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OFFICE OF
AIR AND RADIATION
Climate Change Division
Climate Analysis Branch

International Non-CO2 Greenhouse Gas Marginal Abatement Report

Draft Methane and Nitrous from Non-Agricultural Sources
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Chapter 1

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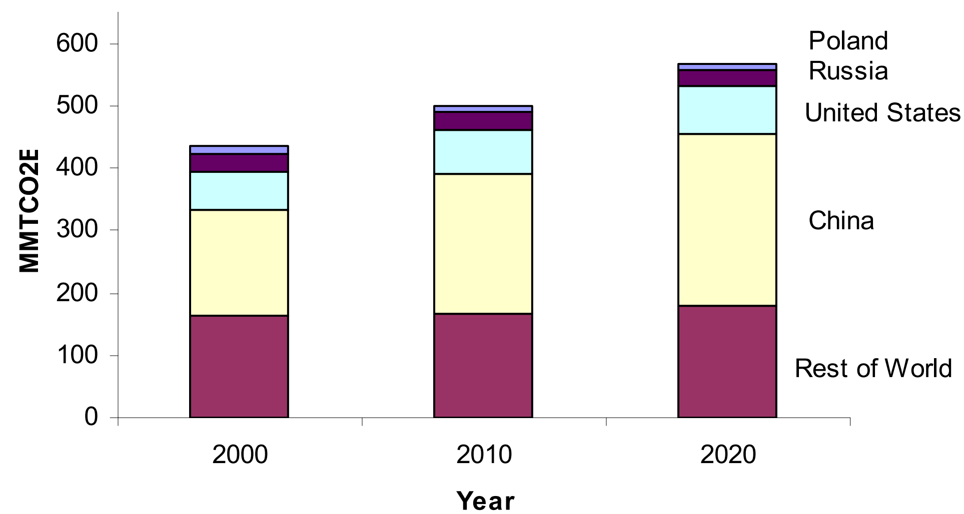
1. Coal Mining Sector

Worldwide, the coal mining industry liberated over 436 million metric tons of carbon dioxide equivalent in 2000, which accounted for 8 percent of total anthropogenic methane emissions in 2000. China, Russia, Poland and the United States account for over 77 percent of coal mining methane emissions (see Exhibit 1-1). Emissions are projected to grow 20 percent from 2000 to 2020, with China increasing its share of worldwide emissions from 40 to 45 percent.

Exhibit 1-1. Methane Emissions by Country from Coal Mining by Country: 2000–2020



Source: EPA, 2005.

1.1 Introduction

Methane is produced during the process of converting organic matter to coal. The methane is stored in pockets within a coal seam until it is released during coal mining operations. The largest source of emissions occurs during mining. However, additional emissions occur during the processing, transport, and storage of coal. Many factors affect the quantity of methane released during mining, including the gas content of the coal, the permeability and porosity of the coal seams, the method of mining used, and the production capacity of the mining operation. The depth of a coal seam and the type of coal determine the amount of methane present (or the gas content) in and around the coal seams. Deep coal seams generally have large amounts of methane because of greater overburden pressures. As a result, over 90 percent of fugitive methane emissions from the coal sector come from underground coal mining.

A high concentration of methane in underground coal mines is a safety hazard. The methane must be extracted before mining operations can be undertaken. Degasification prior to mining and ventilation air systems during operations are employed to maintain low levels of methane in the mine. Traditionally the methane extracted from the mine is released or vented into the atmosphere. Abatement options have been developed to mitigate these emissions.

Three coal mine abatement options addressed in this chapter include (1) degasification (degas), where holes are drilled and methane is captured (not vented) before mining operations begin (or, in the case of gob gas wells, during and after mining operations); (2) enhanced degas, where advanced drilling technologies are used and captured low-grade gas is purified; and (3) ventilation air methane (VAM) abatement, where low concentrations of methane ventilation air exhaust flows are oxidized to generate heat for process use and/or electricity generation.

The following discussion offers a brief explanation of how methane is emitted from coal mines, followed by a discussion of international baseline emissions for methane from coal mining and projections for future baseline emissions. Next we characterize possible abatement technologies, outlining their technical specifications, costs and possible benefits, and potential in selected countries. The final section of this chapter discusses emission reductions that occur following the implementation of each abatement technology, and how these reductions are reflected in the marginal abatement cost curves.

1.2 Baseline Emission Estimates

The methodology discussed in detail in Section 5of this report is used to estimate baseline emissions from coal mining. Baseline emission estimates are calculated through the development of activity factors and emission factors per unit of activity. The activity factor for coal mining's level of coal production and the emission factor are expressed in terms of the quantity of methane release per ton of coal produced.

Methane and coal are created through a combination of biological and geological forces, where plant biomass is converted to coal. Methane is stored in natural wells and is also diffused inside the coal itself. Methane is contained within the coal seam or strata layer by pressure surrounding the seam. When this pressure drops due to natural erosion, faulting, and underground and surface mining, methane emissions occur. Methane emissions vary by type of coal mine and type of mining operation. A small number of emissions occur during processing, storage, and transport of coal (referred to as post-mining operations). Abandoned mines are also a source of methane emissions.

Underground Mines. The quantity of methane present in a mine is determined significantly by the coal depth. Geologic pressure increases with depth, trapping more methane. Coal from underground mines also tends to have a higher carbon content, which is associated with a higher methane content.

Ventilation air systems are used in underground mines to maintain low concentration levels of methane during mining operations. Methane is combustible at concentrations between 5 and 15 percent. For this reason as a safety precaution, countries such as the United States require the use of ventilation systems in mines that have any detectable levels of methane. Ventilation systems maintain a methane concentration below 1 percent by using large fans to inject fresh air from the surface into the mine, thereby lowering the in-mine methane concentration. This ventilation air is extracted from the mine and vented to the atmosphere through ventilation shafts or bleeder shafts (see explanatory note 1). The vent air contains very low concentrations of methane (typically below 1 percent).

Degasification systems consist of a network of vertical wells drilled from the surface or boreholes drilled within the mine and gathering systems to pull the methane from the wells to the surface. These wells extract large quantities of methane contained in the coal seam before and after mining operations. Methane extracted by degasification systems has higher concentrations (30 to 90 percent) than ventilation air methane. Concentrations vary depending on the type of coal mined and the degasification technique used.

Surface Mines. Surface mining is a technique used to extract coal from shallow depths below the Earth's surface. The geologic pressure at shallow depths is much lower, and as a result methane content is generally much lower because there is insufficient pressure to contain high concentrations of methane (see explanatory note 2). As the overlying surface is removed and the coal is exposed, methane is emitted directly to the atmosphere. Surface mines contribute only a small fraction of a country's overall emissions. Surface mining is only applicable in certain geographic regions. For example, in the United States in 2003 surface mining accounted for 67 percent of total domestic coal production. In countries such as China, there is very little surface mining; coal seams are present only at greater depths.

Post-mining Operations. The primary source of methane emissions in coal mining is the underground production of coal. However, some emissions occur during processing, storage, and transport of coal. The rate of emissions depends on the type of coal and the way it is handled. For example, the highest rate of emissions occurs when coal is crushed, sized, and dried for industrial and utility uses.

Abandoned Mines. Abandoned mines are another source of methane emissions. Emissions are released through old wells and ventilation shafts. In some cases, the methane from these mines has been captured and used as a source of natural gas or to generate electricity. Currently these emissions are not included in the baseline estimates.

In summary, the majority of the methane emitted from coal mining comes from gassy underground mines through ventilation and degasification systems. Future emission levels and the potential for methane recovery and use will be determined by trends in the management of methane gas at gassy underground mines.

1.2.1 Activity Data

Historical Activity Data

Worldwide coal consumption has increased over time, with the exception of Western Europe, Eastern Europe, and the former Soviet Republics (excluding Russia). Coal consumption decreased 30 percent in Western Europe and 40 percent in Eastern Europe and the Former Soviet Union from 1990 to 2001. Exhibit 1-2 reports coal mining activity for selected countries over the same time period.

Exhibit 1-2. Historical Coal Mining Activity Data for Selected Countries (Million Metric Tonne)

Country	1990	1995	2000	2001	2002
China	1,079.9	1,394.3	1,192.5	1,323.4	1,380.0
United States	933.6	937.1	974.0	1,023.0	992.3
India	224.6	290.8	334.7	349.4	356.2
Australia	204.8	241.8	306.8	329.2	342.6
Russia	NA	245.7	240.3	248.0	235.2
South Africa	175.3	206.2	225.4	227.1	222.5
Germany	NA	248.7	204.4	204.7	209.5
Poland	215.1	199.7	161.7	162.3	161.3
Indonesia	10.5	41.1	76.6	92.5	101.2
Ukraine	NA	85.8	81.0	83.9	84.0
Kazakhstan	NA	83.4	72.3	74.9	73.2
Greece	51.9	57.7	63.9	66.3	68.0
Canada	68.3	75.0	69.2	70.4	66.4
Czech Republic	NA	74.9	65.2	66.1	63.9
Turkey	47.4	55.0	63.1	65.8	53.3

Note: NA suggests data are unavailable.

Source: EIA, 2004.

In the 1990s the majority of China's coal mines were operated without modern mining techniques. Typical mechanization includes cutting equipment, hydraulic pumps, power roof supports, and automated loading devices. However, over the past decade countries such as China have instituted programs to modernize their coal mining operations, allowing them to mine at greater depths. However, several countries experienced decreased demand for coal in the late 1990s. In response, these countries cut mining production until their surplus supply could be reduced. China dramatically reduced its coal production between 1995 and 2000 and has spent the past 4 years expanding its exports of coal to reduce its coal surplus. Policies and market forces such as these counteract the effects of modernization in mining operations and the subsequent increases in methane emissions.

Projected Activity Data

Estimated methane emissions baselines are directly related to projections for coal production. Sixty percent of the world's recoverable reserves are located in three countries: the United States (25 percent), Former Soviet Union (23 percent), and China (12 percent) [EIA, 2001]). However, China is projected to have the largest increase in coal projections because of rapid economic growth. China is projected to almost double coal consumption by 2025 (EIA, 2004).

1.2.2 Emissions Factors and Related Assumptions

Historical Emission Factors

Emission factors for coal mining vary depending on the type of coal being mined, the depth at which the mining face is located, and how much coal is being produced in a given year. Emission factors for 56 gassy mines in the United States ranged from 57 to 6,000 million cf of methane per mine annually in 2000. Emission factors for 34 Russian gassy mines ranged from 17 to 3,200 million cf per mine. For China's 678 state-run mines, emission factors ranged from 17 to 6,000 million cf per mine annually from coal production. While the range of emission factors for the United States and China is similar, China has significantly more mines with higher emission factors. Intergovernmental Panel on Climate Change (IPCC) estimates average emission factors by country. Exhibit 1-3 reports emission factors for selected countries.

Exhibit 1-3. IPCC Suggested Underground Emissions Factors for Selected Countries

Country	Emission Factor (m^3/tonne)
Former Soviet Union	17.8 – 22.2
United States	11.0 – 15.3
Germany	22.4
United Kingdom	15.3
Poland	6.8 – 12.0
Czechoslovakia	23.9
Australia	15.6

Source: IPCC, 1996. Adapted from Reference Manual Table 1-54.

Projected Emission Factors and Related Assumptions

Improvements in mining technology over the past 20 years have resulted in the ability to extract coal from increasingly greater depths. Developing countries' adoption of advanced mining technology has allowed countries such as China and India to reach deeper into their existing coalbed reserves. As discussed earlier, the volume of methane in the coal seam increases at deeper depths because of increasing geological pressure. Methane emissions will rise as technology allows large coal-producing countries to mine deeper, thereby increasing the volume of methane emitted.

1.2.3 Emissions Estimates and Related Assumptions

Historical Emission Estimates

Baseline emissions for Annex I countries are built using publicly available reports produced by the countries themselves. IPCC Guidelines' methodology was used to estimate emissions in each country, ensuring comparability across countries. The U.S. Environmental Protection Agency's (EPA's) baselines assume a "business as usual" scenario that does not include climate change mitigation efforts or other national policies that may indirectly reduce the emissions of greenhouse gases.

Exhibit 1-4 reports countries with the largest historical methane baseline emissions for the years 1990, 1995, and 2000. Methane emissions declined worldwide between 1990 and 2000 at an average annual rate of about 10 percent.

Projected Emission Estimates

Worldwide methane emissions from coal mining are projected to increase over the next 20 years. This increase is paralleled by a projected increase in coal consumption over the same period. At the same time, coal's share of overall energy consumption is expected to steadily decrease as a result of the technology advances in other energy markets such as natural gas.

Technology adoption and organizational restructuring will improve countries' ability to produce larger amounts of coal each year. Exhibit 1-5 reports predicted methane baseline emission for the largest coal-producing countries in the world, assuming the absence of methane abatement technologies.

1.3 Cost of Methane Emission Reductions from Coal Mining

The following is a discussion of the abatement technologies and their costs and benefits.

Exhibit 1-4. Historic Baseline Emissions for Coal Mine Methane for Selected Countries (MMTCO2E)

Country	1990	1995	2000
China	184.3	217.8	171.8
United States	85.3	73.6	60.7
Ukraine	52.6	30.1	33.8
Russian Federation	60.9	37.8	29.4
North Korea	25.3	27.2	26.9
Australia	15.8	17.5	19.6
Poland	16.8	15.6	11.9
Germany	25.8	17.6	10.2
India	6.9	8.7	10.1
Kazakhstan	24.9	17.2	10.0
South Africa	6.7	6.7	7.1
United Kingdom	17.2	10.6	5.6
Czech Republic	7.6	5.8	5.0
Indonesia	0.7	1.7	3.4
Romania	3.9	4.2	3.0

Source: EPA, 2005.

Exhibit 1-5. Projected Baseline Emissions for Coal Mine Methane for Selected Countries (MMTCO2E)

Country	2005	2010	2015	2020
China	198.2	224.6	251.1	277.5
Turkey	65.8	71.0	70.1	73.9
Greece	31.4	29.2	28.4	27.8
Viet Nam	28.8	28.1	27.5	26.9
Brazil	25.6	24.3	23.1	21.9
Spain	21.8	26.4	28.2	29.7
Bulgaria	11.3	10.8	10.3	9.8
South Korea	8.4	7.7	7.1	5.9
Rest of Africa	12.4	14.7	18.1	21.5
Canada	6.7	6.4	6.1	5.8
Japan	7.4	7.2	7.1	7.4
Hungary	5.4	5.2	5.1	4.9
Slovak Republic	4.8	3.9	3.1	3.0
Iran	4.2	4.8	5.6	6.4
New Zealand	3.1	3.1	3.1	3.0

Source: EPA, 2005.

1.3.1 Abatement Option Opportunities

Three abatement opportunities currently available to the coal mining sector are

- degasification,
- enhanced degasification, and
- oxidation of ventilation air methane (VAM).

Engineering costs for each abatement option are based on individual mine characteristics, such as annual mine production, gassiness of the coal deposits, and methane concentration in ventilation flows. Exhibit 1-6 provides a summary of the one-time investment costs, annual operation and maintenance (O&M) costs, and benefits from using the captured methane as an energy source, for each of the three coal mining abatement options included in the analysis.

Exhibit 1-6. Summary of Average Abatement Costs and Benefits for U.S. Coal Mines
Based on a population of 57 U.S. coal mines, accounting for 75 percent of the total liberated methane from U.S. coal production.

	Average Costs/Benefits ($Millions)		
	Degas	**Enhanced Degas**[a]	**VAM**[b]
One-Time Costs			
Compressor capital	$1.00	$0.39	N/A
Gathering line capital	$0.90	$0.20	N/A
Processing capital	$0.04	$2.56	N/A
Ventilation capital	N/A	N/A	$18.64
Miscellaneous capital	$0.38	$0.14	N/A
Annual Costs			
Drilling capital	$0.50	$0.36	N/A
Drilling materials	$0.94	$0.31	N/A
Compressors energy (kWh)	$0.33	$0.13	N/A
Gathering lines labor	$0.25	$0.96	N/A
Processing materials	$0.13	$0.18	N/A
Ventilation operating costs	N/A	N/A	$0.91
Miscellaneous labor	$0.28	$0.12	N/A
Annual After-Tax Benefits			
Methane sold or purchases offset	$0.97	$0.34	$2.78
Depreciation Tax Benefits	$0.02	$0.24	$0.14

N/A = Not applicable

[a]Incremental costs and benefits in addition to degas (Option 1).

[b]Underlying VAM costs are from (Delhotal et al., 2005).

Source: Gallaher and Delhotal, 2005.

Degasification and Pipeline Injection

High-quality methane is recovered from coal seams by drilling vertical wells up to 10 years in advance of a mining operation or horizontal boreholes up to 1 year before mining. Most mine operators exercise "just-in-time management" of gate road development; subsequently, horizontal cross-panel boreholes are installed and drain gas for 6 months or less. Long horizontal boreholes are used by only a few operators in the United States and Australia.

In some cases high-quality methane also can be obtained from gob wells. Gob gas methane concentrations can range from 50 percent to over 90 percent (EPA, 1999). The gas recovered is injected into a natural gas pipeline requiring virtually no purification in the initial stages of production but necessitating treatment over time to upgrade the gas to pipeline quality. Gob gas sales from a given location typically decline over time because of declining levels of concentration. In the United States, the methane recovered from degasification (or gas drainage as it is often called), 57 percent can be directly used for pipeline injection. (EPA, 1999).

Information was available on 56 underground U.S. coal mines for 2000. These 56 mines accounted for 75 percent of the total liberated methane associated with U.S. coal production. Engineering costs for each abatement option were calculated based on individual mine characteristics, such as annual mine production, gassiness of the coal deposits, and methane concentration in ventilation flows. Exhibit 1-4 provides a summary of the one-time investment costs, annual O&M costs, and benefits from using the captured methane as an energy source. Detailed engineering cost information was not available for non-U.S. underground coal mines. Thus, costs were estimated as a function of mine production and liberated methane.

Cost Analysis

- **Capital Costs.** Include the one-time (upfront) costs of purchasing compressors, gathering lines, dehydrators, and other miscellaneous capital such as safety equipment and licenses. Exhibit A-2 in the appendix for this chapter offers a detailed description of the factors that determine the required number of each capital component by mine.
- **Annual Costs.** Include materials and labor for drilling, moving gathering lines, and maintaining the dehydrators. Drilling capital is also considered an annual cost because drilling is conducted annually. Annual costs generally increase or decrease proportionally to the volume of methane liberated at the individual mine. Exhibit A-2 offers a detailed description of the factors that determine these costs.

- **Cost Savings.** Cost savings result from the capture and reuse of natural gas. For basic degasification, it is assumed that 57 percent of gas capture is suitable for injection into the natural gas pipelines and hence can be sold directly into the system (EPA, 1999).

Enhanced Degasification and Pipeline Injection

Methane is recovered in the same fashion as previously described for degasification, 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 medium-quality gob well gas by removing impurities, allowing for larger quantities of methane to be captured and used. This option also assumes tighter well spacing to increase recovery. The enrichment process and tighter spacing improve recovery efficiency by 20 percent over the first option discussed above (EPA, 1999). All costs and benefits presented in Exhibit 1-6 for enhanced degasification are *incremental* in that they represent *additional* abatement costs and methane sales above and beyond the basic degasification.

Cost Analysis

- **Capital Costs.** Enhanced degasification requires the same capital equipment as the degasification option. In addition, the enhanced option requires an NRU with an estimated average cost of $200,000 per unit.
- **Annual Costs.** Similar to degasification, enhanced degasification's annual costs include materials and labor for drilling, moving gathering lines, and maintaining the dehydrators. However, annual drilling costs are higher for enhanced degasification because the wells are drilled at closer intervals from each other. Costs vary proportionally to the amount of gas liberated.
- **Cost Savings.** It is assumed that 77 percent of the methane captured as part of enhanced degasification can be injected into the natural gas pipeline system. This 21 percent increase over the basic degasification mitigation option (incremental benefits) results because gas processing equipment facilitates nitrogen removal.

Oxidation of Ventilation Air Methane

Oxidation technologies (both thermal and catalytic) have the potential to use methane emitted from coal mine ventilation air. It is not economically feasible to sell this gas to a pipeline because of its extremely low methane concentration levels (typically below 1.0 percent). However, ventilation air methane can be oxidized to generate carbon dioxide and heat, which in turn may be used directly to heat water or to generate electricity. If oxidizer technology were applied to all mine ventilation air with concentrations greater than 0.15 percent methane, approximately 97 percent of the methane from the ventilation air could be mitigated.

Cost Analysis

- **Capital Costs.** Capital costs for VAM oxidation are a function of the level of methane concentration in the ventilation air and the ventilation air flow rate.
- **Annual Costs.** Annual costs consist of primarily the labor and electricity costs associated with running the oxidizer. Both of these are proportional to coal production.
- **Cost Savings.** Heat generated by oxidation systems can be used to heat water (e.g., for steam or district heating applications) or to generate electricity.

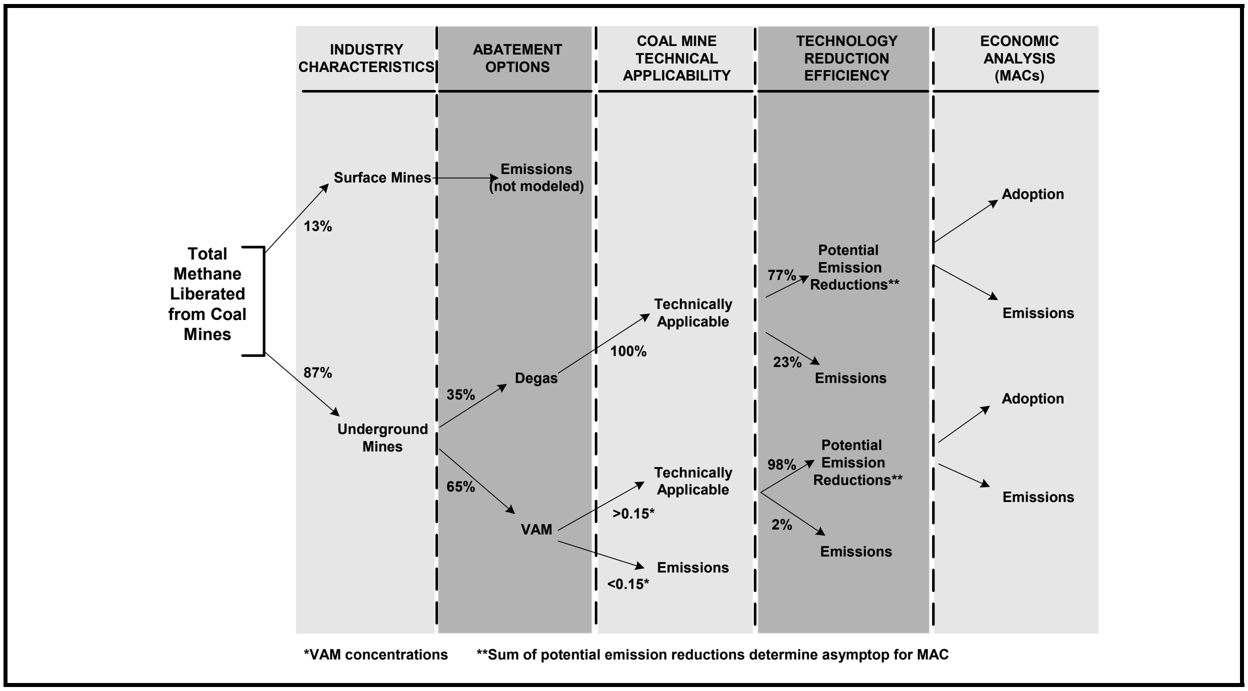
1.3.2 Adjustment Factors Used in Coal Mining Technology Analysis

Exhibit 1-7 summarizes the key parameters that determine the share of methane emissions that can be captured as a function of individual mine and technology characteristics. Note that the technical potential defines the vertical asymptote of the marginal abatement curve (MAC). The technical potential can change over time as

- baseline emissions change;
- mine characteristics change, including
  - the relative number of underground vs. surface mines and
  - the maximum percentage of methane that can be liberated and recovered via pre-mine drilling (degas)
- limitations of VAM technology are overcome (e.g., current technologies require methane concentration >0.15 percent); and
- reduction efficiency of degas and VAM technologies increases (i.e., the share of methane abated versus emitted).

All of the factors will potentially change over time as a result of enhancements to existing technologies or introduction of new processes and procedures. For example, in the United States, advances in surface mining are projected to decrease underground mining activities, reducing the technical potential for methane abatement. Also, VAM technology is projected to improve over the next 20 years, decreasing the technical applicability concentration level below 0.15 percent methane. Exhibit 1-8 provides the assumptions affecting technical potential over time that are used in the analysis. These specific technology trends are used, in addition to the general price and productivity trends that influence capital and annual costs (described in the introduction to the industrial section).

Exhibit 1-7. Key Parameters in Coal Mine Model



**The asymptote refers to the MAC curve approaching a limit of total potential reductions. The curve goes inelastic at a given point because of the engineering limitations of current technologies.

Exhibit 1-8. Trends Affecting Technical Potential Over Time for Coal Mines

	Actual (2000)	Projected (2030)
Share of coal production from underground mines	87%	75%
Percentage of total methane liberated by degasification (versus liberated through mine shafts)	36%	39%
Technical applicability for VAM: lowest feasible methane concentration	0.15%	0.075%
Reduction efficiency for degas	77%	87%
Reduction efficiency for VAM	97%	98%

Note: Trends are used for all mines globally and are based on expert judgment and are not intended to represent official analysis by EPA.

Share of Domestically Supplied Factors of Production for Coal Mine Options

While the price of production inputs varies by country, the overall contribution or share of capital, labor, and materials provided domestically may not always be 100 percent. Therefore, EPA estimated an initial share of domestically provided capital, labor, and materials. For example, China currently relies on capital and material imported from the United States, EU, and Japan. As technical information is transferred over time, China will shift away from imported factors of production and begin to supply the required capital and material domestically. The shift toward domestically supplied inputs will result in a reduction in the cost of implementing the abatement technology.

The initial share of domestically supplied factors of production is estimated based on the relative maturity of the coal mining industry and the technology intensity in each country. Exhibit 1-9 shows domestic input shares for China in 2000 and 2030.

Exhibit 1-9. Share of Domestic Inputs for Chinese Coal Mines Abatement Options

	2000 (Estimate)	2030 (Projection)
Domestic share of labor	75%	100%
Domestic share of capital	0%	80%
Domestic share of materials	50%	88%

1.4 Results

Applying the cost analysis and trends described above, we developed shifts in the MACs for selected countries for 10-year intervals from 2000 to 2030. Individual country methane MACs are provided in Appendix B. Several of the MACs are discussed below to illustrate differences MAC curves which estimate technical change over time and those that do not as well as highlight factors underlying the shifts in the curves over time.

1.4.1 Data Tables and Graphs

Exhibits 1-10, 1-11, and 1-12 show the MACs for 2000, 2010, 2020, and 2030 for the United States' and Chinese coal mining sectors. The magnitude of the shifts reflects both changes in abatement technologies and trends in the share of underground versus surface mining. For example, after 2020, the shift in the U.S. MACs slows because underground mine production is projected to decrease slightly. However, technology improvements continue, driving down costs, which in turn increases the adoption of abatement options.

Exhibit 1-13 summarizes the factors driving the shifts in the MACs for the coal mining sector in terms of percentage changes from 2000 to 2030. As shown in the exhibits, over time the cost of abatement options decreases while their reduction efficiency increases. These factors combine to increase economic viability of the mitigation options, hence lowering their breakeven price and shifting the MACs downward. As shown in the exhibits, the change in reduction efficiency is technology specific and assumed to be constant across countries, increasing on average between 11 to 14 percent by 2030 (all abatement technologies for any given price. In contrast, the MACs for China shift out and downward countries are assumed to use similar technologies provided by developed countries). However, changes in costs vary greatly across each country because of the changing shares of domestic versus foreign inputs over time.

Exhibit 1-10. Comparison of MACs With and Without Technical Change Estimates: Coal Mining in 2020

		Breakeven Prices ($/TCE)							
Source	**Country**	**–$20**	**–$10**	**$0**	**$10**	**$20**	**$30**	**$40**	**$50**
With tech change	United States	11.32%	45.39%	56.48%	60.63%	61.43%	62.29%	62.68%	63.07%
W/o tech change	United States	0.00%	0.00%	49.22%	49.24%	66.51%	85.97%	85.97%	85.97%
With tech change	China	0.00%	38.72%	76.30%	83.56%	85.63%	87.12%	89.24%	89.82%
W/o tech change	China	0.00%	0.00%	0.00%	0.80%	49.66%	84.45%	84.45%	84.45%
With tech change	Russia	0.00%	0.00%	84.95%	88.74%	89.38%	89.44%	89.46%	89.47%
W/o tech change	Russia	0.00%	0.00%	27.65%	40.41%	51.35%	84.29%	84.29%	84.29%

Note: EMF only reports IMAC curves for the Eastern European Region. Poland was omitted from this table due to lack of country specific data from EMF.

Exhibit 1-11. Shift in the United States' MAC for the Coal Mining Sector Over 30 Years

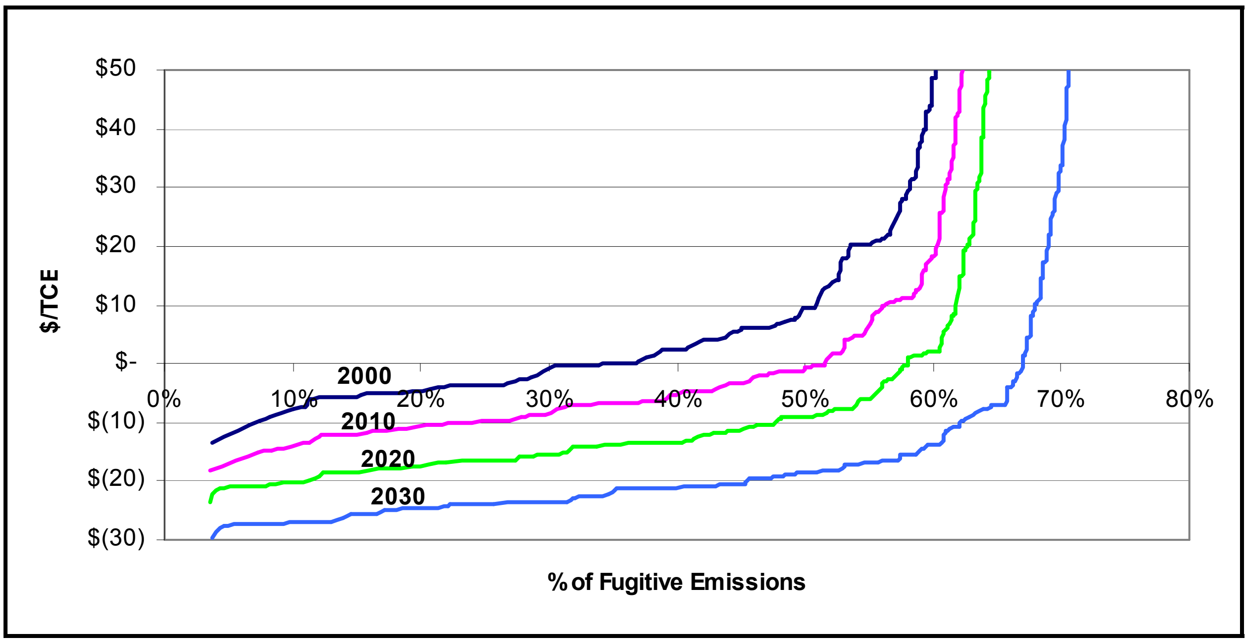


Exhibit 1-12. Shift in China's MAC for Coal Mining Over 30 Years

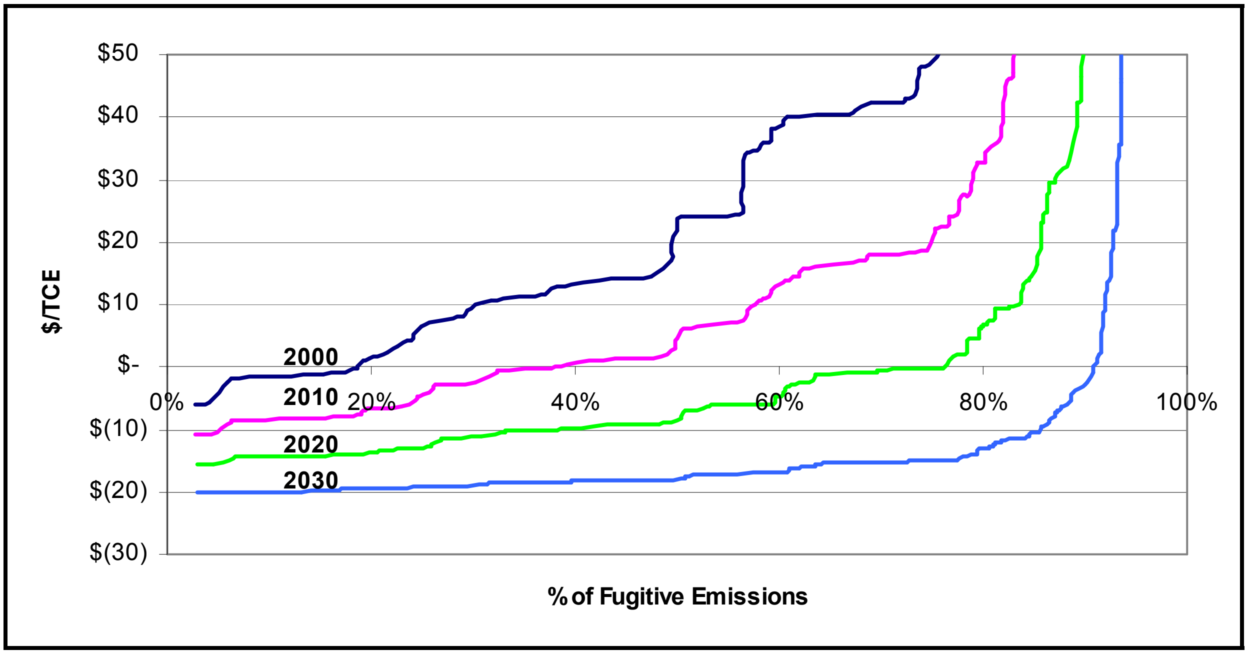


Exhibit 1-13. Percentage Change from 2000 to 2030 in Key Factors Affecting Coal Mining MACs

Year	Change in One-Time-Costs	Change in Annual Costs	Change in Reduction Efficiency
U.S.	49%	10%	14.0%
China	89%	85%	14.0%
Russia	91%	44%	14.0%
Poland	94%	32%	14.0%

Exhibit 1-14 shows the percentage changes for the coal mining sector that result from the trends implemented in our analysis. U.S. one-time costs and annual costs decrease by 49 percent and 10 percent, respectively, as a result of applying U.S. trends discussed at the beginning of the industry sections. The difference in the rate of change between one-time and annual costs is due to their relative level of capital versus labor intensity. Because the real wage rate is projected to increase, offsetting labor productivity, labor-intensive activities are not projected to have as large a decrease in costs as capital-intensive activities. And, for all the coal mining abatement options, one-time costs are capital intensive and annual costs are labor intensive.

China, Russia, and Poland have greater decreases in costs because they are currently importing most inputs, but they are projected to increase the use of significantly lower-cost domestic capital, labor, and materials over time. This can be seen in the MACs, resulting in greater downward shifts in these

Exhibit 1-14. Trends Affecting Technical Potential Over Time for Chinese Coal Mines

		2030		
	2000	Lower Bound	Original Projection	Upper Bound
Scenario 1:				
Technical applicability for VAM	0.15%	0.10%	0.075%	0.05%
Reduction efficiency degas	77%	82%	87%	92%
Reduction efficiency VAM	97%	97.5%	98%	98.5%
Scenario 2:				
Domestic share of labor	75%	85%	100%	100%
Domestic share of capital	0%	40%	80%	100%
Domestic share of materials	50%	69%	88%	100%

countries' curves over time relative to the United States. The changes in costs are also a function of each country's relative prices (see Relative Price Factor Table). For example, the percentage change in annual costs is not as great in Russia and Poland, compared to China, because China has lower wages than these countries and thus experiences a greater decrease in annual costs when switching to domestic labor.

1.4.2 Sensitivity Analysis

The MAC curves presented in Exhibits 1-11 and 1-12 are the result of simultaneously applying several technology feasibility, efficiency, and import trends. Each contributes to lowering the cost and/or increasing the benefits associated with abatement technologies and hence shifts the MACs. Sensitivity analysis was conducted to investigate which trends have the most significant impact on the MACs over time. Two scenarios are modeled for the development of Chinese MAC curves for coal mines: the first focuses on the rate of change in the technical applicability and reduction efficiency of abatement technologies, and the second focuses on the share of domestic versus foreign labor, capital, and materials used in the mitigation options. Exhibit 1-14 presents the lower and upper bounds used in the sensitivity analysis for the two scenarios.

The sensitivity analysis for Scenario 1 (technical applicability and efficiency) in the year 2030 is presented in Exhibit 1-15. The lower and upper bounds are shown as a range for the shifts of the MAC curve. Similarly, Exhibit 1-16 presents the lower and upper bounds for the sensitivity analysis for Scenario 2 (the share of domestic inputs). The two sensitivity scenarios indicate that the MAC curves are more sensitive to the projected trends in the share of domestic inputs and less sensitive to projected changes in technical applicability and reduction efficiency. This is due to the abundant availability of low-wage labor in China and the relative maturity of abatement technologies for coal production (see explanatory note 3).

1.4.3 Uncertainties and Limitations

Several key limitations in current data availability constrain the accuracy of this analysis. Successfully addressing these issues would improve the development of the MACs and predictions of their behavior as a function of time. Some of these limitations include the following:

- *Accurate Distribution of Mine Type for Each Country:* Extrapolating from available information about individual mines to project fugitive emissions at a national level implies that the available data are representative of the country's coal production that is not included in the existing database. A more accurate distribution of representative mines would improve the accuracy of the cost estimates and the shape of each MAC. These data would include mines of all sizes, emission factors, and production levels. This lack of information becomes increasingly problematic when evaluating a country such as China, where the majority of mines are small private mines that are not represented in currently available data sources.
- *International Technology Trends:* In this analysis, technology trends for real price and production efficiency in the U.S. capital, labor, materials, and energy markets were applied to mines in all countries. In the future, country-specific forecasted rates of change for the real price and production efficiencies for each factor of production would increase the accuracy of the MAC curve estimates for 2010 and 2020.
- *Country-Specific Tax and Discount Rates:* In this analysis, a single tax rate is applied to mines in all countries to calculate the annual benefits of each technology. In reality, however, tax rates vary across countries, and in the case of state-run mines in China, taxes may not even be applicable. Similarly the discount rate may vary by country. Improving the level of country-specific detail will help analysts more accurately quantify benefits and breakeven prices.
- *Improved Information on Public Infrastructure:* A more detailed understanding of each foreign country's natural gas infrastructure would improve the estimates of costs associated with transporting methane from a coal mine to the pipeline. Countries with little infrastructure will have a much higher transportation cost associated with degas and enhanced degas technologies.

Exhibit 1-15. Sensitivity Analysis for China Coal Mining 2030: Scenario 1

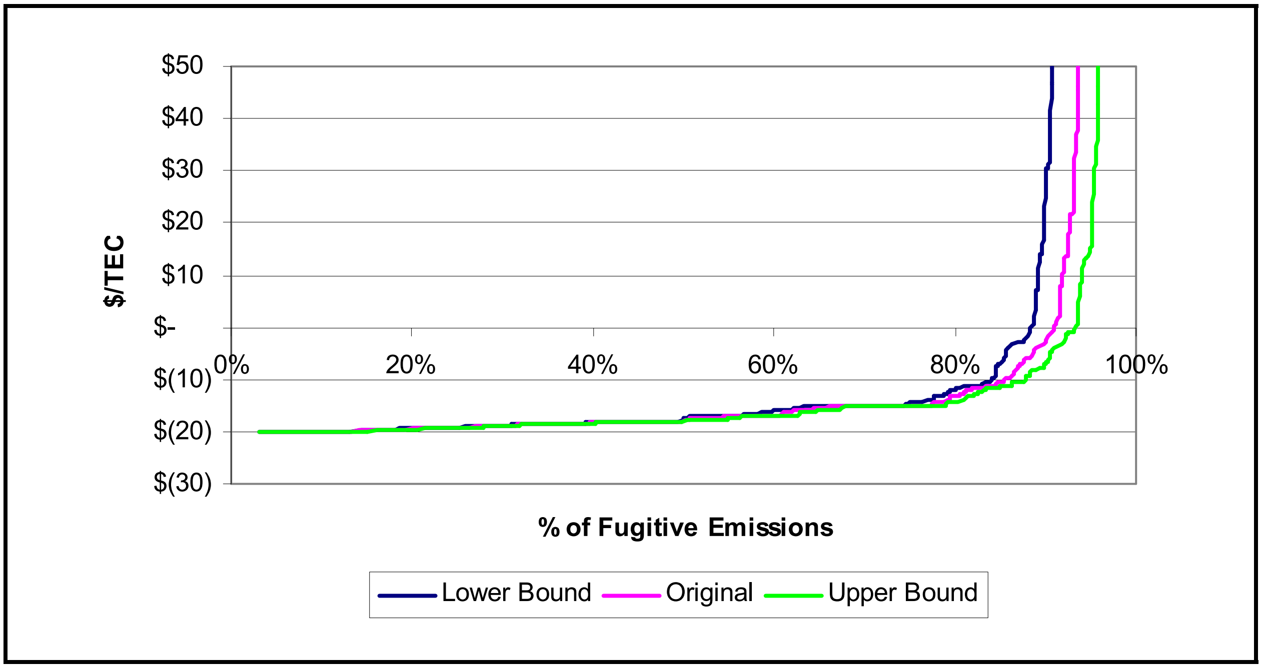
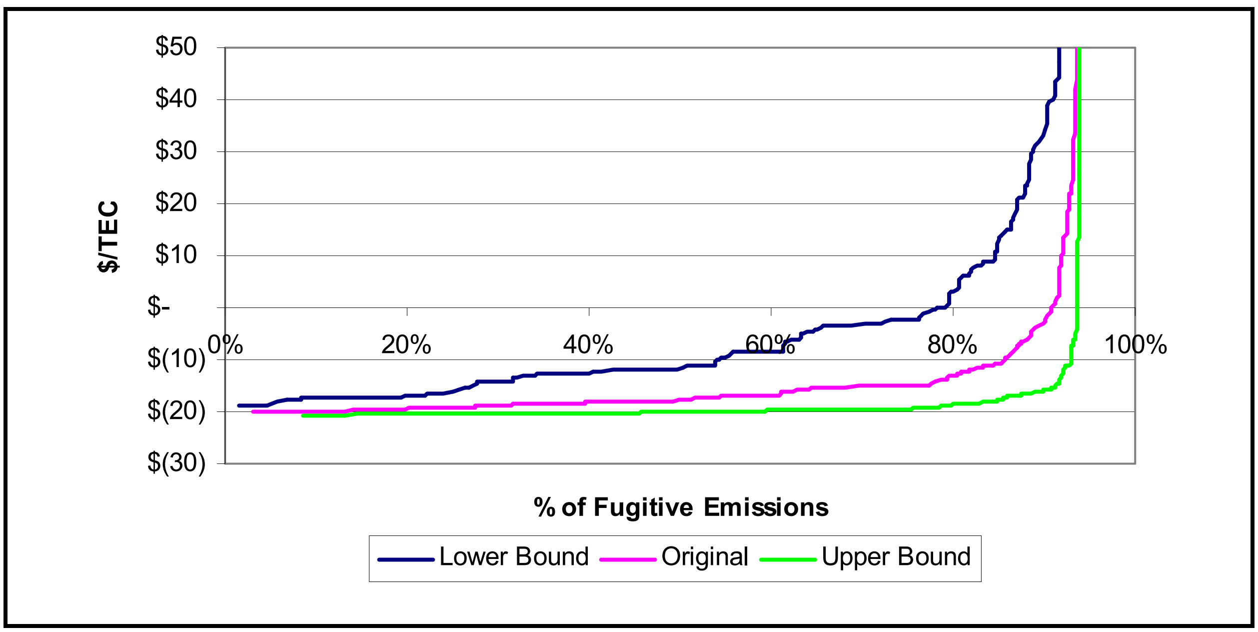


Exhibit 1-16. Sensitivity Analysis for China Coal Mining 2030: Scenario 2



- *Concentrations for VAM in International Mines:* The effectiveness and applicability of VAM technology depends on ventilation air methane concentration and mine-specific coal production rates. In this analysis, a proxy was used to represent VAM methane concentration because more detailed information was not available for most mines. Improved data on the VAM methane concentration levels for individual mines would enhance the accuracy of cost estimates. This information would also help to more accurately identify the minimum threshold concentration levels that make VAM oxidation an economically viable option.
- *Adjusting Costs for Specific Domestic Situations:* Currently, the technologies considered in this analysis are available in the U.S. Canada and Western Europe for the cost indicated. However, other countries may be faced with higher costs due to transportation and tariffs associated with purchasing the technology from abroad. At some point, these other nations could ultimately adopt domestic production of these technologies, resulting in lower costs relative to importation. However, data on domestically produced technologies (e.g., both costs and reduction efficiencies) for these countries are not currently available.
- *Adoption Rates over Time:* In this analysis, we have not considered adoption of technologies over time. Because not all countries will adopt mitigation options as soon as they become economically viable, "no regret" options will likely persist for most time periods. It may be possible to determine historical adoption rates in the United States, use the rates to estimate a typical s-shaped adoption curve, and apply the curve over time. EPA is looking into the availability of data for this analysis.

1.5 Summary and Analysis

The methodology and data discussed in this section describes the successful integration of technical change with mine-level data to estimate MACs for 2010 and 2020. MACs are generated for the coal mining sector for the United States, China, Russia, and Poland. These estimates represent an improvement over previously published MACs for two primary reasons. First, the mine-level data smooth out the stepwise function (based on representative entities), and second, the curves are shifted over time to account for technical change. The methodology is also applicable for projecting MACs through 2050 and 2100. However, data constraints become increasingly problematic as the time horizon increases.

The inclusion of technical change in MACs over time is important because it provides researchers and policy makers with insights into more accurate behavioral responses to potential future carbon prices. For example, MACs illustrate how the adoption of abatement technologies becomes more attractive—through decreased costs and increased benefits—as a result of changes over time in technical applicability and reduction efficiency as well as in the share of domestic versus foreign inputs. As new technologies are adopted, in turn MACs shift downward, potentially increasing technology adoption at any given carbon price.

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Explanatory Notes

1 Bleeder shafts are currently used in only a limited number of countries including the United States and Russia.

2 There are exceptions. In Kazakhstan, for example, the surface mines in Ekibastuz are very gassy and prone to outbursts; this is the rare exception, though.

3 There is projected to be virtually no surface mining activity in China through 2030, because surface mining is capital intensive and geological characteristics of coal seams in China make surface mining difficult.

Coal Chapter Appendix: Supporting Material for the Analysis of Coal Mining

Exhibit A-1. Historical Coal Production for Selected Countries. This exhibit details the historical and projected data for underground coal mining production in selected countries. The data are used to determine and project emissions factors for each country.

Exhibit A-1. Historical Coal Production for Selected Countries

Region	1990	1995	2000	2001	2002
North America	1,010	1,021	1,054	1,105	1,070
Central & South America	30	35	52	56	58
Western Europe	792	504	447	453	445
Eastern Europe & Former U.S.S.R.	1,211	780	697	716	693
Africa	182	213	232	233	229
Asia and Oceania	1,625	2,052	1,989	2,179	2,268
World Total	4,851	4,607	4,472	4,742	4,765

The information on coal production and methane liberated from individual mines for China, Russia, and Poland was extracted from several international methane reports provided by EPA. Information on the production of coal and methane emissions in China was extracted from the EPA report entitled *Reducing Methane Emissions from Coal Mines in China: The Potential for Coalbed Methane Development* (EPA, 1996a). Detailed data on a large majority of the state-run mines in China account for 43 percent of the coal produced and comprised 40 percent of the methane liberated by the country's mines in 1994. Data on individual mines in Russia were extracted from *Reducing Methane Emissions from Coal Mines in Russia: A Handbook for Expanding Coalbed Methane Recovery and Use in the Kuznetsk Coal Basin* (EPA, 1996b). The data for Russia account for almost 25 percent of total coal production and almost 40 of the methane liberated from the country's coal mining operations. Data on individual mines in Poland were extracted from *Reducing Methane Emissions From Coal Mines in Poland: A Handbook for Coalbed Methane Recovery and Use in the Upper Silesian Coal Basin* (EPA, 1995) and account for nearly 50 percent of coal production and almost 75 percent of the total methane liberated within the country.

Exhibit A-2. Components of the Coal Mining Abatement Options. This exhibit identifies the various components required for each of the three methane recovery and use options evaluated in this analysis.

Exhibit A-2. Components of Coal Mining Abatement Options

Cost Component	Markets	Description	Degas	Enhanced Degas	VAM
Drilling	Annual capital	Drilling is continual through the life of the mine; thus, capital costs are classified as "annual" costs. Costs are proportional to annual coal production.	√	√	
	Annual materials	Material costs for drilling are estimated based on the volume of methane liberated.[a]	√	√	
	Annual labor	Annual labor costs related to drilling.	√	√	
Compressors	One-time capital	Number of compressors is proportional to the amount of methane liberated per unit time.[b]	√	√	
	Gas	Natural gas used by compressors is proportional to the amount of methane liberated per unit time.	√	√	
Gathering Lines	One-time capital	Costs are proportional to coal production.	√	√	
	Annual labor	Annual costs are primarily labor related to moving the lines each year.[c]	√	√	
Other Fixed Costs	One-time capital	Costs are proportional to coal production. Capital costs include safety equipment, licenses, and designs.[d]	√	√	
Processing	One-time capital	Costs are proportional to both coal production and methane liberated and include dehydrators and enrichment units.[e]		√	
	Annual materials	Annual costs are primarily the material used for maintenance.		√	
VAM	One-time capital	Costs are proportional to both coal production and the flow of VAM. Capital costs are primarily oxidizer units, fans, and ducts.			√
	Annual labor	Annual costs are primarily the labor associated with running the oxidizer.			√

[a]Material costs are related to the development rate of mines (i.e., access to drill boreholes) or the actual amount of drilling. However, because this information was not available, the volume of methane liberated was used as a proxy.

[b]Methane production levels of a typical mine site will ramp up in a step-wise fashion until a point is reached that new wells replenish production of depleted wells and production becomes flat. Compression is added as appropriate during the increase in production.

[c]In some instances it may cost more in labor to move in-mine gas pipelines than to install a new line and leave old lines in the workings.

[d]Other fixed costs may also include monitoring, reclamation, and gas ownership (royalties).

[e]Processing one-time capital costs are related to the gas recovery technique that is used. For example, more processing will be required for gob gas recovery than inseam.

Source: RTI International, 2003.

For China, Russia and Poland, regression analysis was used to estimate cost relationships based on the known costs for the given 56 U.S. mines as a function of coal production and/or methane liberated. Individual regressions were run for each cost component/factor listed in Exhibit A-2 (e.g., annual drilling costs, one-time compressor costs), and separate sets of regressions were run for each of the three abatement options. The coefficients were then applied to the known value of coal production and methane liberated for non-U.S. mines to generate cost components for each abatement technology. Details of the regression analysis are available in Gallaher and Delhotal (2005).

Following drilling of vertical or horizontal wells, compressors extract gas from the well and push the methane from the well to a centralized receiving point. Then a satellite compressor is used to pump captured methane from a centralized receiving point to a facility capable of injecting recovered methane into a natural gas pipeline. At the facility, a sale compressor matches the pressure of the recovered methane with the natural gas pipeline

Costs for compressors are a function of the needed horsepower to compress a volume of gas. Horsepower required varies across mines depending on the level of gassiness within the mine. Generally wellhead compressors require much less horsepower than the satellite or sales compressors. Annual costs for compressors include regular or unscheduled maintenance and labor to manage the methane recovery operations.

Gathering lines placed between wellheads and compressor carry recovered methane from the wellhead to the satellite compressor and on to the facility where the gas can be injected into a natural gas pipeline.

Detailed engineering cost information was not available for Chinese underground coal mines. Thus, costs were estimated as a function of mine production and liberated methane, which was obtained from the EPA report *Reducing Methane Emissions from Coal Mines in China: The Potential for Coalbed Methane Development* (EPA, 1996a).

Regression analysis was used to estimate cost relationships based on the known costs for the given 56 U.S. mines as a function of coal production and/or methane liberated. Individual regressions were run for each cost component/factor listed in Table A-1 (e.g., annual drilling costs, one-time compressor costs), and separate sets of regressions were run for each of the three abatement options. The coefficients were then applied to the known value of coal production and methane liberated for the Chinese mines to generate cost components for each abatement technology.