Technical Change in Energy-Related Methane Abatement

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ABSTRACT

This paper presents a framework developed by the U.S. Environmental Protection Agency and RTI for incorporating technical change in non-CO_2 greenhouse gas (GHG) mitigation projections over time. The framework is demonstrated for coal-related methane sources, but it is applicable for the full range of non-CO_2 GHG abatement options. Changes in emissions over time depend on both the rate of technical change in mitigation technologies and technology adoption. Estimates of technical change incorporate increased efficiency in current technologies, reduction of costs in mitigation technologies over time, and the entrance of new technologies into the market. Efficiency and price trends for shifting the MACs are based on data from abatement technology experts.

1.0 INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) has developed marginal abatement curves (MACs) reflecting the cost of mitigating methane emissions in 21 regions of the world for five major anthropogenic sources: coal mining; livestock manure management; natural gas production, processing, transmission and distribution; oil production; and solid waste management (EPA, 1999; EPA, 2001). The International Marginal Abatement Curve (I-MAC) model provides analysts with a transparent methodology that can be used to conduct similar analyses for other countries and provides reliable data that can be integrated into a wide range of climate control models.

The MACs provide an estimate of methane reductions from the baseline level for 2010 and 2020. However, the analysis is based on current costs and reduction efficiency and considers only currently available technologies. This paper presents a framework for adjusting MACs produced by I-MAC to account for technical change and technology adoption. The approach for incorporating technical change is illustrated for the coal mining sector, with the result being that MACs shift outward over time, increasing methane reductions for any given carbon price.

Technical change affects the cost and benefits of mitigation options over time. New technologies follow a life-cycle where early installation and operating costs are high, but then decrease over time as methods are refined. Technical improvements lead to reductions in capital and labor costs, and increase the reduction efficiency of mitigation options. In addition, knowledge spillovers and the expiration of patents lead to increased competition that lowers market prices.

Technology adoption plays an important role in the timing of realized emissions reductions. Expensive installations by early adopters serve to demonstrate the technology, lowering the perceived risk for following adopters. In addition, early adopters are also involved in the development of solutions for integrating new technologies into legacy systems, hence lowering costs to later adopters. In this ways, it is the heterogeneous cost and benefit characteristics of individual sources that determine the rate of adoption, with entities in the tails of the distributions significantly affecting the timing of adoption by “mainstream” or “typical” entities.

The majority of this paper focuses on integrating technical change into MACs. After a review of how MACs are generated and used in greenhouse gas (GHG) models, an approach for incorporating technical change is presented and demonstrated using coal mining mitigation options as an example. Trends in real prices and productivity (for both capital and labor) are used to shift MACs downward over time, reflecting that the installation and operating costs of options are likely to decrease and the benefits from sales of recovered methane are likely to increase over time. Options are partitioned into capital, labor, materials, and energy cost/benefit share and these components are then linked to individual price indices and productivity trends. The approach is flexible in that regional trends can be employed relatively simply to capture differences across global regions. In addition, trends can vary across mitigation options to capture option-specific changes, such as unique trends in equipment performance (capital productivity) or learning by doing (labor productivity).

2.0 INCORPORATING MACS INTO GHG MODELS

Until very recently, modeling economic consequences of climate change strategies focused on carbon dioxide emissions because these are the most significant contributors to GHG concentrations and are directly tied to consumption of fossil fuels, which are easily monitored and quantified. Several options exist for incorporating non-CO_2 gas controls in models, depending on the type of model used in analyzing GHG control. These options include the following: (1) create an “emissions control” sector that uses inputs from other industries and provides emissions control as an output; (2) give agents access to new, and presumably more costly, technologies for producing goods that result in fewer emissions than conventional technologies; (3) introduce emissions control by modeling gases as inputs to production and determine an elasticity of substitution between emissions and other inputs so that the resulting MACs replicate estimates from engineering studies[1]; and (4) exogenously compare an estimated carbon price to the MACs to find the level of non-CO_2 reductions at that price and then re-estimate the model with fewer carbon reductions required to meet an overall GHG target.

The first option, modeling an emissions control activity, requires a significant amount of information to allow models to endogenously create marginal abatement curves. The approach is most similar to methods used by “bottom-up” models, which characterize specific technologies when investigating GHG controls. Each sector of the economy will have different options for reducing emissions and will need a different mix of capital, labor, and other inputs to achieve reductions. This approach is conceptually similar to how some models address other types of emissions reductions. For example, utility dispatch models, such as the Integrated Planning Model (IPM)[2] specify a particular technology such as scrubbers, which are designed to reduce SO_2 emissions from electricity generation. Capital and operating costs are estimated, along with

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[1] This third option is similar to how carbon emissions are typically modeled as an input to production processes in CGE models.

[2] See http://www.icfconsulting.com/Markets/Energy/ipm.asp.

the technology's ability to lower emissions. The model then decides how many scrubbers to build and install on existing utility boilers to meet a given emissions target.

The second option, incorporation of new technologies in models, would require similar information to the first option. Again, this type of approach can most easily be applied in technology rich "bottom-up" models, although "top-down" computable general equilibrium (CGE) models could employ it as well. Rather than including a separate "environmental clean-up" activity, as in the first option, an entirely new production technology would be specified. For example, a new mitigation option for mining coal, resulting in lower emissions, would be provided as an option and the model would decide whether to implement the option based on cost and policy scenarios. To adopt this approach, modelers would need the flexibility to characterize new, cleaner production processes in their models. They would also need to have enough available model dimensions to allow them to include a wide variety of alternative technologies. The second option would also require data on the extent of emissions reduction opportunities from each technology. Models will always choose the least-cost option presented to them; consequently, the modeler would need to specify a variety of options and their associated market potentials to prevent "bang-bang" solutions in which a model implemented the least costly option in unrealistic amounts. Currently, work is underway to incorporate non-CO_2 abatement technologies into MARKAL-MACRO for the U.S. using this approach.[3]

The third option, adjusting elasticities to match MAC functions, is simpler than the other two and involves specifying an elasticity of substitution between inputs of non-CO_2 gases and other types of inputs in the model. This option has already been employed by the "top-down"

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[3] The MARKAL-MACRO model was developed by Brookhaven National Laboratory (BNL). See http://www.bnl.gov/est/MARKAL-MACRO.htm.

CGE model at MIT (Emissions Prediction and Policy Analysis [EPPA] Model).[4] The elasticity can be selected so that overall costs of controlling emissions are similar to those from engineering studies. However, this option does not make use of information, if available, on the types of production inputs needed to reduce emissions. The MAC functions assume that emissions reductions are achieved through proportional changes in use of current production inputs.

The fourth option, exogenously reading MACs, avoids the need to explicitly include non-CO_2 reduction options within a model and can be used with any type of model. This is the simplest approach of the four and does not require any information beyond the shape of the MAC. However, as noted by Hyman et al. (2002),[5] use of exogenous MACs will miss some of the model interactions that would occur if they were endogenous. Spillover effects on non-CO_2 emissions from carbon limits are not captured, nor are some of the implications for trade and investment. An additional omission is that this option does not explicitly take into consideration the fact that resources (e.g., capital, labor) are necessary to achieve the emissions reductions associated with a MAC function and therefore must be diverted from other productive uses in the economy. Models such as MERGE,[6] SGM,[7] etc. have used this approach in modeling multigas scenarios.

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[4] See Hyman et al. (2002).

[5] See http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt94.pdf.

[6] See Manne et al. (1995) and http://www.stanford.edu/group/MERGE.

[7] The Second Generation Model (SGM) was developed by Pacific Northwest National Laboratory (PNNL). See http://www.pnl.gov/China/sands-jiang.pdf.

An additional caveat for the third option is that, initially, “no-regrets” options characterized in EPA’s bottom up modeling of non-CO_2 gases (i.e., options that appear to be profitable without a GHG price) must be assumed to have some positive cost in model structures that assume perfect markets and rational agents. For example, if a model uses constant elasticities of substitution (CES) production functions, all input cost shares have to be greater than zero, removing the possibility of emissions reductions at negative costs (i.e., more cost-efficient technologies are available today than businesses are using). Two possible methods can be used to address these “no regrets” options: shift the MAC curve up so that it starts at a zero (or small positive) price or remove the emissions associated with the “no regrets” options from baseline emissions projections and eliminate that part of the MAC.

2.2 Using MACS to Model GHG Policies

Regardless of which approach is adopted to incorporate MACs, it is important to have information on how these functions will change over time because the models used to examine GHG policies generally have long horizons. Including information on how mitigation technologies’ costs and emissions reductions may change over time allows modelers to better characterize the effects of including non-CO_2 controls in climate change policies. As MAC functions shift outward/downward over time in response to declining costs and increased efficiencies, non-CO_2 gases will continue to play an important role in future emissions reductions. New technology options will also shift the MACs and influence their shape. Incorporating these changes in models will give policy makers a more accurate picture of the advantages of climate policies including all GHG gases. This study provides information, both technology specific and at the more aggregated level of the MAC curve, on how technical change is expected to effect abatement opportunities between 2000 and 2020. From this, general estimates beyond 2020 can be made using the rates of technical change presented.

3.0 OVERVIEW OF I-MAC MODEL

The underlying objective of the I-MAC model is the construction of region-specific marginal abatement cost curves that describe methane abatement opportunities. The model builds on the USEPA's engineering-economic cost analysis for the United States and similar work by the European Union (EPA, 2001a, 1999; EC, 2001). Methane sources currently analyzed in the model include coal mining; livestock manure management; natural gas production, processing, transmission, and distribution; oil production; and solid waste management.

3.1 Determining Abatement Potential

The model calculates a technology option's emissions reduction per year in million metric tons of carbon equivalent (MMTCE) or gigagram of methane (Gg CH_4). This value is estimated for each region and source by multiplying the total baseline emissions in a selected year by an "abatement potential" factor. This factor is a function of specified characteristics of the technology, including availability, reduction efficiency, and technical and economic applicability.

Availability (or "Presence") identifies whether the technology option is available in the sector or region of interest. *Reduction efficiency* determines the actual emissions reductions achievable after the option is applied to an emissions stream. *Technical applicability* is determined by the composition of emission sources in the sector and determines the option's "technically achievable" emissions for abatement. *Economic applicability* captures regional economic and infrastructure constraints.

To compute the abatement potential factor for a particular option, the above-mentioned factors are multiplied together. For example, the abatement potential calculation for the U.S. coal sector's technology option "degasification and pipeline injection" is calculated as follows: a*vailability* yes = 1; t*echnical applicability* for underground mining emissions is 87 percent of the total coal sector emissions in the United States; r*eduction efficiency* of degasification and pipeline injection is 57 percent; e*conomic applicability* is 100 percent. Therefore, the abatement potential factor for this option is computed to be 1 * 87% * 57% * 100% = 49.5%.

3.2 Calculating the Breakeven Price

The discounted cash flow analysis uses fixed cost, recurring cost, and total revenue (or benefit) of each technology option to calculate the "breakeven price" for each technology by sector. The cost/revenue estimates come primarily from U.S. and EU bottom-up engineering analysis. To allow for regional variation, the model adjusts these cost/revenue using regional labor rates, gas prices, or electricity prices.

The analysis solves the following equation for the breakeven price (P):

$$\sum_{t=1}^{T}\left[\frac{(PxER)}{(1+DR)^{t}}\right]=CC+\sum_{t=1}^{T}\left[\frac{\left(O\,\&\,M-R-TB\right)}{\left(1+DR\right)^{t}}\right]$$

where

P = the breakeven price of the option in \$/TCE or \$/TCH$_4$,

ER = the emissions reduction achieved by the technology,

DR = the selected discount rate,

T = the option's lifetime,

CC = the one-time fixed-cost of the option,

O&M = the recurring cost of the option (scaled based on regional labor costs), R = the after tax benefits generated from energy production or sales of by-products of abatement (scaled based on regional energy prices), and

TB = the tax benefit from depreciation equal to CC/T * tax rate.

3.3 Construction of the Marginal Abatement Curve

After the abatement potential and breakeven price are computed, the I-MAC model constructs the MAC curves in the following manner. First, options are ordered from least expensive (lowest breakeven price) to most expensive (highest breakeven price). The model then sums up the reductions for all options in a particular sector to determine total abatement at a given price. As shown in Figure 1, the individual abatement options plotted in the price–quantity space trace out the MAC.

4.0 METHODOLOGY FOR INTEGRATING TECHNICAL CHANGE

Technical change has the potential to shift MACs for methane emissions outward over time as abatement potential increases and net costs decrease. In addition, new options are likely to become available in the future that will introduce new (potentially low cost) segments into the MAC. The result is that the marginal cost of methane abatement will decrease, leading to greater potential emissions reductions at any given price.

4.1 Impact of Technology Change on Abatement Potential

Abatement potential will likely increase over time as a result of technology change. In terms of the I-MAC model input parameters, this will primarily be driven by more potential options becoming feasible (changes in availability/presence), increases in reduction efficiency, and infrastructure expansion (changes in economic applicability). These technology trends will shift the abatement curve out as low-cost options increase their abatement share relative to total emissions (i.e., the option points in Figure 1 shift out horizontally).

Operationally, this can be modeled in I-MAC by changing the presence and economic applicability input matrices over time and by introducing a trend in reduction efficiency over time. Changes in the presence and economic applicability matrices could be linked to regional factors such as growth in natural gas pipeline infrastructure. Changes in reduction efficiency could be linked to regional or global technology trends related to the specific abatement technology or, in the absence of specific abatement technology trends, linked to general economy-wide technology trends.

It is less clear how technical applicability will change over time as a result of technology advances. This parameter is primarily a function of the fundamental characteristics of individual emissions sources and individual abatement options, which may or may not change over time. For example, the technical applicability of coal abatement options depends largely on the quantity and concentration of methane associated with the mines in a geographic region. The average characteristics of mines will change over time as old mines close and new ones open. However, for a specific option, technology change may not influence technical applicability as much as shifts in geographic characteristics.

4.2 Impact of Technology Change on Breakeven Price

One-time costs, annual costs, and annual benefits are all likely to be affected by technology change over time affecting the breakeven price for an abatement option. The one-time costs and annual costs input into the I-MAC model are typically built up from detailed engineering analysis and incorporate a wide range of production factors, including expenditures on capital, labor, material, and energy. Each of these input factors may have different productivity and price trends resulting from technology change over time. In addition, trends in factor inputs may vary by country or region. For example, in developing countries where skilled labor is in short supply, average labor productivity may increase at a faster rate compared to developed countries. In contrast, trends in the energy consumption of abatement technologies may be the same across most countries and regions through the world.

To capture this richness of differing technology trends, input costs for abatement options are separated into cost share by factors of production. As shown in Table 1, aggregate one-time costs and annual cost estimates can be partitioned into expenditures on capital, labor, material, and energy. These cost shares can then be expressed in terms of price times quantity (normalizing price equal to one). Expressing cost shares in terms of price and quantity allows increased flexibility in integrating trends resulting from technology change.

In a perfectly competitive global market, price trends would be the same throughout the world and would be closely tied to productivity increases in each factor of production. However, because perfectly efficient global markets do not exist everywhere, our approach allows for the use of regional trends in both price and quantity (changes in quantity reflecting productivity changes). Price trends reflect regional changes in supply and demand, as well as production costs. Productivity trends reflect regions' adoption of new technologies, along with changes in skill level (education) of the local labor force. Table 2 illustrates the time trends in price and quantity that capture technical change.

The final column in Table 1 illustrates how price and quantity trends can be applied to the cost shares and then costs recalculated to obtain adjusted one-time costs and annual costs that reflect technology change. A similar approach is used to incorporate technology change into annual benefits, where benefits are disaggregated into their benefit shares (energy and nonenergy) and recalculated after applying price and reduction efficiency trends.

An important feature of this modeling approach is its flexibility in the level of detail in the trend analysis needed to operationalize the model. To operationalize the approach for incorporating technology change, trends in price and productivity are needed for the country or region being analyzed. A simplifying feature is that, because abatement options are defined in terms of capital, labor, materials, and energy, the trends shown in Table 2 can be constant across all options, sectors, and emission sources. This approach minimized the amount of trend analysis needed to populate the technology change components of the model.

However, the approach also has the flexibility to incorporate more detailed information on technical change. In countries such as the United States where detailed price or productivity studies are available, these time trends can be used in place of the more general regional capital, labor, materials, and energy price and productivity trends. For example, horizontal drilling for coal mine abatement options may significantly increase the productivity of drilling equipment. Using this option-specific productivity trend would be preferable to using an average national productivity increase for capital.

An additional level of detail supported by the modeling approach is to first partition an abatement option into its core components or activities. For example, coal mine degasification and pipeline injection activities can be grouped as drilling, compressors, fan and ventilation, enrichment, on-site conversion into electricity or process heat, and pipeline injection. The benefits of partitioning costs into components and activities are described in the following section and illustrated using coal mining abatement options as an example.

5.0 COAL MINING OPTION EXAMPLE

Coal mining abatement options are used to illustrate our methodology for incorporating technology change in the development of MACs. Our example for integrating technology change into future MACs focuses on trends in the cost and benefit parameters that are used in the net present value analysis to determine the breakeven price. This is in part driven by practical considerations reflecting that cost and benefit input parameters are simpler to link to publicly available price and productivity trends published by academic and government organizations.

The EPA's I-MAC modeling system currently includes three technological options for mitigating methane emissions from coal mines. These options are listed below.

- **Degasification and Pipeline Injection**

  In the first option, high quality methane is recovered from coal seams by drilling vertical wells 5 years in advance of a mining operation, horizontal boreholes 1 year before mining, and gob wells. The gas recovered is injected into a natural gas pipeline requiring virtually no purification. This option assumes that gob gas sales decline over time because of declining levels of concentration.

- **Enhanced Degasification, Gas Enrichment, and Pipeline Injection**

  Under this option, methane is recovered in the same fashion as the first option using vertical wells, horizontal boreholes, and gob wells. In addition, the mine invests in enrichment technologies such as nitrogen removal units (NRUs) and dehydrators, used primarily to enhance gob well gas by removing impurities. This option also assumes tighter well spacing to increase recovery. The enrichment process and tighter spacing improve recovery efficiency by 20 percent (EPA, 1999).

- **Flow Reversal Oxidizers**

  These technologies have the potential to be applied to the methane emitted from a coal mine's ventilation air. It is not economically feasible to sell this gas into a pipeline because of extremely low concentration levels. However, by ducting ventilation air into a flow reversal oxidizer, approximately 95 percent of the methane from the ventilation air could be mitigated, generating useful heat as a by-product.

These abatement options can be broken into their basic components and activities, as indicated in Table 3. The advantage of segmenting options into their core building blocks is that these blocks (and the associated technology trends) can potentially be reused in assessing abatement options within and across sectors. As shown in Table 3, Degas and Enhanced Degas coal mine options modeled in the I-MAC system use similar activities and equipment for recovery and mitigation.

5.1.1 Drilling

Drilling is associated with both degasification and enhanced degasification. Vertical wells and in-mine horizontal boreholes are used to recover methane prior to mining and from gob wells. In-mine horizontal drills and surface rigs are required for recovery. Costs associated with drilling vary depending on the length and/or depth requirements, mine location, and the geological composition of the drill site. In addition, the drilling cost should be higher for the enhanced degasification option because of the increased number of wells drilled.

5.1.2 Compressors

Once methane has been accessed by drilling, it must be moved through the specified abatement technology process to its final use. Extracting gas from under the ground requires pumps and compression to bring it to the surface. Techniques vary depending on whether the gas is coming from wells or ventilation air. Gas from wells must be pressurized using compressors and pumps. In addition, compressors are used to push the gas through the local gathering systems to commercial pipelines.

Costs include materials, labor, and energy associated with initial setup and annual operation and maintenance. The I-MAC model accounts for one compressor per wellhead, in addition to a compressor at the purification site. In the case of pipeline injection, one or more compressors are required to move the gas to the point of injection. There are a variety of use options once the gas is extracted from a mine. Different use options may be employed, depending on gas quality and the specific characteristics of the mine.

5.1.3 Fans and Ventilation Ducts

The recovery of methane from ventilation air requires a system of surface ductwork and fans to move the air from the ventilation opening to the oxidation system.

5.1.4 Enrichment

Coal mine methane varies in the concentration level depending on its origin and thus requires a process of purification before it can be sold into a natural gas pipeline. Gas recovered in advance of mining is nearly pure methane and often simply requires dehydration or some CO_2 rejection. Gob well gas is typically between 30 percent and 95 percent methane concentration and thus requires various levels of purification.

The medium quality gob gas requires an enhancement system that can remove nitrogen, oxygen, carbon dioxide, and water vapor from the methane. The system consists of an nitrogen rejection unit (NRU), which is the most critical and often most expensive component of the system. Three NRU technologies are available: cryogenics using heat exchangers, pressure swing absorption (PSA) using pressurized absorption, and selective absorption using solvents with different absorption capacities.

5.1.5 Pipeline Injection

Most natural gas companies require 97 percent methane concentration. As stated earlier, the gas recovered in advance of mining tends to be relatively pure and requires little purification. Gob well gas requires additional purification. Once concentration levels have been met, the gas must be carried to the nearest natural gas pipeline by building a feeder pipeline and compressor stations to deliver it.

Table 4 is an option cost worksheet that can be used to disaggregate coal mining options into cost shares for integrating technical change. Once the cost shares are identified, price and quantity trends can be applied and the shifts in the MACs calculated over time. Given the cost shares presented in Table 4 and the annual trends presented in Table 5, a series of MACs can be calculated.

5.1.6 Direct (On-Site) Conversion

Although not currently included as one of the three coal mining abatement options used to develop EPA's MACs, medium to high quality methane (CH_4 concentration of 30 percent or higher) can be used for on-site power generation. The most common on-site conversion technologies are internal combustion turbines. In addition, methane can be used in on-site or nearby industrial boilers, as a primary fuel or co-fired with coal, to produce process heat.

5.2 Example Curve Shifts for Coal Mining Options

The procedure for integrating technical changes described in Section 4 was implemented for the U.S. coal mining sector. The percent changes listed in Table 5 were applied to the cost and benefit components illustrated in Table 4.

As shown in Table 6a and Table 6b, one-time-costs decrease about 23 percent in 2010 and 40 percent in 2020 as the projected equipment costs decrease over time. The decreases in costs and increases in benefits lead to shifts in the 2010 and 2020 MACs as shown in Figure 2a and Figure 2b. The changes in costs and benefits shift the MACs downward.

Because the reduction efficiency and technical applicability were not changed in this scenario, the level of emissions reduced (MMTCE) remains unchanged for each option. However, both will be affected by technology change over time. For example, reverse flow oxidation is currently 86 percent efficient, but is projected to increase in the near future. Also, oxidation is currently feasible for methane concentrations as low as 2 percent, but research is being conducted to reduce this to 1 percent and below. These factors would result in an additional horizontal shift in the "with technology" curves in Figure 2a and Figure 2b.

5.3 Incorporating New Options

Technology advances will continue to reduce the cost and improve the reduction efficiency of abatement technologies. Some changes will be incremental improvement of existing technologies or processes and will be captured by the trends noted in Table 5. For example, the future use of horizontal surface drilling may continue to decrease average drilling costs in the future. Other technology innovations will represent new components added to existing options. The development of micro turbines is an example of a new generation technology that may be available in the near future. Micro turbines will be used for on-site energy generation between 30kW and 2MW and may be able to use ventilation gas as their primary fuel. These can be modeled by adding new components to existing options in Table 4. An advantage of the component structure in Table 4 is that new components can be simply integrated in all appropriate abatement options. For example, direct on-site conversion using micro turbine technologies are likely to be applicable across many sectors. Technology trends in the price and efficiency of micro turbines will be the same for coal mines as for livestock applications within a region. Thus, conducting the analysis on the component level will simplify the analysis and help minimize the amount of trend inputs needed to incorporate technology change. New options or components can be added to the analysis as information becomes available. In the time frame of the study, it is unlikely that options unheard of today would enter into the market.

6.0 METHODOLOGY FOR INTEGRATING TECHNOLOGY ADOPTION

I-MAC currently models technology adoption using financial analysis for a representative entity within a region. Under this approach, all emission sources within a sector are assumed to be similar and will adopt a mitigation option when the price ($/TCE) exceeds the breakeven price of the option. The upward slope of the MACs results from multiple options being applied to individual sources and the general trend of higher reduction efficiency options being more costly.

However, in reality, empirical analysis has found that adopting new technologies typically occurs over time and can be represented by S-shaped cumulative adoption curves as shown in Figure 3. Adoption models such as the three parameter Bass diffusion model specify this as a dynamic process where the probability of adoption is a function of the economically feasible population (M_t) and cumulative number of adoptions (N_t):

$$n_t = \frac{\partial N_t}{\partial t} = \left[p + q\frac{N_t}{M_t} \right] \left[M_t - N_t \right].$$

Whereas S-shaped adoption curves have been motivated by a variety of theoretical underpinnings, an important principle common to all is the heterogeneity of agents making the adoption decision. Individual agents differ with respect to the cost of installation, benefits/returns to investment, availability/cost of funding, required rates of return (alternative investment opportunities), etc. As a result, the differences across entities lead to different adoption decision under different market and technology conditions.

In terms of the coal mining mitigation options discussed earlier, different coal mines will have different drilling costs as a result of geographic characteristics, quantity and quality of methane, and pipeline connection costs due to distances to pipelines and terrain. These differences will be reflected in their one-time costs, annual costs, and annual benefits and will result in each individual mine having its own breakeven price.

Not all the technology adoption factors discussed above can be explicitly modeled in MACs because of the static nature of the curves. For this reason we begin by grouping technology adoption factors into what is referred to as either static or dynamic.

6.1 Static Adoption Factors

The heterogeneity across sources within a sector could be directly incorporated into the I-MAC model by introducing variations in the cost, benefit, and applicability input data. The simplest, but most data intensive, approach would be to develop customized information for each individual source that reflected different vintages of capital and other site-specific characteristics. This individual-source approach may be feasible for sectors/regions with a limited number of sites, such as a coal mine in the U.S. where approximately 45 mines account for the large majority of methane emissions. For example, if the distance of each mine to a natural gas pipeline was known, unique breakeven prices for each mine could be calculated and used to develop an "option-level" MAC curve for each coal mining abatement option that involved pipeline injection. These option-level curves could then be aggregated to produce a sector-level coal mining MAC (as shown in Figure 1) that more accurately reflected individual adoption decisions.

However, for most sectors and regions of the world, detailed information on individual sources is not available and not economically practical to develop. In these instances, adoption can be modeled using input distributions that capture the underlying heterogeneity of the population sources. This would support the more realistic gradual adoption of technologies. For example, if forecasts are available for the growth of natural gas pipelines in China I-MAC could project the gradual (distributional) adoption of coal mine mitigation options in China. This would replace the all-or-nothing (dichotomous switching) behavior currently predominant in I-MAC.

Figure 4 illustrates the type of information needed to drive a gradual adoption process. In this example, the share of mines within 100, 50, and 10 miles of a natural gas pipeline gradually increases over time. This in turn shifts out the option-level MAC for the coal mining pipeline injection option as shown in Figure 5. This example could be operationalized in the I-MAC model by creating three representative mines that differ only by distance to a pipeline and then shifting the weighting of the representative mines over time. This approach maintains the convenience of representative data for most inputs and focuses on the key parameter (distance) for which variations over time drive adoption trends.

6.2 Dynamic Adoption Factors

As shown in the Bass diffusion model equation, part of what influences adoption is dynamic in that it depends on the cumulative stock of adopters to date. For example, in information models, such as learning by doing, the cost and/or risk of implementing abatement options decreases over time as pilot projects and early adopters refine the processes and technologies. In addition, economies of scale that further reduce costs may be realized as a critical mass of adopters is obtained.

However, the cumulative number of adoptions is a function of past prices. Thus, explicitly modeling learning-by-doing or economies of scale requires the abatement potential in any given year to be path dependent (i.e., a function of the time series of previous prices). Because carbon prices are not endogenous in the I-MAC model, these factors cannot be explicitly modeled. One alternative solution is to capture these effects in the exogenous time trends shown in Table 5. In this way the cost trends for specific technologies have embedded in them assumptions on the timing of technology diffusion based on expert judgment. Although this is a second best solution, it can be used to capture the important influences of adoption time paths.

7.0 CONCLUSION

MACs provide GHG models with an off-line, nonendogenous approach for including methane in multigas scenarios. However, developing MACs for modeling scenarios through 2020 and beyond presents many challenges. In particular, current USEPA MACs for methane reduction, with a few exceptions, do not account for technical change or technology adoption. This paper presents an approach for shifting MACs over time to account for these two factors and demonstrates its feasibility using coal mining abatement options for methane.

To estimate technical change, abatement options are dissagregated into basic components/activities onto which specific trends in productivity and cost can be mapped. The use of component/activities as the building blocks for the analysis leverages similarities across options to minimize the number of unique time trends needed for the analysis. Technology adoption is captured through introducing heterogeneity across emission sources, either on a source-by-source basis or by specifying the frequency distribution of key inputs, hence allowing adoption decisions to vary across entities dependent of vintaging and evolving market/infrastructure trends.

REFERENCES

de la Chesnaye, F.C., and D. Kruger. 2002. "Stabilizing Global Methane Emissions: A Feasibility Assessment." Proceedings of the 3rd International Symposium on Non-CO_2 Greenhouse Gases, January 21-23, Maastricht, Netherlands.

Delhotal, K.C., F.C. de la Chesnaye, and H.M. Pitcher. 2002. "Estimating Methane Mitigation in the USA and Internationally Beyond 2020." Proceedings of the 3rd International Symposium on Non-CO_2 Greenhouse Gases, January 21-23, Maastricht, Netherlands.

EC (European Commission) 2001. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Brussels. <http://europa.eu.int/comm/environment/enveco/climate_change/sectoral_objectives.htm>

Edmonds, J.A., C.N. MacCracken, R.D. Sands, and S.H. Kim. September 1998. "Unfinished Business: The Economics of the Kyoto Protocol." <http://www.pnl.gov/globalchang /pubs/gtsp/kyoto_paper_98.PDF>.

Energy Technology Systems Analysis Programme Annex VII (1999-2001). "Contributing to the Kyoto Protocol: MARKAL." <http://www.ecn.nl/unit_bs/etsap/markal/main.html>. Accessed April 2003.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. De Masin, and H.D. Jacoby. December 2002. "Modeling Non-CO_2 Greenhouse Gas Abatement." Report No. 94. MIT Joint Program on the Science and Policy of Global Change. <http://web.mit.edu/globalchange /www/MITJPSPGC_Rpt94.pdf>.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: Mitigation Report.* <http://www.grida.no/climate/ipcc_tar/wg3/index.htm>.

MacCracken, C.N., S.L. Legro, J.A. Edmonds, W.U. Chandler. "Climate Change Mitigation Costs: The Roles of Research and Economic Reform." <http://www.pnl.gov /globalchange/pubs/gtsp/maccr.pdf>.

Manne A, Mendelsohn R, Richels RG. 1995. "MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies." *Energy Policy* 23(1):17-34.

Manne, A.S., and R.G. Richels. April 2000. "A Multi-Gas Approach to Climate Policy—With and Without GWPs." <http://www.stanford.edu/group/MERGE/multigas.pdf>.

Seebregts, Ad J., Gary A. Goldstein, and Koen Smekens. 2001. "Energy/Environmental Modeling with the MARKAL Family of Models." <ftp://ftp.ecn.nl/pub/ www/library/report/2001/rx01039.pdf>.

U.S. Environmental Protection Agency (EPA). 1999. *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions.* EPA 430-R-99-013.

U.S. Environmental Protection Agency (EPA). 2001a. *Addendum Update to U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*. Washington, DC.

Figure 1. U.S. Marginal Abatement Cost Curve for Coal Mining (2010)

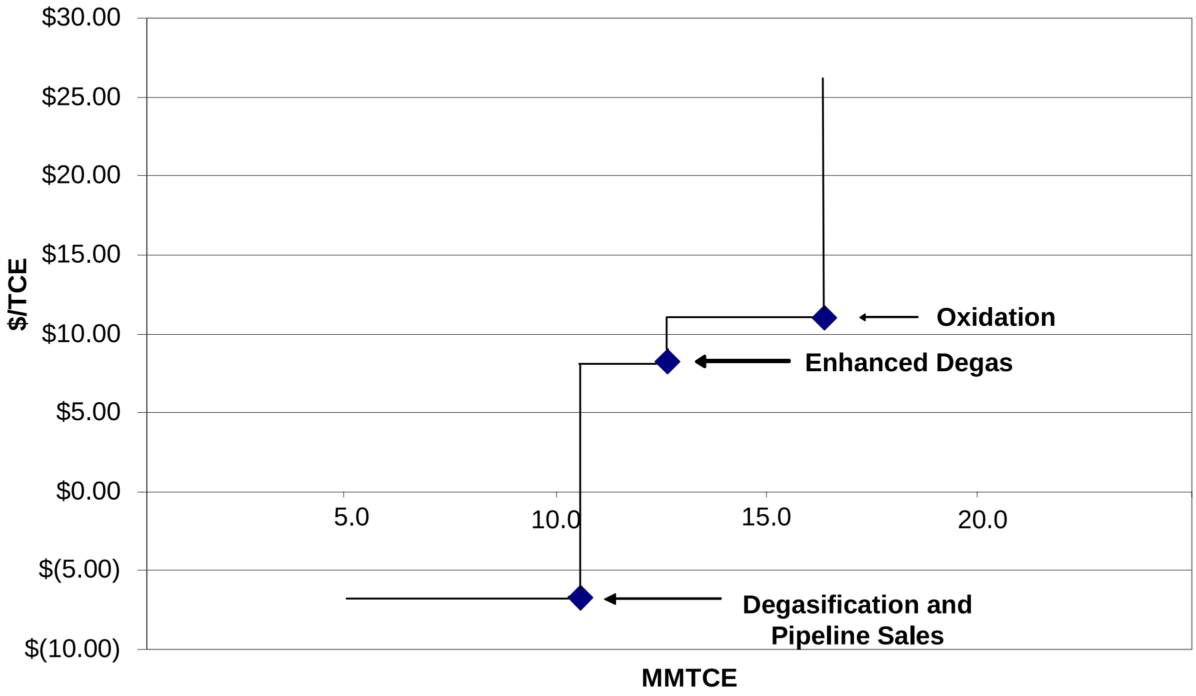

Figure 2a. MAC Shift with Technical Change (2010 U.S. Coal Mining)

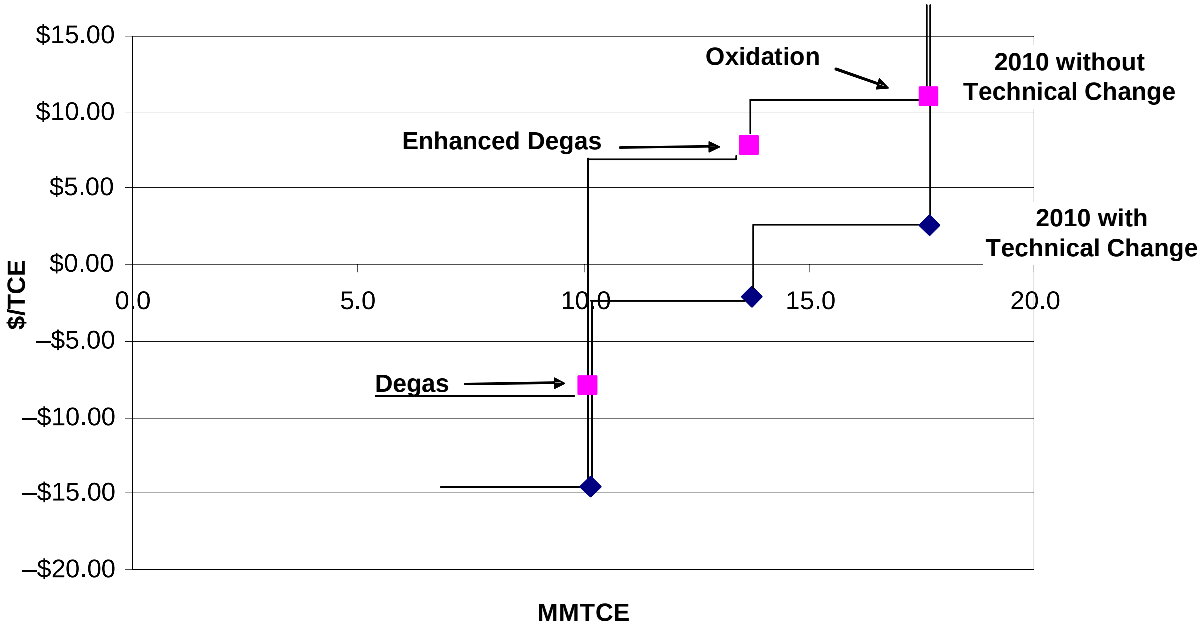

Figure 2b. MAC Shift with Technical Change (2020 U.S. Coal Mining)

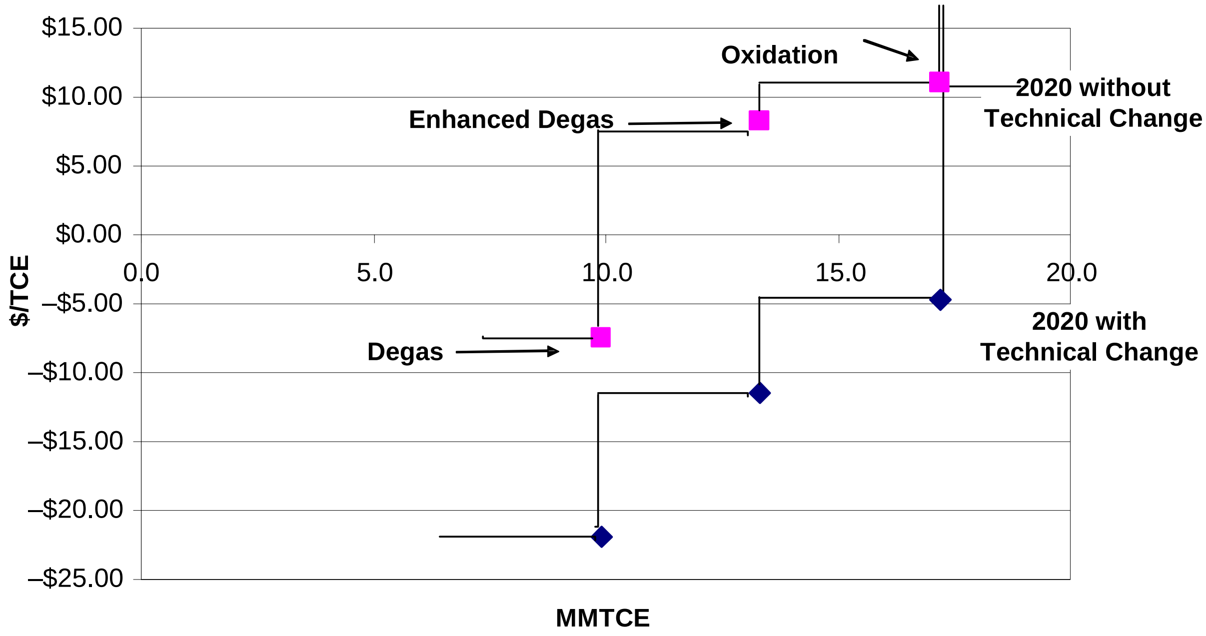

Figure 3. Illustration of Technology Adoption

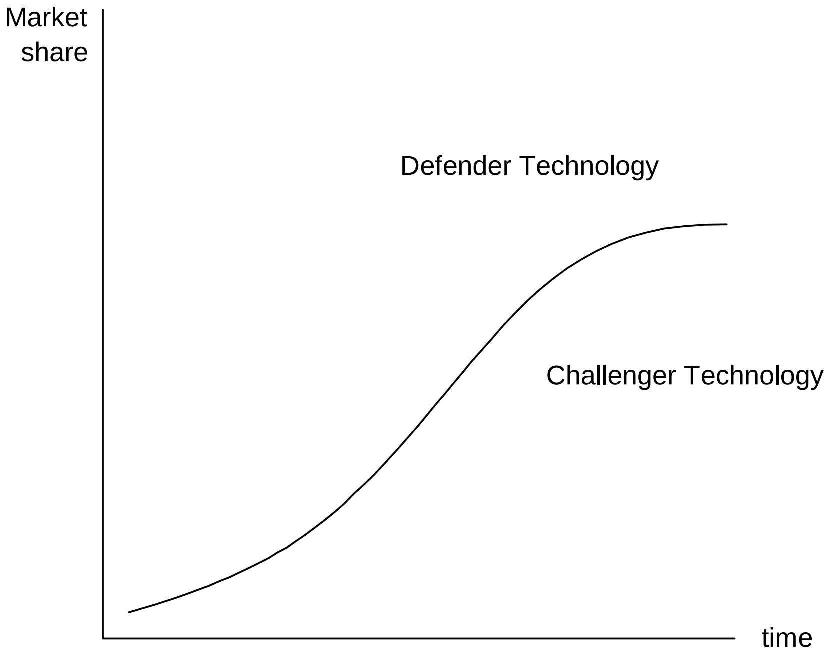

Figure 4. Type of Information Needed to Drive a Gradual Adoption Process

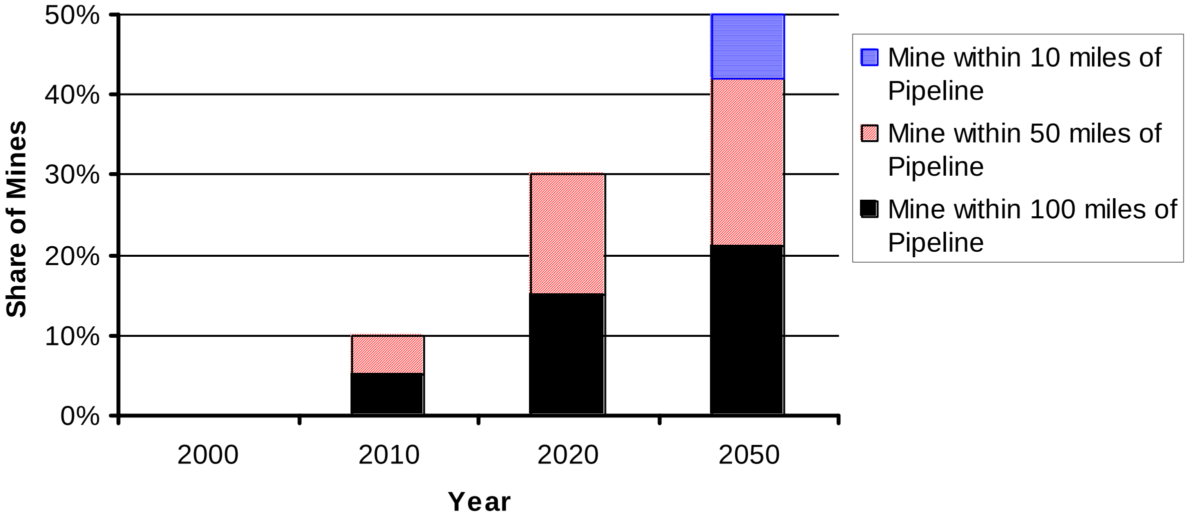

Figure 5. Sublevel MAC for Coal Mining Pipeline Injection

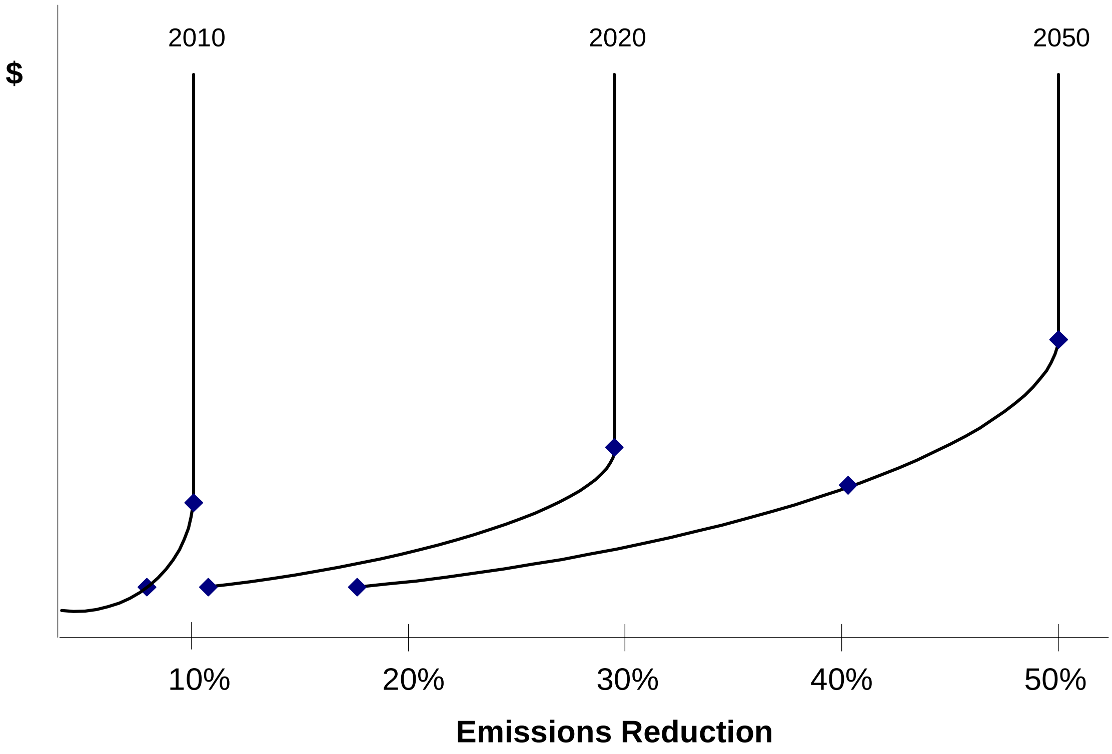

Table 1. Expressing Costs in Terms of Factors of Production

MAC Model Parameter	**Factors of Production**	**Input Shares**	**Cost Shares**	**= P * Q**		**Adjusting Costs for Technical Change**
One-time cost ($/tC)	Capital	%	$	P	Q	(A1*P) * (B1*Q)
	Labor	%	$	P	Q	(A2*P) * (B2*Q)
	Materials	%	$	P	Q	(A3*P) * (B3*Q)
	Energy Inputs	%	$	P	Q	(A4*P) * (B4*Q)
Annual costs ($/tC)	Capital	%	$	P	Q	(A1*P) * (B1*Q)
	Labor	%	$	P	Q	(A2*P) * (B2*Q)
	Materials	%	$	P	Q	(A3*P) * (B3*Q)
	Energy Inputs	%	$	P	Q	(A4*P) * (B4*Q)
Annual benefits ($/tC)	Energy Sales	%	$	P	Q	(A5*P) * (Q)
	Non energy	%	$	P	Q	NA

Table 2. Time Trends in Price and Efficiency (by country or region)

	Price	**Quantity**
Capital	A1 – ΔPrice index	B1 – ΔTechnical efficiency
Labor	A2 – ΔWage rate	B2 – ΔLabor productivity
Materials	A3 – ΔPrice index	B3 – ΔTechnical efficiency
Energy inputs	A4 – ΔEnergy price index	B4 – ΔEnergy efficiency
Energy sales	A5 – ΔNG price index	NA

NA: Not applicable.

Table 3. Basic Components and Activities Associated with Coal Mining Options

Abatement Option	Drilling	Compressors	Fans and Ducts	Enrichment	On-Site Conversion.	Pipeline Injection
1. Degas	x	x				x
2. Enhanced Degas	x	x		x		x
3. Catalytic oxidation			x		x	

Table 4. Option Cost Worksheet

Sector: Coal Mine Gas Options
Option 1: Degasification and Pipeline Injection

Activity	Cost/Benefit Category	Cost/Benefit Component	One-Time Costs	Annual Costs	Annual Benefits
Boreholes and wells	Vertical drilling	Capital	20%		
		Labor			
		Energy			
	Horizontal drilling	Capital			
		Labor			
		Energy			
Gas recovery	Fans and ducts	Capital			
		Labor			
		Maintenance/materials			
		Energy (kWh—consumed)			
	Compressors	Capital	25%		
		Labor		10%	
		Maintenance/materials		0%	
		Energy (kWh—consumed)		10%	
Enrichment	Gas purification	Capital	10%		
		Labor		10%	
		Maintenance/materials		5%	
		Energy (kWh—consumed)		10%	
Direct conversion		Capital			
		Labor			
		Maintenance/materials			
		Energy (kWh substitution)			
		Energy (gas substitution)			
Pipeline injection	Pipeline	Capital	25%		
		Labor	10%	40%	
		Maintenance/materials		5%	
		Energy (kWh)	20%	10%	
		Energy (pipeline injection)			100%
Other costs (NEC)					
Total percentage			100%	100%	100%
I-MAC cost entry	($ millions)		21	13	22

Table 5. Annual Trends in Price and Efficiency (U.S.)

	Real Price ($2000)	**Quantity (productivity change)**
Capital	–1.5%[a]	–2%[b]
Labor	+4.1%[c]	–2.1%[d]
Materials	–1.5%[a]	–1.0%[b]
Energy	–0.01%e	–1%[f]
Energy benefits (natural gas)	+1.8%[g]	NA

NA: Not applicable.

[a] U.S. Department of Commerce. 2003. Bureau of Economic Analysis. *National Income and Product Account Tables*. [Computer File]. <http://www.bea.gov/bea/dn/nipaweb/TableViewFixed.asp#Mid>. As obtained on May 13, 2003.

[b] Temporary assumed value.

[c] Department of Labor. 2003. Bureau of Labor Statistics. Occupational Employment Statistic Survey. <http://www.bls.gov/oes/oes_dl.htm>. As obtained on May 13, 2003.

[d] Congressional Budget Office. 2003. *The Budget and Economic Outlook: Fiscal Years 2004-2013.* Washington DC: Congressional Budget Office.

[e] U.S. Department of Energy. Energy Information Agency. 2003. *Annual Energy Outlook 2003: Appendix Table A: Reference Case Forecast, Annual 2000-2025, Table 1 . Total Energy Supply and Disposition Summary.* <http://www.eia.doe.gov/oiaf/aeo/results.html>. As obtained on May 14, 2003.

[f] NEMS model. U.S. Department of Energy. 2003. Energy Information Agency. *The National Energy Modeling System: An Overview 2003.* March 4, 2003 Washington D.C.: Energy Information Agency. <http://www.eia.doe.gov/oiaf/aeo/overview/overview.html>. As obtained on May 15, 2003.

[g] U.S. Department of Energy. Energy Information Agency. 2003. *Annual Energy Outlook 2003: Table 14 Natural Gas Prices, Margins and Revenues.* <www.eia.doe.gov/oiaf/aeo/aeotab_14.htm>. As obtained on May 13, 2003.

Table 6a. Change in 2010 Cost and Benefit Inputs to I-MAC due to Technical Change ($ millions)

Sector: Coal
Region: United States

2010 Costs Without Technical Change	**Option 1**	**Option 2**	**Option 3**
One-time costs	$20.71	$78.90	$166.92
Annual costs	$12.74	$22.88	$10.83
Cost offsets—energy benefits	$22.30	$22.30	$15.19
Cost offsets—nonenergy	$—	$—	$—
Breakeven price ($/TCE)	–$7.56	$8.18	$11.04
Emissions reduction (MMTCE)	10.13	3.55	4.01
2010 Costs With Technical Change	**Option 1**	**Option 2**	**Option 3**
One-time costs	$16.02	$61.01	$129.06
Annual costs	$10.37	$18.61	$8.81
Cost offsets—Energy benefits	$26.66	$26.66	$18.16
Cost offsets—nonenergy	$—	$—	$—
Breakeven price ($/TCE)	–$14.75	–$2.17	$2.56
Emissions reduction (MMTCE)	10.13	3.55	4.01

Table 6b. Change in 2020 Cost and Benefit Inputs to I-MAC due to Technical Change ($ millions)

Sector: Coal
Region: United States

2020 Costs Without Technical Change	Option 1	Option 2	Option 3
One-time costs	$20.71	$78.90	$166.92
Annual costs	$12.74	$22.88	$10.83
Cost offsets—energy benefits	$22.30	$22.30	$15.19
Cost offsets—nonenergy	$—	$—	$—
Breakeven price ($/TCE)	–$7.56	$8.18	$11.04
Emissions reduction (MMTCE)	9.85	3.46	3.90
2020 Costs With Technical Change	**Option 1**	**Option 2**	**Option 3**
One-time costs	$12.89	$49.12	$103.91
Annual costs	$8.76	$15.72	$7.44
Cost offsets—energy benefits	$31.86	$31.86	$21.70
Cost offsets—nonenergy	—	—	$—
Breakeven price ($/TCE)	–$21.86	–$11.41	–$4.68
Emissions reduction (MMTCE)	9.85	3.46	3.90