Technical Change and the Marginal Cost of Abatement[*]

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[*] Running Head: Increased MAC

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Abstract

We address one aspect of the treatment of technical change in the environmental economics literature: how technical change impacts the marginal cost of abatement. We review a selection of papers that employ a variety of representations of technical change, and show that these representations have quite different, and sometimes surprising, effects on the marginal costs of pollution reductions. We argue that these varied representations in fact correspond to a variety of different technology options. We then present results indicating that this representation matters – the impacts of technical change on the marginal cost of abatement can crucially impact policy analysis.

JEL classification: H21, D58, O33, C61.

Keywords: CO_2 abatement costs; Policy instruments; Carbon dioxide capture and storage; Endogenous technical change.

1 Introduction

Economic researchers have long been interested in the relationship between environmental policy and technical change. This interest has taken on a renewed vigor in recent years in response to increasing concerns about climate change. The ability of pollution reduction policies to induce technical change influences their dynamic efficiency and, in the climate context, has potentially important ramifications for the appropriate stringency of near-term emissions reductions. Moreover, a broader suite of policies to foster technical change (e.g., publicly-funded R&D) are becoming increasingly accepted as integral to a comprehensive approach to climate change.

Appropriate environmental policy depends not just on *whether* and *how much* technology responds to policy, it also depends on *which* technologies respond. Improvements in solar cells, for example, may have different impacts on carbon dioxide emissions reduction possibilities than improvements in the efficiency of fossil fuel power plants. While not explicitly acknowledging this fact, researchers using theoretical models as well as applied aggregate-level (or "top-down") integrated assessment models have employed a variety of differing simplified representations of technical change. These differing representations lead to differing impacts on the marginal costs of emissions reductions and, in turn, to differing policy implications. For example, Baker, Clarke, and Weyant [2] have shown that different representations of technical change have very different effects on the optimal societal investment in climate change technology R&D in the face of uncertainty. Yet the empirical basis for this aspect of technical change—how it effects marginal abatement costs—has been largely ignored in the construction of these models.

This paper addresses the treatment of technical change in theoretical and aggregate-level models. The paper has two related purposes. The first is to demonstrate that theoretical and aggregate-level applied models have, indeed, used a number of different formulations for technical change and, furthermore, that these different formulations can lead to very different impacts on the marginal costs of pollution reductions. In Section 2, we review a variety of approaches from the literature, and show that these representations have quite different, and sometimes surprising, effects on the marginal costs of pollution reductions. In particular, we highlight the interesting case of formulations in which technical change increases marginal abatement costs at higher levels of abatement.

In Section 3 we provide examples to demonstrate that this phenomenon— technical change increasing marginal costs—is not an error or an anomalous special case, but rather is a reasonable representation of improvements in technologies that might be employed at low or intermediate levels of abatement, but that would be substituted away from at higher levels of abatement. Efficiency improvements in fossil fuel technologies serve as one important example. We focus our examples on climate change, but the issues addressed in this paper should apply more generally to any environmental issue where technical change is fundamental.

The second purpose of this paper is to demonstrate that the differences in the representation of technical change matter; that is, that implied policy prescriptions might be different with differing representations. In Section 4 we first review previous results in the literature; we then re-work the seminal paper on *Firm Incentives to Promote Technical Change in Pollution Control* by Milliman and Prince [29] and show, for example, that different policy instruments may provide incentives for different types of technical change. Section 5 concludes the paper.

2 Representation of Technical Change in Models

In this Section we discuss a number of approaches to modeling technical change in top-down and theoretical models.[1] This section has two purposes. One purpose is to demonstrate that there are, indeed, a variety of differing representations and that these lead to differing impacts on marginal abatement

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[1] See Gillingham, Newell, and Pizer [21], Clarke & Weyant [10], Grubb, et al. [24], Loschel [28], Clarke, et al. [8], and Clarke, et al. [9] for surveys focusing on how technical change is made endogenous in formal models of energy and the environment.

	Impacts to MAC	Impacts to cost of abatement	Emissions-output ratio	Production function / Profit function	
	Assumes lower MAC	**Pivots down**		**Reduces cost / increase output of non-fossil energy**	**Substitutes knowledge for non-fossil or overall energy**
Decreasing MAC	Fischer, Parry & Pizer [17]	Baker & Adu-Bonnah [1]		Baker & Shittu [4]	Goulder & Schneider [23]
	Goulder & Schneider [23]	Baker, Clarke & Weyant [2]		Popp [38]	Popp [37] [38]
	Jung et al. [26]	Montero [30]		Gerlagh & van der Zwaan [18] [19]	Sue Wing [42]
	Milliman & Prince [29]	Goulder & Mathai [22]		van der Zwaan et al. [44]	
	Downing & White [12]	Parry [34]			
		Pivots right	**Reduces emissions –output ratio**	**Reduces carbon content/emissions -output ratio**	**Substitutes knowledge for fossil energy**
Increasing MAC		Baker & Adu-Bonnah [1]	Nordhaus [33]	Baker & Shittu [4]	Goulder & Schneider [23]
		Baker, Clarke & Weyant [2]	Gerlagh & van der Zwaan [18]	Farzin & Kort [14]	Sue Wing [42]
			Buonano et al. [7]		

Table 1: Categorization of representations of technical change in a selection of papers. Some papers have multiple representations of technical change.

costs. The second purpose is to demonstrate that a number of models use formulations that can lead to increasing marginal costs at higher levels of abatement. In Section 3 we discuss whether the assumptions leading to a higher marginal abatement cost curve (MAC) at high levels of abatement are reasonable. Table 1 categorizes a non-exhaustive list of models that include assumptions about technical change.

All the papers in the top row of Table 1 use formulations that lead to decreasing marginal costs at all levels of abatement. There are, however, important differences among these formulations. The papers in the first box (the upper left square) make assumptions about how technical change will impact the MAC directly. All papers in this group assume that technical change will decrease the MAC. In fact, all the papers assume that technical change will pivot the MAC downward, for at least part of the paper (Fischer et al. [17] in computational part; Goulder and Schneider [23] in theoretical part). The group

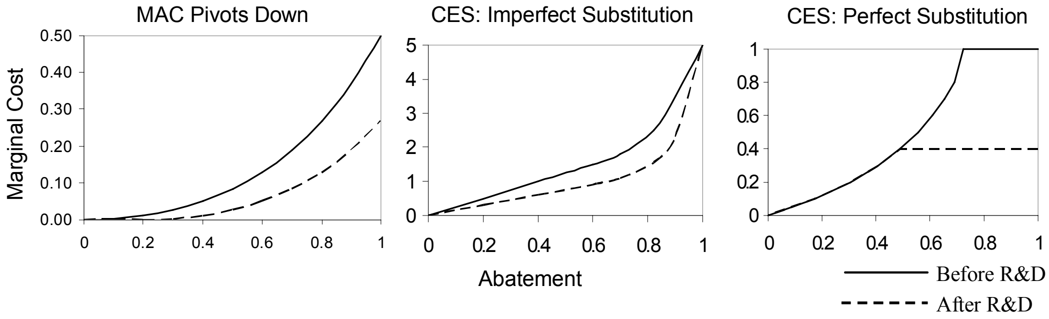

Figure 1: The first panel illustrates a MAC that is pivoted down; the second and third panels illustrate the impact on the MAC of a reduction in the cost of non-fossil inputs, assuming a CES production function with imperfect and perfect substitution, respectively.

of papers in the next square to the right assume that technical change will pivot the abatement cost curve down. If the cost of abatement μ is $c(\mu)$ before technical change, then it is $\phi c(\mu)$ after technical change, where $\phi < 1$. This leads to a lower MAC, and in fact leads to a MAC that is pivoted downward if $c'(0) = 0$. The far left panel in Figure 1 illustrates the representations in the first two boxes.

Moving to the right, Popp [38], Baker and Shittu [4], and Gerlagh and van der Zwaan [18][19] assume that technical change will reduce the cost of non-fossil energy. This assumption leads to a lower MAC everywhere (as long as the elasticity of substitution between fossil and non-fossil energy is greater than 1). The two panels on the right of Figure 1 show, however, that the MAC is not necessarily pivoted downward: the impact depends on the elasticity of substitution between fossil and non-fossil fuel. The assumption in van der Zwaan et al. [44], that technical change increases the output of non-fossil energy, has a similar impact.

Finally, the most complicated set of assumptions are in the fifth column, where technical change is represented as knowledge substituting for inputs. In Popp [37][38] knowledge substitutes for overall energy; in [23] and [42], knowledge substitutes for non-fossil energy. Here we focus on knowledge as a substitute for overall energy and present a simplified, pared-down model to underline the concepts. In this representation technical change increases energy efficiency, by substituting knowledge H for energy.

Energy is produced from carbon and non-carbon energy e_c, e_{nc}. Output is produced through a nested CES production function as follows:

$$y = \left[\left(e_c^{\rho} + e_{nc}^{\rho} \right)^{\frac{\rho_e}{\rho}} + H^{\rho_e} \right]^{\frac{1}{\rho_e}} \tag{1}$$

Where $\sigma = \frac{1}{1-\rho}$ is the elasticity of substitution between carbon and non-carbon energy and $\sigma_e = \frac{1}{1-\rho_e}$ is the elasticity of substitution between knowledge and overall energy. Assuming input prices $P_i \; i = c, nc$, a fixed amount of knowledge H and an emissions cap $\bar{e}$ this results in a cost function to the firm of

$$C\left(y; P_c, P_{nc}, H, \bar{e}\right) = \min_{e_c, e_{nc}} P_c e_c + P_{nc} e_{nc} \tag{2}$$

$$y = \left[\left(e_c^{\rho} + e_{nc}^{\rho} \right)^{\frac{\rho_e}{\rho}} + H^{\rho_e} \right]^{\frac{1}{\rho_e}} \tag{3}$$

$$e_c \leq \bar{e} \tag{4}$$

This problem can be set up as a Kuhn-Tucker problem, with Kuhn-Tucker multiplier $\lambda_E \geq 0$ and $\lambda_E = 0$ if $e_c < \bar{e}$. Assuming that $e_c = \bar{e}$ (i.e. abatement takes place) then we can solve for λ_E as follows

$$\lambda_E = P_{nc} \bar{e}^{\rho - 1} \left[\left(y^{\rho_e} - H^{\rho_e} \right)^{\frac{\rho}{\rho_e}} - \bar{e}^{\rho} \right]^{\left(\frac{1-\rho}{\rho} \right)} - P_c \tag{5}$$

Note that by a double application of the envelope theorem the marginal cost of abatement to the firm is just equal to the Kuhn-Tucker multiplier, λ_E. It is easy to show that λ_E decreases in H, that is, that the MAC is decreased by technical change. (See appendix for details). The left panel in Figure 3 shows the MAC under low and high knowledge when $\sigma = 4$ ($\rho = .75$) and $\sigma_e = 2$ ($\rho_e = .5$).

The more interesting, and surprising, result is that some of the representations of technical change – those in the bottom row of Table 1 – increase marginal costs at higher levels of abatement. Each of these examples can be thought of as representing innovation that improves technologies that would

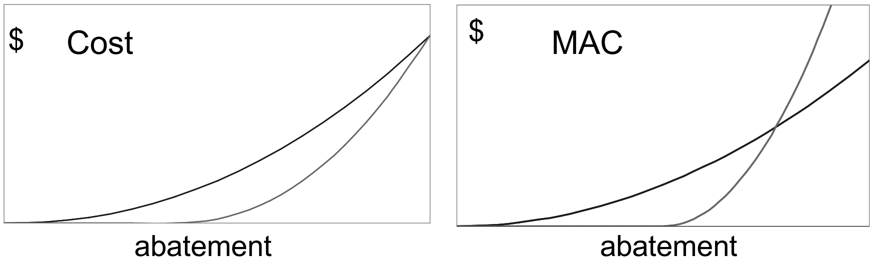

Figure 2: The left hand panel shows the cost of abatement before and after technical change that pivots the cost curve to the right. The right hand panel shows the associated MACs.

be used at low or intermediate levels of abatement. For example, an improvement in the efficiency of coal-fired electricity generation would provide benefits at lower levels of abatement, but virtually no impact at full abatement, since society would not be burning coal at that point (assuming here that 100% carbon capture and storage is not feasible). The first set of papers (in the bottom row, second column) can be used to illustrate this point. These papers assume that technical change pivots the *total* cost function to the right, leaving the cost of full abatement unchanged. If the cost of abatement μ is $c(\mu)$ before technical change, then it is $max\left[c\left(\frac{\mu-\phi}{1-\phi}\right),0\right]$ after technical change, where $\phi < 1$. Figure 2 illustrates this approach. The left hand panel shows the cost of abatement before and after technical change; the right hand panel the associated MACs. Notice that, consistent with any reasonable theory of technical change, the cost of abatement is everywhere lower after technical change. This is because a firm, or society, could always choose to discontinue use of a new technology if it increased costs. Note, however, that the abatement cost curve is steeper at high levels of abatement. Since the MAC is simply the slope of the abatement cost curve, the MAC is higher where the slope is steeper.

The next group of papers (bottom row, third column) includes representations in which technical change reduces the emissions-to-output ratio in the economy. In this formulation, emissions ε are taken to be some proportion σ of total output in the economy Y. Technical change reduces the proportion σ. Emissions can also be reduced through abatement μ—essentially substitution toward lower polluting technologies or fuels—or through output reduction. Thus, the relation between emissions and output is $\varepsilon = (1-\mu)\,\sigma Y$. For a given emission-to-output ratio σ, the marginal cost of abatement is equal to the marginal cost of achieving μ plus the marginal cost of output reduction. It is clear, from the above formulation, that in order to achieve full abatement ($\varepsilon = 0$) then $\mu = 1$ (or, unreasonably, $Y = 0$) *regardless of the value* of σ. Thus, this representation is equivalent to the representation in Figure 2 above: it pivots the abatement cost curve to the right. Imagine reducing σ by half, from 1 to .5. Then the cost of reducing emissions by 50% below the original baseline has gone to zero. But the cost of reducing emissions to zero has not changed.

The fourth column includes very similar representations. Farzin and Kort [14] allow for abatement through output reduction or technical change that reduces the emission-to-output ratio. In Baker & Shittu [4], technical change reduces the carbon intensity of the fossil energy input, leading to a similar phenomenon.

The fifth column includes models in which knowledge is an input to production, only here it serves as a substitute for fossil energy. We again present a simple model to underline the concepts. We assume that output is produced from carbon and non-carbon energy inputs; and carbon knowledge can substitute for carbon energy inputs. We again use a nested CES function with H_c representing accumulated knowledge in carbon energy. Output for a given level of inputs and knowledge is

$$y = \left(\left(e_c^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho}{\rho_c}} + e_{nc}^{\rho}\right)^{\frac{1}{\rho}} \tag{6}$$

where $\sigma_c = \frac{1}{1-\rho_c}$ is the elasticity of substitution between knowledge and carbon energy, and ρ is as before. Following the above procedure we find the Kuhn-Tucker multiplier λ_F that represents the MAC

$$\lambda_F = P_{nc}\bar{e}^{\rho_c-1}\left[y^{\rho} - \left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho}{\rho_c}}\right]^{\frac{1-\rho}{\rho}} \left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho-\rho_c}{\rho_c}} - P_c \tag{7}$$

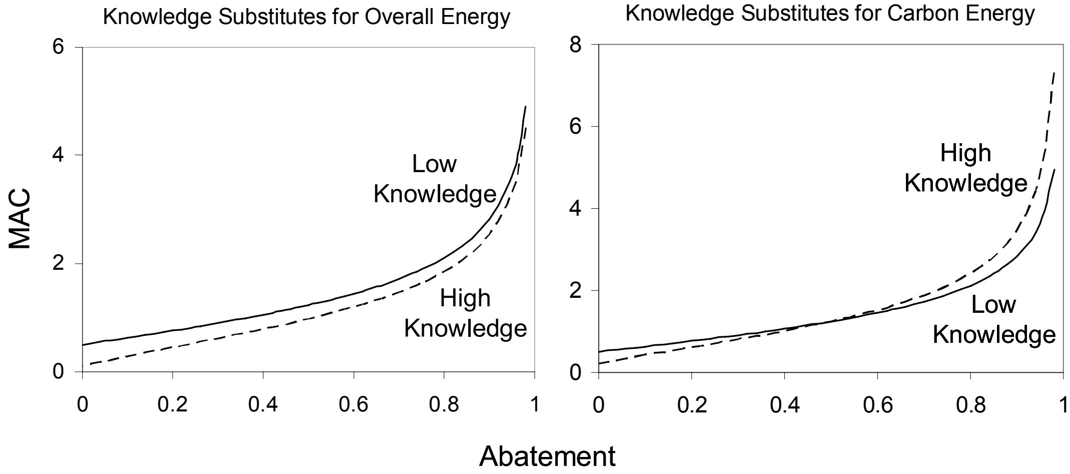

Figure 3: The marginal cost of abatement under assumptions of low and high knowledge. In the left panel knowledge substitutes for energy as in the model in (1); in the right panel knowledge substitutes for carbon energy as in the model in (6).

In order to illustrate that technical change can increase the MAC at high levels of abatement, we consider very high abatement (equivalent to $\bar{e} \approx 0$), so that $\left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right) \approx H_c^{\rho_c}$, and show that

$$\frac{\partial \lambda_F}{\partial H_c} \approx P_{nc} \bar{e}^{\rho_c - 1} \left[y^\rho - H_c^\rho\right]^{\frac{1-\rho}{\rho}} \; H_c^{\rho - \rho_c - 1} \left\{(\rho - 1)\, \frac{H_c^\rho}{y^\rho - H_c^\rho} + (\rho - \rho_c)\right\} \tag{8}$$

(See appendix for details.) As long as H_c is small ($H_c \approx 0$) the quantity above is positive whenever $\rho > \rho_c$. As H_c gets large, however, the first term in the curly brackets will go to negative infinity. Thus, technical change will increase the MAC if abatement is high, knowledge is a small portion of output, and the elasticity of substitution between carbon and non-carbon is higher than the elasticity of substitution between knowledge and carbon. The right hand panel of Figure 3 illustrates this representation when $\sigma = 4$ ($\rho = .75$) and $\sigma_c = 2$ ($\rho_c = .5$).

This case can be considered a gross simplification of the models in Goulder and Schneider [23] and in Sue-Wing [42]. Goulder and Schneider [23] use nested CES functions to represent four intermediate good industries: carbon energy; non-carbon energy; carbon-intensive materials; and non-carbon-intensive materials. The output in each industry is produced through nested CES functions in which the two materials are substitutes; the two kinds of energies are substitutes; energy, material, capital and labor are substitutes; and finally, industry-specific knowledge substitutes with physical inputs. In Goulder and Schneider the elasticity between knowledge and inputs, σ_c, is 1; between carbon-intensive and non-carbon intensive materials is 1.05; and between carbon and non-carbon energy is .9. Knowledge is a small proportion of the input into carbon-intensive materials (1.5%). Thus, an increase in knowledge in the carbon intensive materials industry could lead to a higher MAC at high levels of abatement.[2] Sue-Wing [42] has a related representation in which knowledge substitutes for aggregate inputs for carbon-intensive sectors (with $\sigma_c = 1$); and carbon and non-carbon electricity are perfect substitutes. In general, this representation can lead to a higher MAC at high levels of abatement under fairly reasonable paramaterizations.

3 Can Technical Change Increase the MAC?

In this section we argue that in fact technical change can increase the MAC, that this is not an anomalous case, but rather is a reasonable representation of many improvements to intermediate technologies. We define intermediate technologies as technologies that have lower emissions than "Business as Usual" technologies, but will be substituted away from in the case of very low abatement. Examples of such improvements are increases in efficiency in coal-fired and gas-fired electricity generators, carbon capture and sequestration (of less than 100% of emissions), and cost reduction of efficient gas-fired generators. In the transportation sector examples would be better and less expensive hybrid vehicles and bio-diesel. The salient features of these innovations are that 1) they will be beneficial for small and medium reductions in emissions, but 2) they will be substituted away from in the case of very high abatement.

The idea is this: if a firm improves an intermediate technology, say gas-fired electricity generation,

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[2] To confirm this would require running the full version of the model and generating MACs.

but then wants to achieve an even higher level of abatement, then the firm will substitute away from the new and improved technology. Thus, the jump from the gas-fired technology to the very low-carbon technology will now be higher than it was before. One question that has been asked of Figure 2 is: can the firm (or the economy) simply choose the lower MAC if they end up in a high level of abatement? The answer is no – this logic can be applied to a cost curve, but not to a marginal cost curve. The only way to move back to the original MAC would be to pretend that the intermediate technology had not been improved; and thus ignore the extra pain of substituting away from it. But this, of course, is not rational.

3.1 A simple example

We illustrate this through a very simple electricity-sector, climate change example. Assume three electricity technologies are available: a high-emissions technology (pulverized coal), a moderate-emissions technology (a natural gas combined cycle plant), and a no-carbon power plant (nuclear). Table 2 shows the levelized cost of electricity (COE) and CO_2 emission rates for these plants.[3]

Technology	Plant CO_2 (kg/MWh)	Levelized COE ($/MWh)	Total cost per MWh given tax of .07 $/kg
High-Emissions Plant (coal)	850	24	83.50
Moderate-Emissions Plant (natural gas)	370	57	82.90
Zero-Emissions Technology (nuclear)	0	74	74.00
Innovation 1 (lower cost natural gas)	370	30	55.90
Innovation 2 (carbon capture and storage)	37	66	68.59

Table 2: Parameters for Illustrative Example

We consider two forms of technological advance: Innovation 1, a reduction in the cost of the moderate-emissions technology that makes it a competitive option for intermediate levels of abatement, and Innovation 2, the development of technology that will allow for capture of 90 percent of the

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[3] The base case and the Innovation 2 data have been extracted from Narula et al. [31] while the total cost of producing 1MWh given a tax of .07 $/kg have been calculated using the plant CO_2 emissions and the COE.

carbon emissions from the moderate-emissions, natural gas technology. The cost implications of the two advances are shown in the table.

For simplicity, we consider only abatement through substitution: we do not consider abatement through demand reduction.[4] We model and solve a linear program using the data from Table 2. For the base case, we assume that the first three plants are available; for the two advanced-technology cases we replace the parameters for the moderate-emissions plant with the parameters for the respective innovation. We minimize the cost of electricity in \$/kWh subject to a specific limit on output and on CO_2 emissions. In order to derive the cost of abatement curve, we set the combined power output, P, of these technologies to 1000kWh, and vary the emissions limit, E, from zero to 8500kg, which represents the maximum level of emissions using the base case technology. Abatement is measured as the percentage reduction in emissions below the base case technology. When $P = 1000$, abatement $= (8500 - E)/8500$. The cost of abatement is measured as the cost differential from the baseline cost of 24 \$/MWh.

Figure 4 shows the absolute (left panel) and marginal (right panel) abatement costs for the base case and the two advanced-technology cases. In all cases, zero abatement corresponds to the use of the high-emissions coal technology, and full abatement corresponds to the use of the zero-emissions nuclear technology.

Prior to innovation, the abatement cost function traces out a changing mix of the high-emissions and zero-emissions technologies—the intermediate-emissions technology is not on the efficient frontier. After innovation, the first part, or leftward part of the abatement cost curve represents the cost of substituting from coal to the new, improved gas technology; while the second, steeper part of the curve

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[4] Note that this example is meant to be illustrative of a general principle and abstracts away from a range of issues associated with carbon emissions abatement in the electricity sector, including: issues associated with the relative cost basis of existing versus new power plants; indivisibility (all plants are assumed to be available at any size); the reality of a large and heterogenous set of electricity-generation options including a range of fossil technologies along with renewable technologies such as wind power, solar power, and biomass electricity; and regional heterogeneity in fuel costs. In addition, additional, non-climate environmental costs, such as those associated with the nuclear fuel cycle, are not considered in this simple, illustrative example.

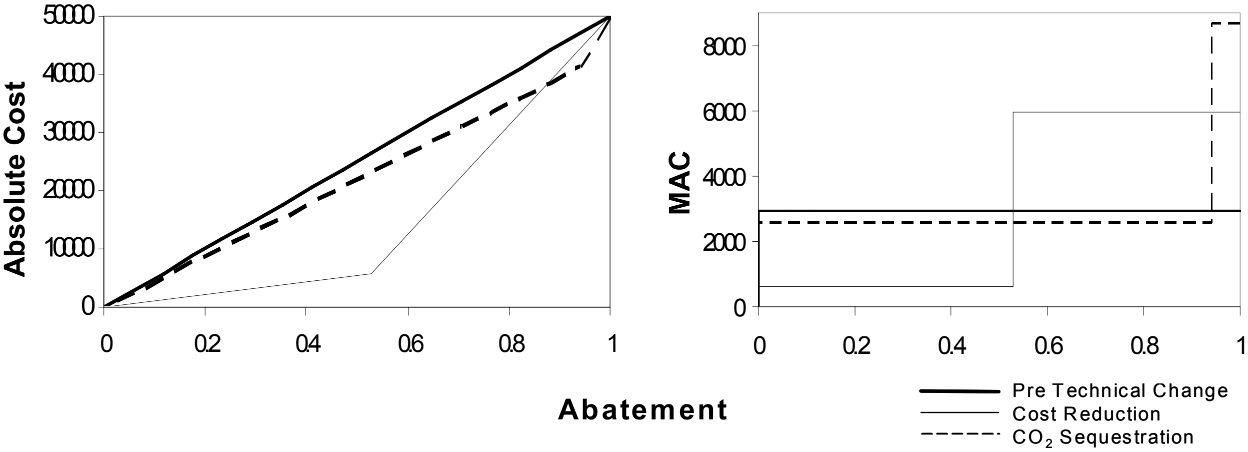

Figure 4: Impact of technical change on abatement cost

represents the cost of substituting from gas to nuclear. In both cases of technological advance, the now-cost-effective intermediate-emissions technology lowers the *absolute* costs of abatement, except at full abatement. Hence, innovation can be considered environmentally-beneficial. In both cases the MAC is initially lower when the new improved technology is being substituted *toward*. However, the MAC is higher at high levels of abatement, when the new improved technology is being substituted *away from*. This property will generally hold for any improvement in technology that will be substituted away from at high levels of abatement. In other words, there is a functional difference between technologies that make partial abatement less costly and those that make full abatement less costly.

This implies that, for a given carbon tax, emissions may be higher after technical change than before. Again, we stress that the firm is strictly better off after technical change, but they may choose to emit more. Consider, for example, a tax of \$.07 per kg of emissions. The last column of Table 2 shows the the total cost of producing 1MWh assuming a tax of \$.07 per kg. The table shows that before innovation the firm would choose to use the nuclear plant for a total cost of \$74 and emissions of 0; after innovation 1 the firm would use the gas plant for a total cost of \$55.90 $(= 30 + .07 * 370)$ and emissions of 370; or after innovation 2, a total cost of \$68.59 and emissions equal to 37. Thus, the total benefit to the firm is positive after innovation; but the firm will emit more after technical change for a given cost of carbon.

This result holds in more general cases where abatement is achieved through output reduction as well as substitution; it holds when the technologies are not perfect substitutes. This will happen any time an innovation is applied to a technology that will be substituted away from at high levels of abatement.

3.2 An Applied Example

The previous example used a simplified, conceptual representation to demonstrate the underlying dynamics that can lead technical change to increase the MAC over some regions. In this section we construct a second, more applied climate-based example using a technologically-detailed integrated assessment model, MiniCAM [6][13].

MiniCAM is a global, partial-equilibrium model, with 14 world regions that includes detailed models of land-use and the energy sector. MiniCAM's time horizon is the end of this century. MiniCAM explicitly represents a range of electricity-generating technologies including various generations of nuclear power, multiple fossil generating technologies, solar and wind power, and electricity from biomass. The model is specifically designed to represent the forces that drive the availability of, interactions between, and costs of technologies.

Two sets of assumptions were generated for the long-term growth of fossil (and biomass) electric efficiencies, one with more aggressive assumptions about efficiency gains (high-tech) than the other (reference). Efficiencies are assumed to increase over time in each of these cases, however the top end on the efficiency trajectory is higher in the high-tech case than in the reference case.

Exploring MACs in a technologically-detailed and multi-period model such as MiniCAM highlights the differences between real-world abatement characteristics and the simplified representations used in theoretical models. Most importantly, MACs are not independent of decisions that have taken place in the past. For example, resource consumption decisions at any point in time will affect resource costs in future years, therefore influencing emissions characteristics of these future years. Similarly, investments in long-lived capital, such as electric power plants, will influence the possible short-term emissions reduction possibilities at later points in time. In addition, economists generally argue for carbon price paths that increase over time in line with the conceptual approach for exhaustible resource extraction.

For the purposes of this exercise, MACs were generated based on the assumption of carbon prices increasing over time at a rate of five percent annually, roughly consistent with a Hotelling price path. Emissions reductions were calculated in the year 2095 as the reduction from the emissions associated with the reference technology case and no price on carbon.

Figure 5 shows the results of the analysis: the MAC in 2095 for the reference and high tech case. A first observation is that higher fossil efficiencies lead to lower carbon emissions in the absence of a price on carbon. This is because the decrease in carbon emissions per unit of electricity produced outweighs the increase in demand from lower electricity prices. The result is a shift to the right in the associated MAC. However, as abatement is increased, the two marginal cost curves intersect, for precisely the reasons discussed in the sections above. The marginal cost of abatement is higher under the high-tech case for abatement of 35% or higher.[5]

The conclusion of this section is that innovation into high or intermediate emissions technologies is likely to lead to a higher MAC at high levels of abatement.

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[5] The long-term viability and applicability of fossil electricity in a carbon-constrained world depends crucially on the viability of carbon capture and storage technology (CCS). If CCS is viable, then a large portion of the technology switching in response to a carbon constraint might result in a switch to coal-fired electricity with CCS as opposed to sources such as renewable energy or nuclear power. If CCS is not viable, as is assumed for this example, then renewable and nuclear sources will be the primary new electricity source, along with a greater degree of electricity demand reduction.

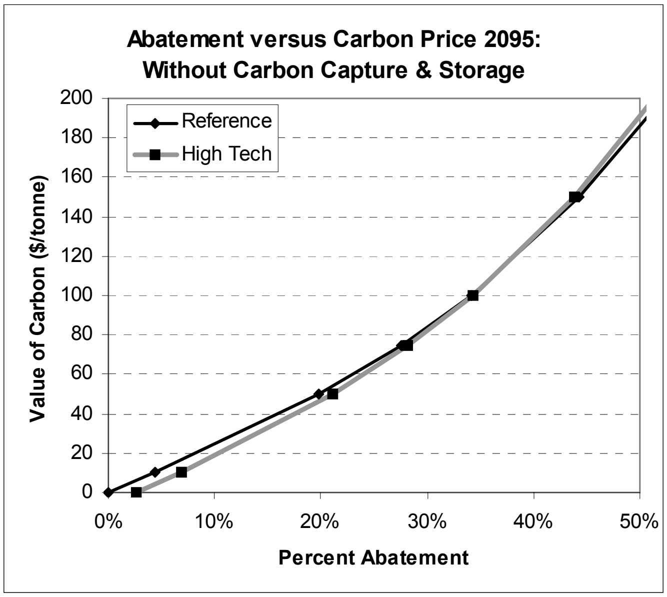

Figure 5: The marginal cost of abatement for a reference case and a high-tech case that includes higher fossil fuel efficiencies.

4 Implications

In the above sections we have shown that technical change is represented in different ways in different models, and argued that these different representations are likely to legitimately represent different categories of technical change. In this section we review some previous results that indicate that findings are impacted by the representation of technical change; and we present a re-working of the seminal Milliman and Prince paper.[6]

4.1 Review of past results

Very little work has been done to date comparing different representations of technical change within top-down models. Here we review four papers that indicate that the representations matter. Baker,

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[6] For papers that cite Milliman and Prince and assume that technical change decreases the MAC see Jung et al. [26], Dosi and Moretto [11], Gersbach and Glazer [20], Goulder and Schneider [23], Jaffe et al. [25], Montero [30], Parry [35], Fischer et al. [17], Requate et al. [40], Bansal and Gangopadhyay [5], Kennedy and Laplante [27], Newell and Stavins [32], Parry et al. [16], Fischer and Newell [15], Jaffe et al. [25].

Clarke, and Weyant [2] consider the socially optimal investment in technology R&D programs in response to uncertain damages from climate change. They present a simple theoretical, social planning model in which the objective is to minimize the sum of the costs of R&D, the expected global costs of abatement, and the expected global damages from emissions:

$$\min_{\alpha} \quad g(\alpha) + \mathrm{E}_z \left\{ \min_{\mu} \quad c(\mu, \alpha) + D(\mu, z) \right\} \tag{9}$$

where α represents the effects of R&D on the abatement cost function. The (opportunity) costs of achieving a particular level of advance α are given by $g(\alpha)$, which is assumed to be increasing and convex. Abatement is represented by μ and $D(\mu, z)$ are the climate damages in the second period resulting from the total stock of emissions resulting from abatement μ, z is a stochastic parameter meant to capture uncertainty in climate damages, and E_z is the expectation operator over z. They consider how the optimal investment in R&D changes with increases in risk (in the Rothschild-Stiglitz [41] sense, i.e. mean-preserving-spreads). Using this model they show that 1) investment in all R&D programs will decrease with some increases in risk; but 2) some programs will increase with some increases in risk. The second point indicates that the representation of R&D makes a difference. In the second part of the paper they present a simple computational example, using a modified version of the DICE model. The results imply that the optimal investment in technical change that pivots the cost curve downward will increase with increases in risk that include a higher probability of high damage scenarios. On the other hand, the optimal investment in technical change that pivots the cost curve to the right (as in Figure 2) tends to decrease in increases in risk.

Baker and Adu-Bonnah [1] extend the above paper to consider uncertainty in the results of the R&D programs. Given an investment of $g(\bar{\alpha})$ they consider three possible outcomes of an R&D program: a breakthrough $\alpha = 1$, failure $\alpha = 0$, or mean advancement $\alpha = \bar{\alpha}$. The probability distribution over the three possible outcomes is as follows:

$$\alpha = \left\{ \begin{array}{cc} \text{value} & \text{probability} \\ 0 & p\left[1-\bar{\alpha}\right] \\ \bar{\alpha} & 1-p \\ 1 & p\bar{\alpha} \end{array} \right\} \tag{10}$$

The parameter p determines the riskiness of the R&D program, with $p = 0$ representing a no-risk program, and $p = 1$ representing a high risk program. Increasing p results in a mean-preserving-spread for any given $\bar{\alpha}$. The expected value of α equals $\bar{\alpha}$ for any p. Increasing $\bar{\alpha}$ results in a first order stochastic shift for any given p. They investigate, both theoretically and computationally using a modified version of DICE, how the riskiness of the program, represented by p, impacts the optimal level of investment in the program, represented by the optimal targeted amount of R&D $\bar{\alpha}^*$. They find that when technical change is represented as pivoting the cost curve down, then investment in a riskier program is considerably higher than in a certain program. When, however, technical change is represented as pivoting the cost curve to the right, the optimal investment is not significantly impacted by the riskiness of the program.

Baker and Shittu [4] consider firms' incentives to adopt technologies as a function of a carbon tax. They compare technical change that reduces the carbon intensity of the carbon input with technical change that reduces the price of the non-carbon input. They show that the marginal benefits to adopting the first technology are proportional to the total carbon tax paid by the firm; the marginal benefits to adopting the second technology are proportional to the unconditional demand for non-carbon inputs. These two quantities – total carbon taxes and unconditional demand for non-carbon inputs – react differently to increases in a carbon tax. The total carbon tax paid by the firm follows a Laffer curve as the carbon tax increases – total carbon taxes first increase in an increase in the tax, but as the tax gets very high the firm substitutes away from carbon energy, and eventually the total tax paid gets very small. The unconditional demand for non-carbon inputs will monotonically increase in a carbon tax, as long as carbon and non-carbon are elastic substitutes. Thus, the incentive to adopt differs by technology.

In the only other work that we are familiar with that compares two representations of technical change[7], van der Zwaan and Gerlagh [18] compare decreases in the cost of non-fossil energy sources with improvements in Carbon Capture and Sequestration (CCS), represented as reducing the emissions to output ratio. They use a learning curve approach, so the cost of non-fossil energy and the cost of CCS decrease as more of the technology gets put into play. They show that the time paths for the two technologies are qualitatively different, with the share of fossil technology that applies CCS first increasing and then decreasing to a stable level through time; whereas the share of non-fossil technology monotonically increases through time. They also point out that in the absence of a representation for CCS, carbon taxes and fossil fuel taxes have an identical impact. They do not compare the share of CCS and of non-fossil fuel across more and more stringent targets. In another paper [43], however, they compare the share of non-fossil energy use to overall energy savings, and find that the relative importance of energy savings first increases as the economy moves toward overall lower carbon rates, but then decreases, as non-fossil energy sources begin to play a larger role.

4.2 Milliman and Prince Revisited

In this section we present an illustrative example of how policy analysis is crucially impacted by assumptions about the impact of technical change on the MAC. We recreate the analysis from Milliman and Prince (MP from here on) under the assumption of increasing MAC, and show that incentives

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[7] Popp [38] includes energy efficiency and reduction in the price of a non-carbon technology; however, the paper does not compare the investment in the two R&D programs. Also, as shown above, both of these representations lead to a lower MAC.

to innovate differ for different technologies. We compare a firm's incentive to innovate and promote diffusion; non-innovating firms' incentives to adopt the innovation, and all firms' incentives to promote optimal agency response, across five different policy instruments: direct emissions caps; emissions subsidies; free permits; auctioned permits; and emissions taxes. We focus on non-patented discoveries. See [3] for details.

Figure 6 shows a single firm with an innovation which shifts its marginal cost curve from MAC to MAC'. The new marginal cost curve is lower over some range of abatement, but is higher at higher levels of abatement. We assume that the overall cost of abatement is always lower after technical change, thus the area bounded by $e^m x$ is larger than the triangle xMI (note that e^m is the business-as-usual emissions level). If we assume that the initial policy induces an emissions level that is to the left of the point x then the analysis from MP remains unchanged. Thus we assume that the initial emissions cap, e^* is to the right of x, where the marginal cost of abatement has been increased by technical change.

Figure 6 can also be interpreted as the marginal cost curves of a large number of identical firms, before and after the innovation has diffused. MD is the industry marginal damage cost associated with changes in the levels of emissions. Before technical change the emissions cap is set at e^* and the equivalent tax or permit price is T^*. After technical change, but before diffusion, the innovating firm will produce emissions given either a direct cap of e^* or a carbon tax, subsidy, or permit price of T^*. After diffusion and optimal policy response the new emissions cap is e^{**} and the equivalent tax or permit price is T^{**}.

See Table 3 for the relative rankings of each instrument from the innovator's point of view for each step of the process: the top half of the table reviews the results from MP; the bottom half shows the results under our assumptions. The ranking of the instruments with respect to the firm's incentive to innovate remains unchanged from MP – direct controls under-perform the other instruments. Under all instruments except direct controls the firm gains the area within $e^m x$ and loses the area within xfa.

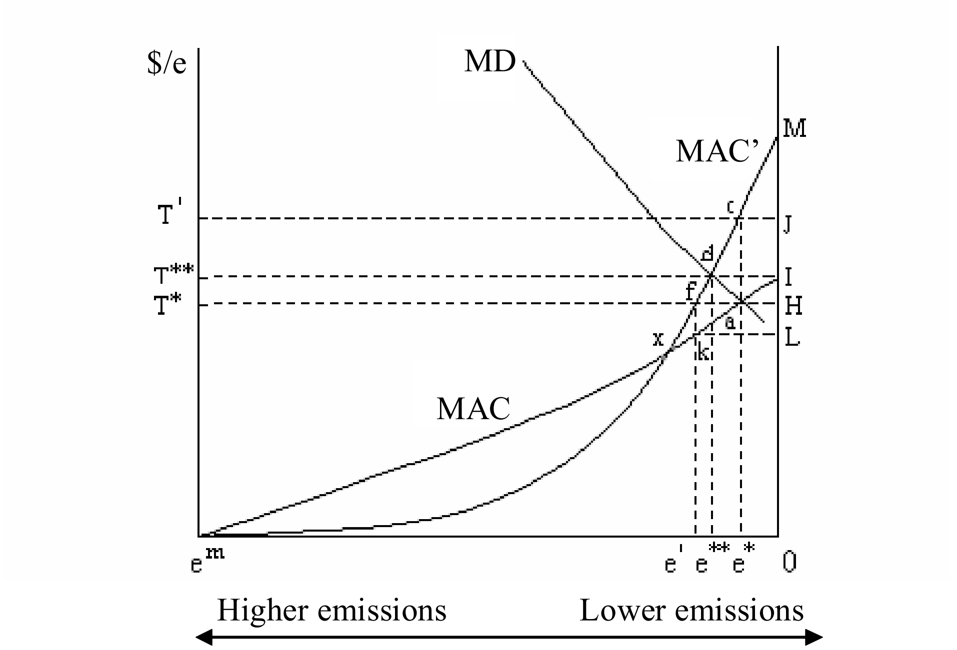

Figure 6: A model of technological change in pollution control

Next we consider the incentives to promote diffusion for both the innovator and the non-innovator. MP found that auctioned permits provided the innovator with a positive diffusion incentive: the auctioned price of permits was lowered through diffusion. In our case, auctioned permits provide the innovator with the most negative incentive: when diffusion shifts MAC to MAC' for all firms, the auctioned permits increase in price from T^* to T'. This is because, here, technical change increases the marginal cost of abatement. The other instruments remain in the same order as MP: taxes, subsidies and direct control have no impact on the incentive; firms are always worse off after diffusion under free permits. Non-innovators profit unambiguously from diffusion under all instruments except auctioned permits. It is possible that the increase in the price of auctioned permits may outweigh the benefit of lowered abatement costs. This would not necessarily prevent diffusion, however – any individual firm, taking the auctioned price as given, would benefit from adopting the new technology (ignoring the cost of adoption).

Next, we consider the firm's incentive to promote optimal agency response. We find that, as noted in MP, the results for optimal agency response are exactly the opposite here as in MP. Given higher marginal costs, the optimal agency response is to increase the emissions limit (i.e. make it less stringent, from e^* to e^{**}) or increase the tax/subsidy (from T^* to T^{**}). Thus, unsurprisingly, the industry has an incentive to support optimal agency response in every case except emissions taxes. In MP, when technical change decreased marginal costs, the optimal agency response is to decrease the limit or decrease the tax/subsidy, thus the opposite results.

Finally, the 4th and 8th rows of Table 3 compare the overall innovator gains from the entire process of technical change. We find that direct controls, emission subsidies, and free permits guarantee positive gains to innovations that increase marginal abatement cost; for auctioned permits and emission taxes the result is ambiguous. This result is in contrast to the result in MP, where auctioned permits and taxes resulted in gains, and direct controls, subsidies, and free permits were ambiguous. The reason for the difference is that under an increasing MAC technical change reduces the stringency of the policy for direct controls and free permits, and increases subsidies. Taxes and auctioned permits, on the other hand, could lead to a loss if the transfer loss due to higher tax/price outweighs the savings in abatement cost. Note that if the marginal damages are constant then there is a clear gain for taxes and auctioned permits as well – it requires steeply sloped marginal damages to get a loss. However, all these calculations are net of the cost of technical change. More generally, this result, like the result in MP is heavily influenced by optimal agency response. If we only look at the combined incentives to innovate and promote diffusion, it can be shown that taxes and subsidies provide the greatest incentive, followed by free permits and direct controls, with auctioned permits last. In fact, it cannot be guaranteed that auctioned permits will lead to a gain after diffusion, because the loss from diffusion is potentially large. Taken altogether the dominant choice is emission subsidies: they tie for first in all rankings. Emission taxes, however, are not far behind, especially if the marginal damages are almost flat. In

MP, auctioned permits are the dominant choice, but again, emissions taxes are not far behind. Thus, as long as marginal damages are not too steep, emission taxes may be the most robust instrument for promoting a variety of technologies. An interesting implication of this exercise is that different policy instruments may provide incentives for firms to move down different paths of innovation. If a firm faces a choice between two technologies that will lower overall costs, but one decreases the MAC while the other increases the MAC, then the presence of emission subsidies may cause firms to choose the technology that increases the MAC. This illustrates the importance of accurately representing technical change when evaluating policy instruments.

MAC Decreasing	Direct Controls	Emissions Subsidy	Free Permits	Auctioned Permits	Emissions Taxes
Innovation Promotion	5th	1st	1st	**1st**	1st
Diffusion Promotion	2th	2nd	5th	**1st**	2nd
Optimal Agency Response	Oppose	Oppose	Oppose	**Oppose**	Favor
Overall Innovator Gain	Uncertain	Uncertain	Uncertain	**Gain**	Gain
MAC Increasing					
Innovation Promotion	5th	**1st**	1st	1st	1st
Diffusion Promotion	1st	**1st**	4th	5th	1st
Optimal Agency Response	Favor	**Favor**	Favor	Favor	Oppose
Overall Innovator Gain	Gain	**Gain**	Gain	uncertain	uncertain

Table 3: Instrument ranking comparison between increasing and decreasing MAC

5 Discussion

Of central interest to environmental economics is understanding how the incentive to innovate is impacted by the economic environment; and how innovation impacts incentives to reduce pollution. Yet, little attention has been paid to how innovation is represented, especially in terms of how it impacts the MAC. In this paper we have pointed out the wide variety of ways in which technical change is represented in top-down and theoretical models, and illustrated that these different representations have complex and diverse impacts on the MAC. We have argued that this diversity is not specious:

it is likely that a diverse set of potential innovations will in fact have a diverse set of impacts on the MAC. We have shown, moreover, that different representations of technical change have implications for model results. Therefore, we conclude that a crucial direction for future work is to do a better job of connecting real-world potential innovations with their representations in models.

In this paper, we focus on one particular distinction – comparing technical change that decreases marginal costs everywhere, with technical change that increases marginal costs at high levels of abatement. We focus on this distinction because it has not been widely recognized that common representations of technical change can cause this phenomenon, nor that this phenomenon may occur in real life. This distinction only has relevance, however, if "high levels of abatement" are relevant. Thus, these results may not appear of central interest if we focus on, say, current estimates for mean damages from climate change. But climate change is really a problem of sequential decision making under uncertainty. To focus exclusively on mean damages is to ignore the "option value" of possible alternatives in terms of dealing with low-probability, high-damage outcomes. Therefore it is important to consider the entire abatement cost curve.

Gaining a better understanding of the relationship between real-world innovations and their impacts on the MAC is relevant to a number of questions. First, it will allow a re-interpretation of a number of results in the literature in terms of actual technologies. Many of the papers in Table 1 above, for example, use one specific representation of technical change, and therefore may apply only to a subset of all possible innovations. In particular, it would likely require a very broad R&D program to tilt the MAC down proportionally. Understanding impacts on the MAC may also provide intuition into results from more technologically detailed, bottom-up type models. Second, by recognizing that a variety of potential innovations are best characterized by a variety of representations, we can improve the state of modeling and address new areas. For example, most of the literature has only examined the dynamic efficiency of policy instruments in frameworks with a single technology; it is possible that insights from this literature could be changed or enriched by considering a portfolio of technological options. Similarly, the economic implications of R&D policies will be much richer when a portfolio of technologies is considered. More generally, hypotheses such as those suggested and tested in a number of the models above can be tested under a variety of representations of technical change. Third, empirical evidence, including engineering estimates, on how technical change impacts the MAC may help technologically detailed models to get their representations right. Finally, it will help researchers to better represent endogenous technical change in energy-economy models. We have shown here that firms' technological responses to environmental policy are complex and depend on the representation of technical change. With a better understanding of impacts on the MAC researchers will be able to more accurately apply past empirical data on technical change to the modeling of potential innovations. For example, Popp presents empirical results on end-use energy efficiency improvements [36]; and on SO_2 and NO_X control [39]. Given an understanding of how these innovations impact the MAC, researchers could then apply these results to other innovations that impact the MAC in similar ways. On the other hand, the empirical results may have limited relevance to innovations that have radically different impacts on the MAC.

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A Appendix

A.1 Substituting Knowledge for Energy

We re-cast the minimization problem described in (2), (3) and (4) as a maximization and form the Lagrangian as follows:

$$L = -P_c e_c - P_{nc} e_{nc} - \lambda \left[(e_c^{\rho} + e_{nc}^{\rho})^{\frac{\rho_e}{\rho}} + H^{\rho_e} - y^{\rho_e} \right] - \lambda_E \left[e_c - \bar{e} \right] - \lambda_{NC} e_{nc} \tag{11}$$

The Kuhn-Tucker first order conditions with respect to e_c, e_{nc} and λ are

$$-P_c - \lambda \rho_e e_c^{\rho-1} (e_c^{\rho} + e_{nc}^{\rho})^{\frac{\rho_e - \rho}{\rho}} - \lambda_E = 0 \tag{12}$$

$$-P_{nc} - \lambda \rho_e e_{nc}^{\rho-1} (e_c^{\rho} + e_{nc}^{\rho})^{\frac{\rho_e - \rho}{\rho}} - \lambda_{NC} = 0 \tag{13}$$

$$\left((e_c^{\rho} + e_{nc}^{\rho})^{\frac{\rho_e}{\rho}} + H^{\rho_e} \right)^{\frac{1}{\rho_e}} = y \tag{14}$$

and the complementary slackness conditions are

$$\lambda_E \geq 0 \text{ if } e_c = \bar{e} \text{ and } \lambda_E = 0 \text{ if } e_c > \bar{e} \tag{15}$$

$$\lambda_{NC} \geq 0 \text{ if } e_{nc} = 0 \text{ and } \lambda_{NC} = 0 \text{ if } e_{nc} > 0 \tag{16}$$

We assume that abatement takes place (implying that $e_c = \bar{e}$ and $e_{nc} > 0$). Substituting into (14), we solve for e_{nc};

$$e_{nc} = \left[(y^{\rho_e} - H^{\rho_e})^{\frac{\rho}{\rho_e}} - \bar{e}^{\rho} \right]^{\frac{1}{\rho}} \tag{17}$$

Substituting $\lambda_{NC} = 0$ and (17) into (13), we solve for λ;

$$\lambda = -P_{nc}\rho_e \left[(y^{\rho_e} - H^{\rho_e})^{\frac{\rho}{\rho_e}} - \bar{e}^{\rho} \right]^{\frac{1-\rho}{\rho}} (y^{\rho_e} - H^{\rho_e})^{\frac{\rho-\rho_e}{\rho_e}} \tag{18}$$

Substituting (18) and (17) into (12) and solving for λ_E, we arrive at the expression in (5).

Taking the derivative of λ_E with respect to H, we have

$$\frac{\partial \lambda_E}{\partial H} = P_{nc}(\frac{1-\rho}{\rho}) \left[(y^{\rho_e} - H^{\rho_e})^{\frac{\rho}{\rho_e}} - \bar{e}^{\rho} \right]^{\frac{1-2\rho}{\rho}} \frac{\rho}{\rho_e} (y^{\rho_e} - H^{\rho_e})^{\frac{\rho-\rho_e}{\rho_e}} (-\rho_e H^{\rho_e - 1}) \tag{19}$$

$$= -P_{nc} H^{\rho_e - 1}(1-\rho) \left[(y^{\rho_e} - H^{\rho_e})^{\frac{\rho}{\rho_e}} - \bar{e}^{\rho} \right]^{\frac{1-2\rho}{\rho}} (y^{\rho_e} - H^{\rho_e})^{\frac{\rho-\rho_e}{\rho_e}} \tag{20}$$

It can be seen that $\frac{\partial \lambda_E}{\partial H}$ is negative, since $\rho \leq 1$ and $\left[(y^{\rho_e} - H^{\rho_e})^{\frac{\rho}{\rho_e}} - \bar{e}^{\rho} \right] = e_{nc}^{\rho} > 0$. That implies that marginal costs are decreasing with knowledge.

A.2 Substituting Knowledge for Fossil Energy

For the nested function defined in (6), we have

$$C(y; P_c, P_{nc}, H_c, \bar{e}) = \max_{e_c, e_{nc}} - P_c e_c - P_{nc} e_{nc} \tag{21}$$

$$\text{s.t. } y = \left(\left(e_c^{\rho_c} + H_c^{\rho_c} \right)^{\frac{\rho}{\rho_c}} + e_{nc}^{\rho} \right)^{\frac{1}{\rho}} \tag{22}$$

$$e_c \leq \bar{e} \tag{23}$$

The Lagrangian is:

$$L = -P_c e_c - P_{nc} e_{nc} - \lambda \left[\left(e_c^{\rho_c} + H_c^{\rho_c} \right)^{\frac{\rho}{\rho_c}} + e_{nc}^{\rho} - y^{\rho} \right] - \lambda_F \left[e_c - \bar{e} \right] - \lambda_{NC} e_{nc} \tag{24}$$

and the complementary slackness conditions are

$$\lambda_F \geq 0 \text{ if } e_c = \bar{e} \text{ and } \lambda_F = 0 \text{ if } e_c > \bar{e} \tag{25}$$

$$\lambda_{NC} \geq 0 \text{ if } e_{nc} = 0 \text{ and } \lambda_{NC} = 0 \text{ if } e_{nc} > 0 \tag{26}$$

The Kuhn-Tucker first order conditions with respect to e_c, e_{nc} and λ are

$$-P_c - \lambda \rho e_c^{\rho-1}(e_c^{\rho} + H_c^{\rho})^{\frac{\rho-\rho_c}{\rho}} - \lambda_F = 0 \tag{27}$$

$$-P_{nc} - \lambda \rho e_{nc}^{\rho-1} = 0 \tag{28}$$

$$\left(\left(e_c^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho}{\rho_c}} + e_{nc}^{\rho}\right)^{\frac{1}{\rho}} = y \tag{29}$$

Substituting $\bar{e} = e_c$ we solve for e_{nc}

$$e_{nc} = \left[y^{\rho} - \left(e_c^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho}{\rho_c}}\right]^{\frac{1}{\rho}} \tag{30}$$

Following a similar analysis as above, we have;

$$\lambda_F = P_{nc}\bar{e}^{\rho_c-1}\left[y^{\rho} - \left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho}{\rho_c}}\right]^{\frac{1-\rho}{\rho}}\left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right)^{\frac{\rho-\rho_c}{\rho_c}} - P_c \tag{31}$$

Substituting $H_c^{\rho_c}$ for $\left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right)$, and taking the derivative of λ_F with respect to H, we have;

$$\frac{\partial \lambda_F}{\partial H_c} \approx P_{nc}\bar{e}^{\rho_c-1}\left\{(\rho-\rho_c)\left[y^{\rho} - H_c^{\rho}\right]^{\frac{1-\rho}{\rho}} H_c^{\rho-\rho_c-1} + \left(\frac{1-\rho}{\rho}\right)(-\rho)\left[y^{\rho} - H_c^{\rho}\right]^{\frac{1-2\rho}{\rho}} H_c^{2\rho-\rho_c-1}\right\} \tag{32}$$

Collecting like terms, and simplifying;

$$\frac{\partial \lambda_F}{\partial H_c} \approx P_{nc}\bar{e}^{\rho_c-1}\left[y^{\rho} - H_c^{\rho}\right]^{\frac{1-\rho}{\rho}} H_c^{\rho-\rho_c-1}\left\{(\rho-1)\frac{H_c^{\rho}}{y^{\rho} - H_c^{\rho}} + (\rho-\rho_c)\right\} \tag{33}$$

Again, note that if $\left(\bar{e}^{\rho_c} + H_c^{\rho_c}\right) \approx H_c^{\rho_c}$ then $y^\rho - H_c^\rho = e_{nc}^\rho > 0$.

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