation possibilities and the expected appropriability of the innovation, not by drawing on the notion of spillovers. This is a somewhat artificial distinction, but at this stage the definition of spillover itself is rather artificial. The distinction between models of “real” investment incentives and heuristic models of “artificial” spillovers will help alleviate misunderstanding and double counting in ITC modeling.

3.4. Distinctions

Even with the recognition that spillovers can as yet only be modeled in an “add-on” heuristic fashion, they are nonetheless fundamental to ITC models. They severely complicate analysis of past and the projection of future trends in technological change. It is important to recognize distinctions about the various forms and levels in which spillovers occur in order to decide what the ITC model should try to capture.

3.4.1. Form of spillover

The first set of distinctions concerns the form of the spillover, or the particular means in which a firm benefits from the knowledge and technology of others. The spillover form may be classified as either embodied or disembodied.

Embodied spillovers reduce the costs of intermediate inputs or investment goods or release new, enhanced, or reduced-cost resources to alternative uses. Griliches refers to embodied spillovers as “pecuniary” externalities from declining real prices [12]. He argues that their social product should be computable in principle from declining real factor prices, and that embodied spillovers are not really pure knowledge spillovers, and thus not really spillovers. Certainly, Griliches is correct in emphasizing that mere cost reductions are not necessarily positive externalities in competitive markets. But in fact the availability of new technologies may carry implications that go beyond mere cost reductions, as implied by the discussions in section 6 of strategic investment incentives and path-dependence. New or different goods may not only reduce another firms costs, but may change its production function or innovation opportunities. Again, the example of the microprocessor comes to mind. In this way, the knowledge "embodied" in the new or cheaper good does serve as a positive externality, even if firms only use the good as an input and do not directly exploit the new knowledge embedded in it.

A more subtle form of the embodied spillover may be deduced from Rosenberg's discussion of "forward" and "backward" linkages of the economy-wide impact of technological innovations [38, ch. 4]. Major innovations in one sector of the economy may spur innovations in related sectors. The growing market in the innovating sector spurs growth, and consequently innovation, in the related sector. We might call this form of embodied spillover a market spillover. If an equilibrium model already captures the related growth among sectors, though, this is not a spillover in the strict sense of being a positive externality from research. The externality in this case arises from market driven growth which spurs additional research.

Disembodied spillovers, referred to more loosely as knowledge spillovers, concern the impact of ideas on the research or development of others. The consequence of the knowledge spillover may simply be the imitation of a product or process, or the use of the idea in subsequent innovation. Romer describes one kind of knowledge spillover from industrial research: as firms develop new technologies, they sometimes make scientific discoveries with more general applicability [33]. Such discoveries may be difficult to patent or keep from the public domain. Grossman and Helpman describe another kind of knowledge spillover that may be characterized as a collective "learning by doing" effect: when innovators bring out successive generations of similar products, each begins where its predecessor left off [13, ch. 4]. This form of knowledge spillover is sometimes referred to as an intertemporal spillover. New or competing firms do not have to start from the ground up; rather, they can inspect the existing state-of-the-art products and extract from them much of the cumulative investment in knowledge.

Knowledge spillovers receive the majority of the focus in empirical and theoretical literature, since they offer the potential to allow the economy to grow without diminishing returns. As a non-rival (unlimited in distribution or ownership) and difficult to appropriate good, with time knowledge naturally disseminates from the innovator. In growth models, knowledge spillovers are typically incorporated in "quality ladders", where, to use Newton's metaphor, today's inventor's stand on the shoulders of giants that keep getting taller and never get old and weak. Examples are found in Caballero and Jaffe [4], who create such a modeling framework based on patents and citations to empirically assess knowledge spillovers, and Jones and Williams [19], who incorporate knowledge spillovers in a theoretical model of optimal investment in R&D.

3.4.2. Level of spillover

The second set of spillover distinctions concerns the level at which they occur: they may be intrasectoral or intersectoral, and they may be local or international. The variation in where the spillover occurs and who benefits greatly complicates the analysis of past returns to R&D and the assessment of future policy options.

Intrasectoral spillovers occur within a particular industry as firms benefit from the innovation and development activities of competitors. This direction of spillover is the most strongly influenced by appropriability. It is most vital in modeling the rate of endogenous change.

Intersectoral spillovers occur between industries, which may borrow products or ideas or be stimulated by developments in related fields. These types of spillovers are even more complicated to analyze. The industries do not necessarily need to be closely related in product classifications or purchase flows of input goods, as is sometimes assumed in empirical estimates. Intersectoral spillovers are not as vital to modeling the rate of technical change within an industry, but most important for assessing the economy-wide impacts of innovation. They are the most important reason why social rates of return to R&D are so much higher than private rates of return.

International spillovers work within and between sectors but also across national boundaries. International spillovers are just starting to be seen as a potentially positive feedback for R&D on environmental control technologies. For example, renewable energy technologies that are competitive in the markets of the OECD economies may also have large global benefits, allowing low-cost emissions reductions in developing countries. However, the empirical studies discussed above do provide evidence that many spillover externalities tend to be limited locally or nationally. A number of authors have suggested that nations may be limited in their capacity to exploit spillovers based on dynamic comparative advantage and their social capability [1,9,13]. Ruttan discusses research on the importance of factor-induced change in explaining different paths and rates of technical change between countries [39].

4. State-of-the-art ITC modeling

In investigating questions about innovation opportunities and resource allocation, the innovation and growth literature emphasizes two forces behind technical change. Technology evolves largely as a result of private investment incentives and appropriability of innovations, and it is spurred

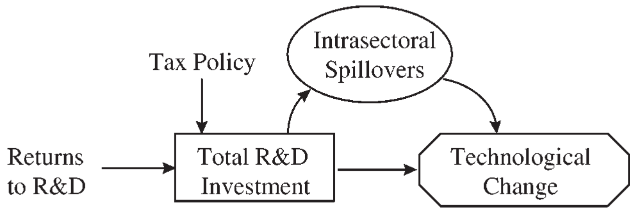

Figure 1. The linear, deterministic model of technical change capturing the essential investment incentive and spillover mechanisms suggested by innovation theory. The investment decision is influenced by exogenous, certain investment incentives (returns to R&D) and certain energy tax policies.

by spillovers, or positive externalities from these investments. Figure 1 summarizes this simplified, linear model of technical change as it is applied to energy and climate policy.

The dynamic in figure 1 is the focus of current state-of-the-art modeling methods for representing induced technological change, though the dynamic may be captured in very different ways. ITC models may be classified into three types: cost-function models, top–down macroeconomic models, and empirical models. The mechanisms, purposes, and strengths and weaknesses of each type is discussed below and summarized in table 1. The focus in this section is on reviewing current modeling methodologies and what they suggest about the importance of ITC – not on modeling extensions or particular policy implications. The significance of the various model characteristics in table 1 is discussed in sections 5 and 6.

4.1. Cost-function models with ITC

The "cost-function" model is a rather simple, crude, yet analytically tractable representation of induced technical change used to study the optimal timing of carbon abatement. The Goulder/Mathai set of models is a prime example [10]. Tol uses a similar modeling framework [43]. The models operate at a high level of abstraction, representing the cost of abatement in any time period as a function of the amount of abatement, as well as the amount of research or cumulative knowledge invested in carbon reduction technologies. Knowledge investment in each period is also costly. In an alternative formulation, Goulder/Mathai represent knowledge accumulation as "free", coming from learning-by-doing as a function of cumulative abatement. The objective is to minimize the discounted cost of abatement and investment with the constraint that carbon concentration always remains below a certain threshold. From basic assumptions about the first and second derivatives of the functions, some general conclusions can be made about the optimal timing of abatement and investment.

By assuming a central planner, this type of model sidesteps the issues of explicitly modeling investment incentives and appropriability. While grossly simplified, it is useful for challenging assumptions about the optimal timing of carbon abatement. Critical to this issue and neglected in the models, though, is the issue of path-dependence and inertia. Time lags are to be expected between research or investment and the actual reduction in carbon emissions. Also, even in such a simple representation of technical change restricted to studying the timing issue, we are reminded of the importance of uncertainty. The presence of low-probability, high-advance innovations in the "tail" of the innovation distribution would bias the result towards earlier abatement. This is especially important considering the long-term time frame of the model.

4.2. Empirical models of ITC

Another method of modeling induced technological change involves empirical observation of past responses to energy price and policy changes. Dowlatabadi and Oravetz study aggregate energy efficiency trends in the U.S. from 1954 to 1994 to construct a model of price induced energy efficiency [8]. They suggest that this model should be used in place of the AEEI parameter in other models. The best known and most complete empirical model of endogenous technical change is the Jorgenson and Wilcoxen (JW) model of responses of the U.S. economy to energy price changes, which they apply in studying the cost of abatement policies [21]. The basic model is a top–down general equilibrium framework, but the "input–output" coefficients are allowed to vary to implicitly capture the effects of induced technological change. The changes are based on extensive time-series data (1947–1985) of inter-industry transaction tables. Principally, by observing the two oil price shocks in the 1970s, JW are able to empirically model the input–output coefficients as a function of energy prices.

The advantage of this type of model is that it implicitly takes into account real world factors in technological change that are difficult to incorporate into conventional economic frameworks (see table 1). That is, they are observing the real thing, not modeling some simplified representation of it. All types and sources of short-term technical change, then, are included. One disadvantage of this aggregation, though, is that information about the underlying costs of R&D is lost. Thus, models are unable to evaluate optimal policies with full consideration of the costs of R&D. Another disadvantage is that the model is as limited as the data set from which it is constructed. Only one historical path can be observed, and it is assumed that tomorrow's economy will respond to energy price changes in the same way as yesterday's economy. Thus, long-term technological change is beyond the feasible reach of this type of model. "Long-term" here refers to periods in which substantial technological development, major innovations, or shifts in technology paths may occur. Since the turnover of most energy capital stock is less than 30–50 years [15], one can understand why JW limit their modeling projections to thirty years. One may question, though, if *any* of the ITC models should be asked to project technological change in the long-term without explicit treatment of uncertainty.

Table 1
ITC model characteristics.

	Goulder/Mathai	Goulder/Schneider	Nordhaus	Jorgenson/Wilcoxen
Model characteristic	Central planner decides carbon abatement or investment timing to minimize cost or maximize benefit	General equilibrium model of response to given carbon tax policy, with endogenous private R&D	Neoclassical growth model where central planner decides optimal tax policy, with endogenous private R&D	General equilibrium model of GDP cost of energy price increases, with tech. responses estimated empirically
ITC model type	Cost-function	Top–down	Top–down	Empirical
Source of tech. change (finance mechanism)				
Public R&D	No	No	No	Implicit
Private R&D: induced change	Implicit	Yes	Yes	Implicit
Spillovers (“free”)	Implicit	Yes	Yes	Implicit
Learning-by-doing (“free”)	Yes	No	No	Implicit
Type of tech. change (degree of discontinuity)				
Diffusion (low)	No	No	No	Implicit
Minor innovations (medium)	Yes	Yes	Yes	Implicit
Major innovations (high)	No	No	No	No
Dimension of tech. change				
Energy/carbon saving	Yes	Yes	Yes	Implicit
Cost reducing	No	Yes	No	Implicit
Extensions of economic framework				
Firm/industry heterogeniety	No	Yes	No	Yes
Strategic R&D incentives	No	No	No	Implicit
Inertia in tech. development	No	No	No	Implicit
Uncertainty in tech. change	No	No	No	No
Time frame	200 years	60 years	100 years	30 years

Nonetheless, empirical modeling of ITC may be valuable for short-term projections, or estimating the short-term cost of policies on the economy. Empirical models may also be valuable in comparing or calibrating short-term projections from other types of ITC models.

4.3. Top–down macroeconomic models with ITC

The most explicit and least abstract of the ITC models developed so far are the top–down macroeconomic representations. In this type of model, private innovation incentives are explicitly considered, and profit motives induce R&D changes as a response to energy price increases via carbon taxes. This formulation in the top–down model allows a rough estimate of how important ITC is in determining optimal policies. It has also proven to be valuable in highlighting the importance of limited R&D resources and the opportunity cost of R&D in the energy sector.

4.3.1. General equilibrium framework: Goulder and Schneider

Goulder and Schneider construct a general equilibrium model in which producers can invest in knowledge [11]. The economy is represented by several representative industries, with the notable distinctions between fossil-based and alternative fuels-based industries, and energy intensive materials and “other” materials industries. Each industry is modeled with a representative firm, which can reduce its input of intermediate goods by accumulating knowledge (technology). The accumulation of knowledge is costly and only partly appropriable. Intrasectoral spillovers are included in the model as an increasing returns effect in addition to the productivity gain from appropriable knowledge. A particular strength of this model is the distinction between alternative and fossil-based fuel industries, which allows the model to begin to address the importance of heterogeneity of firms and investment incentives. However, the model assumes that technological advance in the conventional fuels industry cannot be energy/carbon reducing, only productivity-improving. Thus, the carbon tax is represented as a flat tax on the output of the fossil-based fuels industry. That is, R&D in the conventional fuels industry will only contribute to *more* carbon emissions, not less, through cheaper dirty fuels. This aspect of the Goulder/Schneider model emphasizes the importance of fundamental assumptions about the alternative dimensions of technological advance.

4.3.2. Neoclassical growth framework: Nordhaus

Nordhaus builds on his DICE model [31] to create the R&DICE model [32], which incorporates ITC. The R&DICE model represents the economy in a neoclassical growth framework, in which output is a function of capital, labor, and energy. As with neoclassical growth models, a term $A(t)$ representing exogenous technological improvement is a multiplier on economic output. In addition, it is assumed that there is an initial rate of improvement in energy-efficiency, or a rate of reduction in the elasticity of output with respect to energy/carbon inputs. Endogenous technical change is incorporated by letting this rate of energy-efficiency improvement vary in proportion to the additional research invested in R&D in the energy sector. Thus, instead of assuming a generic cost function for reducing emissions, the mechanism of carbon abatement is through either energy-efficiency improving R&D, or factor substitution of capital inputs for energy inputs. The R&DICE model retains the simplicity and elegance of the DICE model by avoiding the endogenization of all technical change. Instead, just departures from the assumed path of energy-efficiency improvements are endogenized. This allows Nordhaus to isolate the effects of ITC in the energy sector by comparing his DICE and R&DICE results. This approach not only provides insightful results, but also emphasizes that endogenizing technical change in the energy industry is only one of many aspects in which exogenous assumptions can be improved. Incorporating ITC advances one frontier in modeling technology, but leaves many others untouched. Nordhaus recognizes that including ITC is not an ambitious effort to "get technology right" in economic models, but rather making a small step towards better understanding technical change in the energy sector.

In this framework, the model is used to evaluate optimal abatement and tax policies. As with the DICE model, the R&DICE model includes a compact climate change model that translates energy outputs into a damage function reducing total output, and thus per capita consumption. The objective of the model is to maximize the discounted per capita consumption, with the decision variables being per period capital investment, energy R&D, and carbon tax. An important constraint is the opportunity cost of R&D. On the one hand, spillovers are implicitly accounted for by assuming a 50% social rate of return on energy/carbon saving R&D. On the other hand, since R&D resources are limited and costly, the high rate of return to R&D also implies a high opportunity cost of redirecting R&D from other industries to the energy industry.

4.4. Importance of ITC: Conclusions from state-of-the-art models

From the work done with the above models, we can draw some preliminary conclusions about the importance of including ITC in economic models of climate policy. ITC here is understood strictly as endogenizing R&D investment through private incentives, and does not include all the other extensions of technology modeling considered in section 6 below. In general, these early models of ITC do not yet make a strong case for a lower cost of optimal abatement, different optimal carbon taxes, or changes in the optimal timing of abatement. While technological change is still a critical factor in evaluating climate policy, the effects of ITC in models are tempered by offsetting forces and the opportunity cost of R&D.

The Goulder/Mathai cost-function model offers some first-cut generalizations about the importance of ITC in optimal timing of abatement. In general, including ITC may overturn the assumption that postponing abatement is justified. In models with exogenous technical change (e.g., [45]) postponement may be justified, since abatement will be cheaper the longer we wait – even though there is more to abate to reach the same level of cumulative carbon emissions. With ITC, this effect is offset by the stimulus to technology development if some abatement is done early. Still, the net effect is rather ambiguous and does not allow strong conclusions about optimal timing.

The Goulder/Schneider general equilibrium model suggests that including ITC can significantly improve the benefits but not the costs from a given policy. Abatement is not free with endogenously stimulated technology. They find that ITC increases the elasticity of the economy to carbon taxes, so that a given tax leads to larger gross costs, but also larger net benefits. The effects are significant: the GDP sacrifice to achieve the same cumulative abatement is 25% lower with the presence of ITC than without it. However, the higher costs with ITC are a consequence of the opportunity cost of redirecting limited R&D resources to the energy industry. In the model, more than half the GDP cost is from the opportunity cost of R&D devoted to ITC.

The Nordhaus neoclassical growth model also offers insight into the influence of ITC on emissions reductions and technological change. Like the Goulder/Schneider model, Nordhaus finds that the opportunity cost of R&D severely restricts the influence of ITC. In the Nordhaus model, though, the effect is so strong as to make the influence of ITC insignificant. The effect of the induced innovation is to increase energy R&D by less than 2% per decade, reduce the carbon-output ratio by 0.0075% per decade, and reduce the energy–carbon intensity in 2100 by about 0.5% relative to the base path. The key finding is that, due to the costliness of R&D, the effects of substitution of labor and capital for energy swamp the effects of induced innovation. The substitution impacts on demand and supply are responsible for approximately 99% of changes in emissions, concentrations, and temperature change. Again, this does not imply that technological change is unimportant; rather, the isolated effects of the additional, induced technological change are severely restricted.

5. Fundamentals of modeling induced technological change

In reviewing the different ITC models, we may generalize about assumptions that are fundamental to all of them. Whether implicitly or explicitly, all models of ITC address three central features of technological change: (1) investment incentives, (2) spillovers, and (3) characteristics of technological advance. In drawing conclusions about the importance of ITC, we must keep in mind basic assumptions about these features, as well as recognizing important extensions beyond the basic mechanisms (section 6).

5.1. Investment incentives

While it may seem obvious, every ITC model must represent some incentive to induce technical change. This may come in the form of profits from innovations, as in the top–down models. Or, it may be represented at a more aggregate and abstract level, by means of cost-functions, R&D production functions, or empirical estimates. Similarly, the decision maker may either be decentralized industries or representative firms, or it may be a central planner.

Regardless of the model type and investment mechanism chosen, it seems wise to limit to endogenous component of technical change to the energy industry. In top–down models that consider more than the energy industry, this allows greater flexibility and depth in the treatment of ITC. In growth-oriented models, exogenous change in non-energy related technology should still be included.

5.2. Intrasectoral spillovers

Intrasectoral, knowledge spillovers are another essential feature in modeling ITC. It is important to recognize that while the level of investment may be determined by direct investment incentives, the rate of innovation may far exceed that implied by direct investment alone. This basic observation from innovation and growth theory is especially pertinent to models that assume R&D investment based on deterministic payoff functions. Without an allowance for spillovers, or "free" progress above and beyond immediate returns to R&D, the model will either (1) underestimate the rate of innovation (if spillovers are neglected entirely), or (2) overestimate the level of R&D spending (if public and private returns to R&D are considered in the same function). A shortcoming of the cost-function-type models, as in Goulder/Mathai, is that this distinction between public and private returns cannot be made. A central planner decides the amount of investment, and spillovers are implicitly considered in the total cost reduction. Alternatively, top–down models, particularly general equilibrium models like Goulder/Schneider, as particularly well suited to incorporate spillover relationships.

Our limited understanding of spillovers forces us to accept two modeling limitations. First, spillovers should be considered as a heuristic modeling mechanism to account for externalities from research. Spillovers should not be explicitly tied to appropriability and investment incentives in a sort of zero-sum equation, but rather tacked onto models of innovation incentives and appropriability. Second, ITC models should focus on changes in energy technology. Models trying to include the complex interrelations between energy technology and other technologies would likely be too cumbersome or abstract to be of any value.

While intrasectoral, knowledge spillovers are fundamental, we saw in section 3 that there are numerous other dimensions to the forms and levels of spillovers: embodied vs. knowledge, intrasectoral vs. intersectoral, regional vs. international. How essential are these? While not fundamental to ITC modeling, they are important to keep in mind. First, spillovers may be limited to geographic regions more than they are international. The international dimension suggests caution in drawing conclusions from global models that are sensitive to spillovers. Also, the work of Sakurai et al. suggests that the magnitude of spillovers varies considerably between sectors [40]. If models are sensitive to spillover assumptions, further work should be directed to studying the relative magnitudes of spillovers within the energy sector. Second, intersectoral spillovers may benefit firms outside the energy industry. We have recommended that ITC models focus on change in energy technologies, but it is important to realize that improvements in energy technology may benefit research in other fields. Intersectoral knowledge spillovers from energy research may be negligible, but given the importance of energy in the economy, embodied intersectoral spillovers are important. That is, falling energy prices benefits the economy as a whole. Top–down general equilibrium models, such as Goulder/Schneider or Jorgenson/Wilcoxen, are best positioned to address the important issue of embodied, intersectoral spillovers. This type of spillover is important for a complete cost–benefit analysis or optimization of policies.

5.3. Characteristics of technological advance

A third fundamental feature in ITC models is the dimension in which technological change is assumed to progress. Kline and Rosenberg emphasize that there is no simple, single measure or dimensionality to innovation [23]. We might think of innovations as new products or processes, substitution of inputs, or reorganization of production and distribution arrangements.

With regard to energy, we might simplify technical advance into two basic dimensions: cost reducing or energy/carbon saving. The distinction underlies vital modeling assumptions. Cost reducing change makes the producer more efficient, and is likely to increase the volume of product sold. If the product is clean energy, the first-order effect is to reduce carbon emissions, but if the product is fossil-fuel-based energy, the first-order effect is to *increase* carbon emissions. Energy/carbon saving change, on the other hand, will clearly reduce carbon emissions. The Goulder/Schneider model is the only one to consider both types of change, though energy/carbon saving change is not considered explicitly. In this model, the trick around the problem is to model both a conventional energy industry and an alternative energy industry. Though technology is not allowed to change along the energy/carbon saving dimension in either industry, cost reduction is possible in both. Resulting growth in the alternative energy industry may be interpreted as improvements in energy-efficiency.

At a deeper level, it may also be worthwhile to consider that energy/carbon saving improvements may come from two different sources: decarbonization of energy services and reduction in energy intensity of economic activities. The second source of technical advance is much more troublesome to incorporate in ITC models, since it requires consideration of R&D efforts in sectors outside the energy industry. For example, one might miss improvements in transportation technology that reduce energy requirements. We suggested earlier that endogenizing technical change across all industries might be too ambitious in a long-term model. Thus, ITC models may need to incorporate not only exogenous non-energy technology improvements, but also exogenous improvements in certain characteristics of energy technology.

A recent empirical study of the energy sector by Newell, Jaffe, and Stavins emphasizes the importance of considering the multiple dimensions of technological change [30]. Using data from 1958 to 1993, the authors analyze data on room air conditioners, central air conditioners, and gas water heaters to estimate the cost-reduction and energy-efficiency characteristics of technical change. These characteristics may advance through "proportional" or "non-proportional" innovation, depending on the differences in the rates of change in each characteristic. The authors find evidence that the large cumulative energy efficiency improvement that occurred over a span of three decades in the products examined consisted of large components of proportional improvement in technologies, combined with non-proportional components that favored cost reduction in the early years and energy efficiency in later years. Moreover, the direction of change was found to respond significantly to the economic and regulatory environment. The authors empirically estimate the different impacts of prices, labeling requirements, and standards on energy efficiency, finding that each of these instruments had noticeable effects. In the last two decades, fully one-fifth to two-fifths of efficiency improvements were found to be induced by historical changes in energy prices. Still, a large proportion of innovation was found to be "exogenous", or proportional improvement independent of energy prices and regulations. The lesson here is twofold: (1) technological characteristics may advance at different rates, with significant influence from "endogenous" factors, and (2) a significant component of technical advance is "exogenous". Thus, ITC models should consider multiple dimensions of change, but also realize that all technological change is not likely to be captured by endogenous factors. An important question to consider in modeling is how responsive each characteristic is to price and policy. Some types of change may be more easily stimulated than others.

6. Extensions and limitations of ITC modeling

One of the main conclusions to come out of this review of ITC modeling is that modeling technological change endogenously through private investment incentives is only one small piece of the solution to exogenous modeling assumptions. Furthermore, modeling endogenous change is challenging, if not inherently limited in application, due to the dynamic, uncertain, heterogeneous, context-sensitive, and path-dependent nature of technological change. This section, drawing on "appreciative theory" beyond classical equilibrium economics, seeks to understand which extensions of the linear, deterministic model in figure 1 are most helpful in improving upon exogenous models of technological change. The most important extensions of ITC models involve:

- complementary sources of technological change,
- heterogeneity in innovators,
- uncertainty and discontinuity in technological change,
- path-dependence and inertia.

Figure 2 proposes a more complete framework for thinking about induced technological change in the private sector. Though models may not be able to incorporate all the extensions and limitations discussed below, the factors are nonetheless critical in the formulation and analysis process.

6.1. Sources of technical change: Complements to ITC

When economists speak of endogenizing technical change in growth models or ITC models, they most likely mean trying to capture private innovation incentives, as in figure 1. Figure 2 emphasizes that ITC involves more than certain, deterministic financial investment. But it also emphasizes that ITC is only one component of change, and there are significant outside sources of change that are exogenous to ITC as it is defined here.

Moreover, the outside sources of change may have complex complementary or feedback relationships with ITC. For example, Hayami and Ruttan show that public sector agriculture R&D was also induced by differences and changes in relative factor endowments (and prices) [18]. They then go on to consider induced institutional changes. It is important to recognize these relationships between "outside" sources of change and ITC in the private sector. It is also important not to narrowly focus on ITC as the only source of technical change.

Having noted that "outside" sources of technical change may also be induced, it is important to recognize them as sources and opportunities for technical change in their own right. Modelers cannot focus on ITC, or change inspired by profit incentives, as the only source of technical change. First, *spillovers from public R&D* may have significant impact on technology characteristics. ITC as defined here in the private profit incentive context says nothing about the public policy aspect of technology investment. Given the path that innovation theory has taken and from which ITC models have sprung, it is easy to neglect public policy sources of change when analyzing models – innovation literature has focused on *private* knowledge investment. But in fact, publicly financed basic research as well as subsidies to private R&D have been discussed as central pieces of near-term climate change policy. Second, as discussed in sections 3 and 5.2, *intersectoral spillovers* may influence the pace of impact of technological change, whether "induced" or not. For example, metallurgical improvements

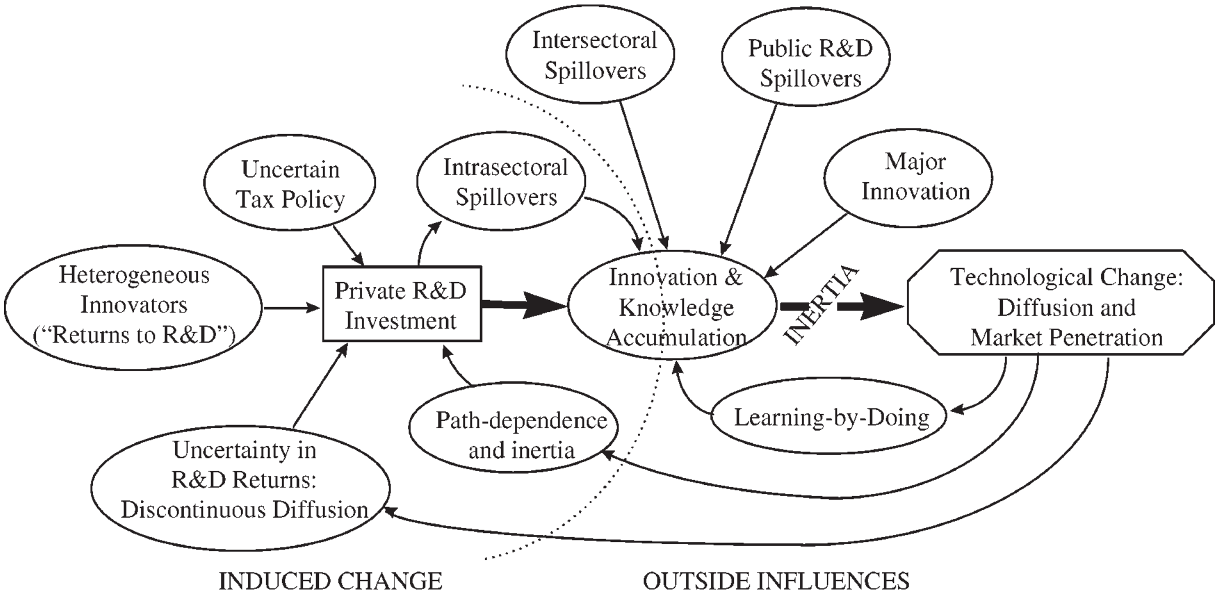

Figure 2. A more complete framework for interpreting and analyzing technical change. Important features of this framework are that private investment incentives, or "induced" changes, are heterogeneous and act under uncertainty, and they are only one of several sources of change. Still, ITC can be influential and interact with other sources of change in important ways.

in this century have made possible gradual improvements in electric power generation by allowing a steady rise in operating temperatures and pressures. Such as source of change is not well represented by profit-seeking investment by the energy sector. A third "outside" source of technical change is groundbreaking, *major innovations*, as from basic scientific research. The extent to which such breakthroughs respond to economic incentives is open to question. More will be said on this factor later in the context of uncertainty.

A fourth "outside" source of technical change is *learning-by-doing*, which Arrow first emphasized in his 1962 article "The Economic Implications of Learning by Doing". Nakicenovic [27] discusses the importance of learning by doing in energy technology, and Messner endogenizes the learning process in energy models [24]. But don't models of ITC address endogenous learning, if anything? No. At its core, ITC is concerned with learning as a result of costly, conscious investment decisions. Learning-by-doing is a happy consequence of those investments, in which learning essentially comes "free" as a result of cumulative experience with new technologies. Learning-by-doing typically refers to reductions in production cost, in which learning takes place on the shop floor through day-to-day operations, not in the R&D lab. The learning-by-doing component of change is significant, too. Kline and Rosenberg discuss industry studies that indicate that learning-by-doing type improvements to processes in some cases contribute more to technological progress than the initial process development itself [23].

Discussion of "learning-by-doing" gives us reason to pause and consider what we mean by research in the first place. Certainly learning-by-doing consequences of routine activities are not research, but on the other hand investment in research should not be interpreted strictly as emanating from an R&D lab. In fact, Kline and Rosenberg argue that the notion that innovation is initiated by research of the scientific sort is wrong most of the time [23]. Innovations evolve through cycles of design, testing, production, and marketing, all of which may draw on states-of-the-art in knowledge and interact with research initiatives. But most ITC models consider technical change a result of investment in "research". We should remember that research here is broadly defined as any additional investment targeted specifically at technological change. Thus, projects to design new energy products or processes are classified as "research", but learning-by-doing is not.

6.2. Heterogeneity in innovators

Besides considering ITC in the context of "outside" sources of technical change, there are important extensions to the ITC models themselves. The first such extension concerns the heterogeneity of firms and nations and their strategic investment incentives. By modeling private sector behavior with "representative" firms or industries, models of ITC may miss important dynamics between firms that arise due to their inherent organizational and strategic differences.

6.2.1. Heterogeneity in firm behavior: Evolutionary and strategic perspectives

The importance of accounting for differences in firm behavior is highlighted well by evolutionary models [28,29]. Evolutionary models of economic growth all draw their inspiration from the process of "creative destruction" outlined by Joseph Schumpeter over fifty years ago in *Capitalism, Socialism and Democracy*. Firms come and go in a "perennial gale of creative destruction" – the problem is not how capitalism administers existing structures, but how it creates and destroys them. The neoclassical focus on the general equilibrium allocation of wealth takes a distinctly secondary role in the Schumpeterian world, where a far more significant concern is how successful an economy is at generating growth. This dynamic perspective on economics is particularly helpful in understanding technological change.

In evolutionary-economic models, firms are distinguished from one another by organizational differences. Firms are regarded as merely the carriers of technologies, or routines or customs, describing how productively they perform in various environments. The routines represent at any time the best the firm "knows and can do" in terms of standard operating procedures as well as investment and innovation behavior. Routines are relatively unchanging in a given firm, but vary widely across firms. Routines or technologies in a firm are analogous to genes in a living organism. Similarly, the market provides a selection mechanism winnowing on technologies and firms. Consequently, the rise and fall of firms and nations can be explained by how well they can survive in the given selection environment, or market. Conditioned by this environment, firms evolve in a process that is partly stochastic, but not wholly random since the evolution and survival of the firm is partly a consequence of its innate "routines". An important consequence of this partly stochastic behavior is that the process of evolution is strongly path-dependent, with no unique, optimized equilibrium. Optimizing characteristics of firms therefore must be understood as local and myopic.

The important point here is not that ITC modeling should be based on evolutionary-economic models, but rather that a whole class of economic models with a tradition dating back to Schumpeter have as their fundamental premise the *differences* between competing firms. It is this difference that gives rise to dynamic growth. ITC models that assume homogeneity in competing firms may easily underestimate firms' investment incentives. Imagine, for example, that the "selection environment" of firms is changed by the addition of carbon taxes. Those firms that are well positioned by their "routines" to capitalize on this change will invest heavily in alternative energy or emissions reducing technologies, while other firms will invest very little at all. The sum total of industry investment may easily be greater than if we assumed that numerous identical firms only invested a small amount.

The importance of firm heterogeneity seen from the evolutionary-economic approach can just as easily be gathered from a business strategy perspective. The notion of "routines" is analogous to the conscious differentiation of firms seeking sources of competitive advantage over rival firms. For our purposes here, it does not matter whether this differentiation occurs through conscious effort or due to embedded "routines". The conclusion regarding ITC remains the same: different firms are positioned to favor different innovation strategies, and some will respond strongly to climate policy and some will respond weakly. The net response is likely underestimated by modeling homogenous, "representative" firms for each industry.

6.2.2. Heterogeneity in innovation incentives: Innovation and diffusion

The focus on differences in firms emphasizes that their investment behavior will differ. That is, firms will make investment decisions based on different beliefs and expectations about their returns from their particular R&D "production function". Firms' outlook on R&D will differ not only because they are geared up differently to innovate and capture profits, but they also have differing incentives based on capturing strategic advantage. Carraro [5] highlights another source of difference in examining R&D investment incentives in relation to energy models. He emphasizes that firms invest not only to pursue new product and process innovation, but also to assimilate and exploit externally available innovation. Thus, models of ITC should consider, at least implicitly, that innovation occurs at two levels. At one level, costly new innovation activities occur, but at another level, much technological change can occur by less expensive imitation and development activities. That is, technology *diffusion* can be induced in addition to innovation. In figure 2, we might draw an arrow directly from "tax policy" to "technological change and diffusion". The distinction between industrialized and developing nations emphasizes that some firms will prefer the former and some the latter. The potential for ITC in developing countries is particularly dramatic, since there is a gap between their technology and the current production frontier. This gap can be closed by diffusion, though the convergence process depends on numerous social factors [9].

6.2.3. Expectations and the limits of "rational" modeling of innovation

In emphasizing the differences between firms in "R&D production functions", we should also note that not all investment activity could even be captured by models of rational behavior. For example, a spirit that defies rational behavior often guides the entrepreneur, accepting the high probability of failure for the shot at success. Schumpeter, focused on higher-level innovations, went so far as to argue that innovation is a process that cannot be characterized by rational behavior:

> ... the assumption that business behavior is rational and prompt, and also that in principle it is the same with all firms, works tolerably well only within the precincts of tried experience and familiar motive. It breaks down as soon as we leave those precincts and allow the business community under study to be faced by – not simply new situations, which occur as soon as external factors unexpectedly intrude but by – new possibilities of business action which are as yet untried and about which the most complete command of routine teaches nothing [42].

Rosenberg, drawing on his experience as an economic historian, makes an equally strong statement:

> The nature of the innovation process, the drastic departure from existing routines, is inherently one that cannot be reduced to mere calculation, although subsequent imitation of the innovation, once accomplished, can so be reduced. Innovation is the creation of knowledge that cannot, and therefore should not, be "anticipated" by the theorist in a purely formal manner, as is done in the theory of decision-making under uncertainty [38, pp. 53–54].

While an important realization for the limits of ITC modeling, it is also discouraging. We will discuss particular implications of uncertainty and suggestions for ITC modeling later in the paper, but for now it is important to realize that *any* models of innovation are destined to come up short in one aspect or another.

However, we can say in general that when the rate of innovation is high, one consequence of second-best, "quasi-rational" behavior is to impede the diffusion of new technologies. Rosenberg has suggested several reasons why expectations about technology act to slow diffusion [36]. Such expectations generally fall outside the scope of most economic models of induced technological change, in which firms decide to invest in knowledge without consideration of technology diffusion. First, expectations about the continued improvement and refinement of a technology, particularly the arrival or development of a major innovation, may lead to postponement of innovation activities or adoption. Firms are reluctant to invest in a fledgling technology when they expect substantial improvements to be forthcoming. As anyone who has bought a PC can attest, no one wants to feel burned by investing in a technology that is immediately rendered obsolete by subsequent improvements. Second, competition from new technology sometimes spurs development in old technology to be more competitive, slowing diffusion of the new entrant. Similarly, because single breakthroughs seldom constitute complete innovations, decisions to adopt an innovation are often postponed "in situations that might otherwise appear to constitute irrationality, excessive caution, or over-attachment to traditional practices in the eyes of uninformed observers" [36].

6.2.4. ITC modeling implications

How can models address the heterogeneity of innovation incentives? A major first step would be to include a model of technology diffusion, particularly with respect to developing countries. Diffusion can be a significant source of change in energy technology, and it does not require substantial R&D investment.

Another start in including considerations of heterogeneity would be to qualify model results with qualitative insights. One insight would be that diffusion, though an important mechanism for change, would likely be slower than modeled, due to expectations and competing technologies. Modelers may wish to consider this in incorporating inertia or time lags into the system. Another insight would be that there is likely to be more innovation and R&D investment than homogenous, profit-focused models predict. Differentiated technical skills and strategic incentives would "induce" change in some firms more than others.

Some might attempt to explicitly model the effect of heterogeneous firms on the rate of innovation, but this would be a difficult endeavor in which an overly simple model may misrepresent the dynamics entirely. For example, much of the literature on "strategic" R&D incentives focuses on game theoretic "tournament" models, in which competing firms race to capture the same innovation to the exclusion of others. As another example, Jones and Williams choose to consider the strategic aspect of innovation incentives as a detriment to progress, since firms are wasting R&D effort working on the same problems independently [19]. They call this effect "congestion externalities", modeling it as a negative externality in economic growth. However, in long-term models of industry-wide technological change, it seems unreasonable to assume that firms would compete for a preset, limited stock of innovations. Rather, the point is that firms are differentiated strategically, and they will each pursue different paths of innovation. Particular policies will favor some paths more than others, and R&D along the favored path will be disproportionately stimulated. Regardless of modeling difficulties, this qualitative insight about firm heterogeneity should be prominent in policy considerations and model interpretations.

While competition among differentiated firms is difficult to capture, models can address the more basic economic impacts of heterogeneous *industries and technologies*. In particular, general equilibrium models like Goulder/Schneider can distinguish between carbon-intensive and non-carbon-intensive industries. The level of aggregation is higher, but in considering cost and efficiency responses to energy policies, this is a great leap forward. Models can include a generic alternative energy industry and a fossil-fuel-based industry, in which investment incentives differ considerably. Chakrovorty et al. show that in considering changes in carbon emissions, it is mostly technical change in the backstop (alternative energy) technologies that makes a difference, not change in conventional fossil fuel technologies [6]. *Making the distinction between fossil-fuel-based and alternative energy industries or technologies is essential.*

6.3. Uncertainty and discontinuity in innovation

Perhaps the most important element of modeling innovation is the inherent uncertainty in technological change. On one level, the uncertainty arises because the consequences of given technological changes are so difficult to predict. Rosenberg offers several observations on the difficulty of foreseeing the path of a particular invention [37]. At a more fundamental level, though, uncertainty arises because we are simply unsure how technology will evolve in the distant future. That is, not only do we not know what impact an invention will have, but we do not even know what will be invented. This latter question, rather than the question of particular consequences, is of most immediate concern for long-term climate policy models.

Innovation and growth theory offer one window into future technological development through the perspective of firms' economic profit incentives and spillovers. Most models of technological change assume that firms have complete information about returns to R&D investment, which takes the form of a continuous function. But even with the most extensive model, though, there remains a substantial component of technological change that, for all practical purposes, is stochastic. We suggest that the ITC modeler needs to consider two aspects of uncertainty in technological change: (1) major innovations, (2) heterogeneity and discontinuity in technology development.

6.3.1. Uncertainty in major innovations

The most obvious uncertainty concerns major, groundbreaking, Schumpeterian-style innovations. Mokyr draws a useful distinction between *microinventions* and *macroinventions* [26]. Microinventions are "small, incremental steps that improve, adapt, and streamline existing techniques already in use, reducing costs, improving form and function, increasing durability, and reducing energy and raw material requirements". These improvements are consistent with the continuous learning-by-doing or induced innovation models of endogenous technological growth typically seen in economics. On the other hand, macroinventions are those inventions in which a radical new idea emerges without precedent. These do not seem to obey obvious laws, are not necessarily preceded by profit incentives, and "defy most attempts to relate them to exogenous economic variables". Also, according to Mokyr, "the essential feature of technological progress is that the macroinventions and microinventions are not substitutes but complements".

Thus, it would seem that models of long-term climate policy would be lacking without addressing the possibility of new and unexpected technologies. In the past, conventional energy policy oriented models have focused on time frames of 20–50 years, depending on the scope of analysis. In this time frame, it was justified to consider only continuous, incremental improvements in technology. Innovation literature and conventional economic frameworks provided the ideal basis for these models, as they concentrated on continuous innovation induced by profit-seeking investment. With the climate change issue, though, the scope is often extended to 2100 or beyond. Extrapolating this focus on microinventions into long-term models of technical change may introduce significant error. Witness, for example, the unprecedented emergence of nuclear power during mid-century after as late as the 1930s leading scientists claimed power could never be harnessed from the atom. While microinventions and the "D" of R&D account for the majority of technological activity and may be accurately represented endogenously in an economic framework, long-term models of technological change are incomplete without consideration of macroinventions.

The distinction between micro and macro inventions concerns not only the magnitude and frequency of the changes, but also the *responsiveness* of the inventions to economic activity. In modeling endogenous technological change, we assume that technological advance will be responsive to the economic climate (sensitive to price). This is valid for modeling microinventions, which have been the focus of most modeling. The two levels of invention are complements, so one would expect at least a second-order "induced" change in macroinventions, too. But the strength of this "complementary" bond is open to question, and historical observation indicates that major innovations are not necessarily preceded by a vast commitment of resources. In a sense, they occur more or less randomly, though their occurrence gives rise to a subsequent large-scale commitment of scientific and technological resources to complementary microinventions. Rosenberg has emphasized how technological innovations can influence the science agenda in this fashion [38, ch. 2]. A classic example is the invention of the transistor. Before the advent of the transistor in 1948, solid-state physics was an obscure subdiscipline. After this macroinvention the research and development communities in both the universities and private sector made large-scale commitments to exploit this new path of innovation.

6.3.2. Heterogeneity and discontinuity in technology development

A more subtle influence of uncertainty for the ITC modelers occurs at the level of the microinvention, or typical innovation activities. Of course, with regard to a specific firm's investment or the development of a specific technology, uncertainty is always important. Here, though, we are talking about aggregate representations of innovation activities. Would not all the variation in innovation activities offset, so that we may reliably use a deterministic "R&D returns" function to represent the aggregate improvement? In short, no.

The paths of technological development are discontinuous. That is, even if innovation is continuous and incremental in *individual* technologies, the paths of *characteristics* of technology are not. The development paths are discontinuous because there are many heterogeneous competing energy technologies at once, each with varying technology characteristics. Cumulative minor advances in a less competitive technology may allow it to cross a previous competitive threshold, leading to rapid diffusion and further innovation in the characteristics particular to that technology.

Chakravorty et al. emphasize the importance of heterogeneous technologies and the discontinuous, non-linear development paths they imply [6]. Using a framework of optimal natural resource extraction, they study endogenous substitution of the different energy resources of coal, oil, gas, and solar power in the implications for global warming policy. They find that carbon emissions will experience a sharp drop in the next century as costs of solar generation become more competitive. What seems to be important in affecting emissions, then, is not technological change in the energy sector as a whole, but the magnitude of cost reductions in the backstop technology relative to that of fossil fuels. As a consequence, the energy-efficiency characteristics in the energy sector as a whole undergo a discontinuous shift. With this sort of discontinuity and nonlinearity, addressing uncertainty in returns to "aggregate" R&D or "alternative energy" R&D becomes even more important.

6.3.3. The importance of uncertainty in nonlinear systems

Still, even if there is uncertainty in the improvement of technology characteristics for a given level of investment, can't we represent the "R&D production function" based on expected values of the uncertainty distributions? No – in nonlinear systems point estimates will lead to erroneous conclusions. In the climate change system, damage is a nonlinear function of climate change. Nordhaus has shown the importance of accounting for uncertainty in climate change models [31]. Rather than using the expected values of the uncertain parameters, Nordhaus considered probability distributions on the major uncertain parameters in his DICE model. He found that the optimal carbon tax more than doubles when uncertainty is taken into account, and the optimal control rate increases by slightly less than half.

6.3.4. ITC modeling implications

Explicit representations of uncertainty are a significant element in long-term models of technological change. Nordhaus' treatment of climate change uncertainty, based on Monte Carlo simulation and a decision analytic framework, could serve as a model for dealing with technological uncertainty [31]. Instead of dealing with the gradual revelation of uncertain scientific parameters, though, we are now dealing with the dynamics of technological evolution. We will become more certain about a future date's technology the closer we get to that date. Recognizing the uncertainty, energy policy decisions should be made in an incremental manner, making use of the gradual revelation of uncertainty and preserving options. Projecting technological characteristics far into the future is a daunting task, but this does not mean that we cannot make decisions in the face of uncertainty. By recognizing and modeling the uncertainty, we can use the principles of decision analysis to help us decide the best course of action.

More specifically, how can the uncertainty about technology be represented in ITC models? One can imagine a variety of stochastic or simulation based models for representing both micro and macroinventions. Also, modelers should recognize that deterministic models may not capture the important possibility of sudden, discontinuous shifts from one technology to another.

6.4. Path-dependence and inertia

Consideration of uncertainty and discontinuity in technological change is a first step in understanding path-dependence, a characteristic critical to any long-term climate policy considerations. Technically, by path-dependent we mean that a process is non-ergodic, or that the sequence of historical events conditions future possibilities. Rosenberg has written extensively on the idea of path-dependence based on historical observation of economic and technological change. Rosenberg explains the notion of path-dependence applied to technology:

> . . . the main features of the stock of technological knowledge available at any given time can only be understood by a systematic examination of the earlier history out of which it emerged. There is . . . a strong degree of path-dependence, in the sense that one cannot demonstrate the direction or path in the growth of technological knowledge merely be reference to initial conditions [38, p. 10].

This is a particularly strong statement for ITC modeling. Most economic historians and devotees of evolutionary economics will argue that there is much more involved in the evolution and diffusion of technology than merely prices, production functions, and knowledge stocks. While these latter factors lend themselves to mathematical representation of ITC by means of intertemporal optimization of profits, they alone do not capture the dynamics of technological development. Technological change in optimization and equilibrium models is usually merely a matter of moving along current production or knowledge stock functions, whereas change in reality is highly conditioned on the past paths of major and discontinuous innovations, the development activities of firms, and existing capital stocks.

The notion of path-dependence is critical to policy considerations, because it suggests that the path of technological change evolves with a great deal of inertia, and can be difficult to influence by policy. On the other hand, path-dependent activity may propagate small changes in the system, so that small policy-induced changes today can result in substantial changes in the future.

6.4.1. Inertia of development activities and capital stock

First, the inertia of path-dependent technical development arises because technology capital and R&D organizations are costly to redirect or replace. On a more obvious level, capital stock turnover is a source of inertia. Even if less costly or more efficient technologies are available, old technologies may still be competitive because they are sunk costs. In energy technology, Grubb estimates that for various components of the power generation and energy use infrastructure, capital stock turnover cycles range from twenty to one-hundred years [15]. Grubb [15], Chapuis et al. [7] and Ha-Duong et al. [17] have emphasized the importance of this aspect of inertia in energy models. They argue that inertia tends to increase the optimal near term abatement. Moreover, development activities tend to focus on existing capital, biasing development towards older technologies.

At a deeper level, inertia is generated by the costly nature and limited mobility of development activities. Rosenberg argues that there is an often underappreciated distinction between the availability and implementation of publicly known knowledge or information:

> Development activities accounted for approximately 67% of total R&D spending (in the U.S., according to *1991 Science and Engineering Indicators*). These figures, at the very least, suggest great skepticism about the view that the state of *scientific* knowledge at any time illuminates a wide range of alternative techniques from which the firm may make cost-less, off-the-shelf selections. It thereby also encourages skepticism toward the notion that is so deeply embedded in the neoclassical theory of the firm, that one can draw a sharp and well-delineated distinction between technological change and factor substitution [38, p. 13].

Indeed, technological change depends greatly on how firms have already geared up, or in the language of economics, the point on the production function on which they currently operate. Firms cannot instantaneously shift to alternative technologies, even if the technologies simply involve exploiting available but unfamiliar knowledge.

Thus, the rate of innovation may respond more sluggishly to the economic climate than the neoclassical model of the firm would predict. New technological possibilities must compete on an uneven playing ground, in which established technologies and development routines are already ingrained in organizations. Also, major innovations may establish trajectories of readily available performance improvements and cost reductions that focus engineers on payoffs in existing technology rather than searching for entirely new technologies.

6.4.2. Path sensitivity and technology "lock-in"

While difficult to deliberately redirect, the path of technology is sensitive to perturbations, whatever their source. As discussed in section 6.3.2, path discontinuities may arise from gradual, continuous technological change. Also, major innovations may set up long sequences of path-dependent activities. In either case, resources tend to be refocused on the new path. As an innovation gains a foothold, it becomes embedded in the surrounding infrastructure and a vital aspect of the technological system. Arthur has demonstrated how the stochastic nature of the innovation process may lead to technology "lock-in", even by inferior technologies [3]. In a sense, the innovation benefits from increasing returns to scale against competing technologies, and consequently the new innovation gets "locked-in" to the system. Development activities reinforce the lock-in, as they focus on existing technologies. The existing technologies suggest certain directions where research efforts can be usefully exercised, resulting in series of minor improvements that may amount to significant change over the long term.

A typical example of a path-breaking major innovation that shaped future development is the internal combustion engine. Its rapid development in the early twentieth century made possible numerous other innovations in the automotive and aircraft industries. Moreover, soon after its introduction the internal combustion engine dominated research and engineering efforts in propulsion devices, even though the engine may not have been inherently technologically superior to the competing technologies of electric and steam power for its initial use in cars. Another example is given by the domination of the steam turbine for electricity supply, and the resulting focus of R&D on incremental improvements in that technology.

6.4.3. ITC modeling implications

The notion of path-dependence emphasizes the importance of the particular context of technological change considered by a model or policy decision. Path-sensitivity and "lock-in" suggest that actions and technological choices today are even more important than conventional economic models would indicate. Thus, policies that can induce technological change may not only be important in progressing technological characteristics, but also for redirecting the path of technology. Incorporating path sensitivity in ITC models is a challenge – one that is perhaps not worth the added complication. Realizing the distinction between changes in technology characteristics and technology paths, however, *is* absolutely critical in interpreting model results and analyzing policy. We must respect the limitations of modeling context-sensitive, historically-dependent, stochastic processes. Scholars of the history of technology warn that technology cannot be represented solely in deterministic, economic frameworks.

Still, ITC models can be extended to better complement qualitative insights about path-dependence. A starting point in addressing path-sensitivity and "lock-in" is to include explicit representations of uncertainty and learning-by-doing in models. Representing the inertia aspect of path-dependence is also a reasonable goal. Models can include time lags to account for technological expectations (section 6.2.3), diffusion of innovations, and the costliness of development activities. Time lags would be relatively easy to incorporate into ITC models. Lags in technology development would be particularly relevant to sudden changes in policy or carbon taxes, developments following upon major innovations, or in the exploitation of spillovers.

6.5. Importance of ITC revisited: Conclusions from a broader perspective

The factors relevant to ITC in the "big picture" are summarized in figure 2 and table 2. Some factors need to be recognized by policy analysts as model limitations, while others are more suitable to model extensions.

Table 2
Summary of ITC considerations beyond classical economic framework.

Consideration	Implication for models of induced technological change
Complementary sources of technological change	*Underestimate impact of ITC* Intersectoral spillovers, public R&D, major innovations, and learning-by-doing are all sources of technological change that react and feedback to ITC. Learning-by-doing and stochastic, major innovations could be feasibly included in models. Synergies with public R&D should be considered.
Firm heterogeneity: Strategic incentives	*Underestimate impact of ITC* Differentiated firms will respond to climate policies differently, with the net result likely underestimated by a model of homogenous firms. A general equilibrium model with different types of energy providers helps address this.
Firm heterogeneity: Diffusion versus innovation	*Underestimate impact of ITC* Technological change can be induced at different levels: innovation by leaders, imitation by followers. The potential for imitation and technology diffusion is especially great in less developed countries.
Firm heterogeneity: Expectations and "irrational" behavior	*Underestimate impact of ITC* Rational calculations cannot adequately represent entrepreneurial styles of innovation and investment behavior.
	Underestimate lags between policy and ITC Expectations about old vs. new technology slows diffusion of new technology.
Uncertainty in returns to R&D	*Underestimate impact of ITC* Discontinuous shifts in carbon intensity of technology stock from: (1) major innovations, (2) minor innovations in previously uncompetitive alternative technologies (e.g., solar power becomes competitive after incremental cost reduction). Simulation or decision analysis could be used model a skewed range of possible technical change from a given investment level.
Path-dependence and inertia	*Underestimate lags between policy and ITC* Firms change direction slowly and in a costly manner, even when new knowledge is available. Also, new technologies must compete with existing capital stock at sunk costs. Models could incorporate lags between innovation and aggregate changes in technology characteristics.
	Underestimate influence of small changes today Since technology changes in an evolutionary, path-dependent fashion, small path changes today can propagate into significant differences later. Technology may be "locked-in". Including learning-by-doing and uncertainty in technology will help capture this effect.

In section 4.4, we saw that models suggest that induced technological change has weak, ambiguous, or costly effects on the pace of innovation. At best, considering ITC could marginally increase carbon tax benefits in a costly manner, and at worst ITC has virtually no effect on models of innovation. In considering the possible extensions and limitations of current ITC modeling, these conclusions need to be qualified. There are a number of considerations listed in table 2 that suggest that models that leave out ITC will underestimate the rate of carbon saving innovation. Technological change is more endogenous than conventional economic models may first indicate. Perhaps the most important message for modelers is to recognize the severe limitations of using deterministic, aggregate R&D functions in a world where (1) firms, incentives, and technologies are heterogeneous, and (2) development paths are uncertain and discontinuous. A big first step in addressing this concern is to model fossil-fuel-based and alternative energy technologies individually.

Also, some factors like path-dependence and technological expectations may add inertia to the system, but they will not necessarily dampen the endogeneity of technological change. Moreover, the path-sensitivity of change implies that induced changes in the path of technology can be critical for future prospects. Even if the magnitude of induced change is small, a shift in the direction of the technological system can propagate into major changes over time.

There is a good reason why the extensions to ITC modeling considered here were not included in early ITC models: they are troublesome to represent analytically. It is important to recognize this difficulty and not attempt to endogenize all aspects of technological change at every level. Choosing which aspects of technological change to model endogenously and which aspects can be modeled in a heuristic, exogenous manner can be a strong start. Also, recognizing the difficulties is a first step towards dealing with them, whether through explicit model representations or subjective qualifications of models as a part of policy analysis.

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