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Abstract

The 1990 Canadian long-range transport of air pollutants and acid deposition report divided North America into 40 sources of emission and 15 sensitive receptor sites. For the purpose of national policy making and international negotiation, the use of these large sources and few receptors may prove adequate. Due to inadequate information regarding cost of reducing emissions from each point source, it was felt necessary to design a method to generate cost functions for emission regions.

The objective of this study was to develop aggregate cost functions that relate the cost of SO_2 emission reductions to the amount of reduction achieved. The cost curves generated presume the application of

control technologies to achieve a mandated regional emission reduction in the year 2000. The study has also assumed that trading will take place among plants within a region.

The emissions inventories (GECOT and AIRS for the USA and RDIS for Canada) were used as the major source of data for the study. Cost functions were derived for forty emission regions. The functional forms that best fits estimated costs are either quadratic, power or linear in specifications. Furthermore, the cost functions indicted substantial variation (differences in marginal costs of removal) across emission regions. Preliminary analysis using Environment Canada's Integrated Assessment Modelling platform indicated that strategies that make use of these functions and environmental goals will cost the industry and government the minimum amount compared to those that relay on quantitative emission reductions. Considering the findings of studies that indicated exposure of several watersheds to excess depositions of SO2 compared to critical loads, policy makers should examine ways of reducing emissions beyond what is already committed for the year 2005 or 2010. Future work will investigate interregional trading, especially between the bordering states of the USA and provinces of Canada based on these cost functions.

Introduction

Emission of SO2 is the major contributing factor to acidification of aquatic and terrestrial ecosystems. The impact of acid rain is more pronounced in countries with large resource endowment (e.g., water, forest, soil, and vegetation), such as North America, because of the transboundary movement of its precursors such as SO2 and NOx.

Emissions of SO2 from the US contributes to as much as 60% of the total (wet and dry) acidic depositions in Canada. The contribution of Canadian sources to the US regions, however, is less than 30% (Environment Canada, 1993). Nevertheless, the health of North American ecosystems can best be served if both countries agreed to reduce local and transborder impacts from emissions of SO2. Consequently, Canada and the USA signed an agreement to reduce emission of SO2 by 40% in the year 2000 compared the 1980 level. This reduction level was based on the fact that critical deposition loadings of ecosystems is about 20kg/ha/yr of S04. The Eastern Canada Acid Rain Program, coupled with the U.S. Acid Rain Program that also calls for a 40 percent reduction in SO 2 emissions, is intended to protect moderately sensitive ecosystems from acid deposition. However, various ecosystems exhibit different degrees of sensitivity to acidic depositions.

Canada has achieved a 54 percent reduction in emissions of SO2 in 1994 compared to the 1980 level. This represents a 14% additional reduction than what is documented in the Canada-US air quality agreement (Air Quality, 1996). Similarly, actual US SO2 emission levels for all utility units in the phase I decreased to 5.3 million tonnes from 1980 level of 10.9 million tonnes. Comparison of actual and

projected emissions of SO2 also showed a declining trend (see Fig. 1). In summary, Canada and the USA have made significant progress toward reducing emission of SO2.

Fig. 1. Trends in Actual (1980-1993) and Projected (2000 & 2005) Emissions of SO2 (in kilotonnes)
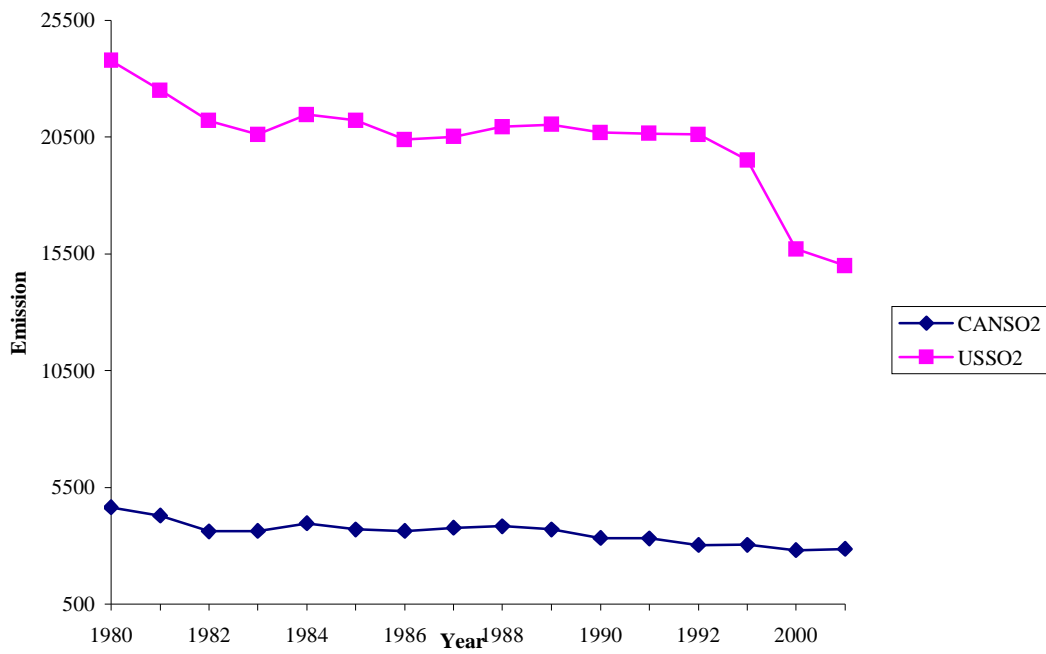
Despite the commitments made by Canadian and US governments to reduce emissions of SO2, wet deposition of SO2 in several watersheds is still greater than critical loads necessary to maintain healthy ecosystems (see Air Quality, 1996).[1] Regardless of the success of the Canada-US agreement to minimize the impacts of acid rain, many ecosystems are still being damaged. Lakes and streams in some areas continue to acidify. There are two main reasons for this finding. The U.S. Acid Rain Program will not be fully implemented until 2010, and many areas are so acid-sensitive that a 40 percent reduction in SO 2 emissions is not great enough to protect them from acidification. Acidification of ecosystems may also be compounded due to the dynamics of acidic deposition. That is, acidic deposition may not be neutralized in a single year. Acidified lakes, forests and vegetation take longer time to recover. The cumulative depositions may cause greater discrepancy between critical load and actual deposition. Therefore, more and more ecosystems may be exposed to serious environmental degradation. In addition, inhalable SO2 particles are becoming a major human health concern.

Some of these environmental, health, and visibility effects will be alleviated when the U.S. Acid Rain Program is fully implemented in 2010. However, a large area of Canada is still expected to receive harmful levels of acid deposition. As a result, the federal and provincial governments are working with stakeholders to develop a new National Strategy on Acidifying Emissions for post-2000 to protect acid-sensitive areas, human health, and visibility in Canada.

Future reductions, mostly through the application of end-of-pipe controls, changes in process or material inputs, may come at increasing costs. Therefore, appropriate mechanisms have to be in place so that implementation of emission reduction strategies to achieve environmental goals would not jeopardize economic growth. Consequently, it is imperative to explore further reduction strategies from what may be attained in the year 2010.

Different approaches could be pursued to reduce emissions of SO2 in order to close the gap between actual and critical deposition loadings. An emission reduction strategy, that would maintain or increase economic growth while allowing acidified ecosystems to regenerate, has to take into account several socioeconomic factors. One such approach is to identify a strategy(ies) that is(are) cost-effective to the industry and the government. However, the selected strategy(ies) should not only satisfy the criteria of cost-effectiveness but also enable the attainment of environmental objectives (that is, reduced acidic deposition). The development of these kinds of strategies requires availability of analytical tools that incorporates models from various disciplines.

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[1] Critical deposition loadings is define as: "The highest deposition of acidifying compounds that will not cause chemical changes leading to long term harmful effects on ecosystem structure and function" (Environment Canada, 1990). At the moment, critical loads are developed only for aquatic ecosystems. Future work in the development of critical loads will incorporate the sensitivity of terrestrial ecosystems and effects on humans.

In the past, environmental decision-making with respect to abatement of SO2 emissions utilized single-pollutant model. This approach doesn't treat interaction of SO2 with other pollutants such as NOx and their corresponding effect on acidification, eutrophication and formation of particulates. Thus, it is necessary to search for a prototype that examines multiple pollutants and multiple effects. This prototype must follow multi-disciplinary approach in designing an environmental management plan. Such a model can identify a strategy that is not only cost-effective but also results in minimal human and ecosystem health impacts.

Environment Canada is pursuing the approach of integrated assessment modeling (IAM) based on an expert system called RAISON (Regional Analysis using Intelligent Systems on Micro Computers) as the main platform. The platform includes fisheries, wild life, biodiversity, forestry and water chemistry models, and socioeconomic (cost-benefit) models. The IAM also incorporates outputs from atmospheric models for SO2 and NOx, uncertainty analysis, emission and depositions of nitrogen and sulfur oxides. This tool enables the inclusion of several factors that affect ecosystem and human health. It links activities such as energy use, emissions, technologies and costs to transport, depositions and impacts of various pollutants. The premise behind this kind of analytical tool is that the selected strategy would not only be economically viable but also ensure the protection of sensitive ecosystems.

The most important parameter to the development of a strategy that allows the attainment of a balance between economic and environmental progress is the explicit consideration of costs to the industry and the society in the promulgation of environmental policies. An inherent behavior of costs is that with increases in the amount of reductions, the additional cost per unit of emission removed tend to increase at a faster rate. Such phenomenon can be captured only if appropriate cost functions are developed for emission sources. Currently there is a trend to use economic instruments to develop cost-effective emission reduction strategies. Implementation of economic instruments undoubtedly requires cost functions. In summary, the most important ingredient to the development of successful abatement strategy is not single-point cost data but cost functions (a series of pair of cost-reduction points).

The objective of the present study is to present approaches to the derivation of cost functions and discusses how these functions would be incorporated into Canada's Integrated Assessment Model and the benefit of such an approach. The 1990 Canadian long-range transport of air pollutants and acid deposition assessment report divided North America into fourty emission and fifteen sensitive receptor regions (see Fig. 2). The present study will develop cost functions for the fourty source regions.

Figure 2. Map of Forty Emission Regions Used for Acid Rain Assessment
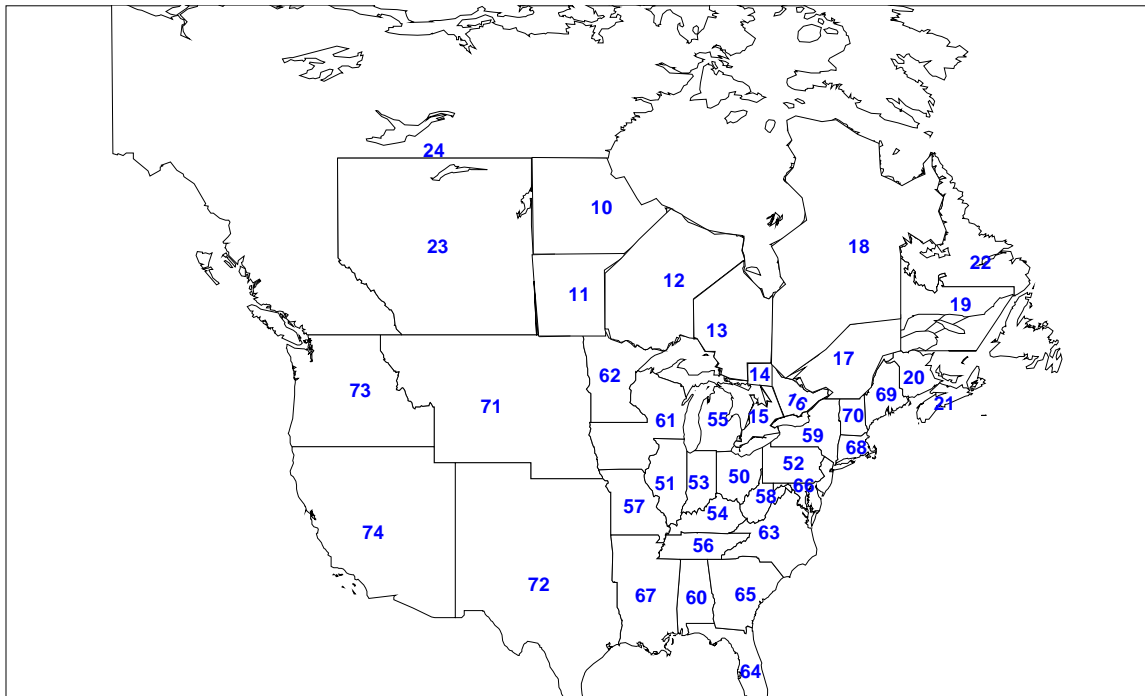
Source: MOI, 1982; and Environment Canada, 1990.

The Need benefit of Cost Functions

Environmental impacts in Canada are not caused only by activities within Canada. It is necessary to consider environmental impacts caused by emissions from both Canada and the US. Analytical tools should be able to analyze data on causes of environmental impacts (emissions, cost of control and the transport of pollutants) from both countries. Moreover, the identification of least-cost emission reduction strategies requires the availability of comparable cost functions for the US and Canadian sources of SO2 emissions.

Environment Canada has detailed engineering cost data for major SO2 emitting plants. There are no comparable cost data for the US. Aggregate cost functions cannot be derived for the emission regions unless similar methodology is utilized to serve similar policy objective. Consequently, this research was initiated to develop aggregate cost functions for the purpose of making indicative national policy making regarding future SO2 emissions reductions plans.

Scope and limitations of the study

The objective of the study was to develop cost functions for SO2 emissions for US and Canadian regions. Costs were estimated as a function of the amount of reduction achieved by the stationary sources.

The present study has the following limitations: i) The selected baseline attempts to represents 1995 operating practice with limited implementation of Phase I provisions of Title IV of the Clean Air Act Amendments of 1990. The Canadian data reflects the emission reductions achieved with the Eastern Canada Acid Rain Control Program until 1990. ii) The aggregate cost functions derived by this study could be viewed as only an order of magnitude estimates. Detailed analysis of policy options for smaller regions would require disaggregation of the scale of the present study. iii) The study was also limited with respect to the set of control options examined. In general, current best practices were represented by these options. Moreover, the study was not dynamic in the sense that timing of adoption or phase-in of controls was not examined.

Methodology

Theory and Model Formulations

Point Estimates of Costs

To calculate the cost of reducing emissions of a specific pollutant from a given plant, recommended Cost Estimating Algorithms (CEA) were used. The CEA used in this study closely follows and adapts the methodology described in the US Office of Air Quality Planning and Standards (OAQPS) control costs manual. These CEA vary by technology. CEA are sequential equations represented by linear, exponential,

etc. functional forms (see SENES, 1995). These CEA require stack parameters such as exhaust temperature, contaminant flow concentration or type of fuel.

The study used conventional engineering approach to estimating plant-level costs. That is, CEA used power law correlations to estimate capital and operating costs for control of a contaminant at a plant based on known costs at a reference plant, and the relative capacities of plants. This involves calibrating a cost function to baseline data and using scaling relationships to extrapolate the baseline data to other plant sizes (see also SENES, 1995). In most cases a single parameter model is adequate to estimate capital investment requirements. The single parameter is a size or capacity related variable. The model used in the present study employs a scaling factor", which is actually an exponential correction for size variation. The equation is of the general form:

$$C_i = C_0 * (CAP_i / CAP_r)^{\alpha} \qquad .... \quad (1)$$

Where C_i and C_0 refer to capital and operating costs for plant i and a reference plant (r), CAP_i and CAP_r are capacity of the plant i and reference plant (r), and is the scaling factor that accounts for non-linearity of the relationship. It is often suggested that a scaling factor of 0.6 is appropriate for many plant types. However, it is best to determine the scaling factor from plant cost data or detailed design data.

These CEA produce what is called an order of magnitude estimate. These estimates reflect product, capacity, utility requirements, raw materials requirements, storage and handling requirements, and building requirements (Molburg, 1996). These are essentially the elements of project scoping. A further limitation of these models is that they apply to new facilities. The present study is directed toward the application of controls to existing facilities. Typically, capital cost for retrofit applications exceeds that for new facilities by a factor of from 1.25 to 3.0. The study has estimated a retrofit factor to adjust the cost estimates. However, the correct value of this factor is site-specific.

The CEA are composed of two types of costs: capital, and operating and maintenance costs. Let capital cost be CC and operating costs be OC. CC include costs to purchase the equipment needed for the control system, labor and material for installation, site preparation and building, and other indirect costs. OC includes direct (DOC) and indirect costs (IOC) and recovery credits (RC). DOC are costs that vary proportionally to quantity of exhaust gas processed by the control system per unit of time. These include raw materials, electricity, water, waste treatment, disposal, parts, maintenance labor, etc. IOC are costs that do not vary with exhaust flow rate. These include administrative charges, taxes, insurance, etc. There are also costs recovered (RC) as a result of recycling or reusing. The value of these credits must also be offset by the cost of their processing, storage, transportation, etc. Mathematically,

$$C = DOC + IOC - RC \qquad \text{... (2)}$$

In order to evenly distribute fixed initial investments over several years and derive uniform costs on a yearly basis, the capital costs have to be converted into yearly flow rates. That is, the OC and CC would be used to calculate the annualized cost of abatement using the following equation:

$$ANC = OC + [CC*K(r)] \qquad \text{….. (3)}$$

Where ANC is total annualized cost, K(r) is a capital recovery factor which converts capital costs to an equivalent stream of equal annual future payments. The anualization of costs is considered to be end-of-year payments in constant (real) dollars which do not reflect the effects of inflation.

$$K(r) = r/(1-(1+r)^{-t}) \qquad \text{.....................................…....... (4)}$$

Where t is the economic life of the control system, and r is a real interest rate. The real interest rate or discount rate is given as:

$$r = (1+i)/(1+I)^{-1} \qquad \text{...… (5)}$$

Where i is the annual or nominal market rate of interest and I is the inflation rate. The discount rate is chosen as a function of a sector, based on weighted average cost of capital (WACC) concept. WACC is used instead of the discount rate to account sector variability in funding environments (see SENES, 1995).

Equations (1) to (5) generate point estimates of annaulized costs and associated emissions reductions. Often, they are used to derive parameters such as cost per ton of pollutant abated or maximum reduction for a given amount of expenditure. Environmental management decisions at federal or provincial level in Canada have been based on the principle of Best Available Control Technology (BACT) or Best Available Control Technology Economically Achievable (BACTEA). These principles are related to either technology, cost or both. In most circumstances, the above equations are used to provide single-point quantitative estimates upon which decisions will be based.

Derivation of Cost Functions

Cost functions are mathematical representations of combinations of discrete emission reduction points and their corresponding total annualized cost. Each point on the curve represents minimal cost of removal. Each level of removal would correspond to a particular control technology with a given level of removal efficiency. However, when aggregate cost functions are derived for the purpose of policy analysis three important issues ought to be considered, among others: i) the functions can not be used to identify anyone plant or it would not be possible to identify a particular plant on the curve, ii) controls applicable to a given level of reduction can not be identified from the curve, and iii) the cost functions represent cumulative removal and costs.

Several steps were followed in deriving SO2 cost functions. Costs of abatement were derived from plant level data. For each source subject to control, control technologies and the capital and operating cost of applying these technologies were identified. The capital costs were annualized and added to annual operating costs. This yields a total annual cost. Then, the emission reduction associated with each of the sources was calculated based on a representative removal efficiency.

For each level of removal, the incremental cost of switching to a more efficient control was calculated for each plant. Controls that were more expensive but less efficient were eliminated. Incremental reduction and cost were calculated for each control. The control with the lowest incremental cost among the next least efficient controls for each plant was selected. This process continued until all options were exhausted. The resulting data would be cumulative costs and the corresponding emissions reductions. The cumulative costs and reductions could, in most cases, be represented by a monotonically increasing function. Mathematically,

$$C_i = \text{Min} \sum c_{ij} s_{ij} \qquad \text{.................................... (6)}$$

Where C_i is total cost of abatement at source i, c_{ij} is the cost of implementing control technology j by source i, and s_{ij} is a binary variable taking 1 if source i adopts control j and 0 otherwise. Equation (6) will identify controls until the following condition is satisfied:

$$\sum e_{ij} s_{ij} \geq E_{target,i} \qquad \text{.................................... (7)}$$

Where e_{ij} is reduction at source i associated with the control j, and $E_{target,i}$ is a total reduction requirement (target) of source i. Equation (7) implies that sources will continue to adopt controls until the desired reduction is at least equal to the targeted reduction.

For each source, the ratio of cost to emission reduction was calculated. The cost per tonne of SO2 reduced was used to rank all sources in a given region according to cost effectiveness of control. Then, each source was added one at a time in order of increasing average cost and effectiveness. The resulting incremental cost and reduction were compiled by emission region. Once the cumulative incremental costs and reductions were derived, functional form of the following type was fitted to the data set:

$$C_i = f(E_i) \qquad \text{..(8)}$$

Where C_i is the cumulative incremental cost for source i and E_i is the corresponding reduction achieved at source i.

Data Requirement

Sources of Data

Most US data was obtained from the GECOT and AIRS database. The most important US sources of sulfur dioxide and their contributions to 1992 emissions are: electric utility fuel combustion (69%), industrial fuel combustion (13.6%), metal processing (3.8%), highway vehicles (3.5%), and other fuel combustion (2.6%). Title IV provisions will result in substantial decline in US utility emissions, while US industrial emissions are expected to remain constant over the next two decades. The industrial sector data from AIRS is reflective of 1990 operations. Some of this data has been updated with the latest available information.

Plant-specific engineering data for Canadian SO2 emitters was obtained from RDIS (Residual Discharge Information System) of Environment Canada. The data was similar to the US AIRS database in scope. This database is the result of voluntary submission of information by individual plants to the provincial Ministry of Environment. Smelters and power generation account for about 60% and 20% total Canadian emissions respectively. The present study included sources that account for 80% of total Canadian SO2 emissions.

The emissions inventories (GECOT,AIRS and RDIS) include plant characteristics for emission sources. These characteristics - such as plant size, fuel use and type, average utilization rate, flow rate, type of

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control, and emissions were used to estimate the cost of retrofit control for one or two control options for each source. Naturally, these set of information are by far less than what is required for detailed engineering cost function analysis (see Weaver, 1973). However, they are adequate to derive aggregate regional cost functions.

Controls Technologies

Several controls have been reviewed for the purpose of undertaking this study. However, considering the fact that i) the output from this project will be used for making national or continental emission reduction strategies, and ii) the limited time devoted to the study, about a dozen commonly used controls were considered . The controls examined include Wet flue gas desulfurization using lime or limestone reagent, dry flue gas desulfurization using lime reagent, sorbent injection, sodium-based scrubbing, hydrodesulfurization, switch to low sulfur coal, switch to natural gas, double contact acid plant, amine scrubbing with claus unit, dual absorption H2SO4 plant, tail gas treatment, and coke oven controls. Detailed information on these and other controls can be found in Molburg (1996) and SENES (1995).

Control technologies identified for this study are also those that are commonly applied in Canada (see SENES, 1996). Moreover, the technologies reflect state-of-the-art and are applicable for plants that emit at least 10 tonnes of SO2. Combinations of these controls are not considered in the present study. Future work will include not only phase-in of these controls based on their estimated productive life but also possible combinations in specific process-based applications. However, the static nature of the analysis that is based on these controls should give an upper bound with respect to cost and levels of removal.

Results of the Analysis

Cost models were developed for application to individual sources that are characterized in the AIRS database (for US sources) or in the RDIS database (for Canadian sources). Since site-specific information in these databases is limited to a few key parameters, the cost models will reflect only the most significant differences between sources of a given type. Generally, these include size, annual average utilization, fuel type, and current level of control.

The cost functions yield the total annual cost of achieving a given amount of emissions reduction. Costs are in US$ at a 1995 price level. The emission reductions are in tons ('000) of sulfur dioxide. Both the costs and emission reductions apply at the regional level. The slope of the cost function is the marginal cost of abatement ($/ton). These cost functions can be used with an interregional optimization program to minimize the cost of achieving overall emission reduction or deposition reduction goals.

US Cost Functions

The equations defining the cost functions for each of the 25 US source regions are summarized in Table 1. These functions were estimated in such a way as to depict estimated costs and removal data. Consequently, there can be 1, 2 or three cost functions for a source for different ranges of removal. This

is the case if a particular range of removal exhibits significantly different form of relationship between costs and removal levels.

Table 1. US Emission Region SO2 Abatement Cost Functions[2]

Emission Region	Range of Emission Reduction		Equation
	minimum	maximum	
50	1000	1750	$Y=4.0816e^{0.0035x}$
51	50	1000	$Y=6.5982e^{0.0053x}$
52	100	400	$Y=7x10^{-6}X^{2.7622}$
53	50	1050	$Y=9.8344e^{0.0046x}$
54	0	160	$Y=0.4258X$
55	0	300	$Y=0.0061X^2+0.8073X$
56	0	250	$Y=.0017X^2+0.1682X$
57	0	500	$Y=0.0003X^2+0.1126X$
58	0	225	$Y=0.0007X^2+0.0806X$
59	0	110	$Y=0.0016X^2+.172X$
60	180	550	$Y=0.0064X^2-2.5673X+264.12$
61	0	250	$Y=0.0021X^2-0.0359X+0.8974$
62	0 70	70 90	$Y=0.0138X^2+0.7649X$ $Y=0.2213X^2-28.958X+1067.4$
63	0	500	$Y=0.0035X^2+0.4415X$
64	0	225	$Y=2x10^{-15}X^{6.8292}$
65	160	420	$Y=0.0003X^2-0.0422X$
66	0 95	95 200	$Y=0.0218e^{0.0626x}$ $Y=1x10^{-7}x^{3.918}$
67	25	325	$Y=0.0076X^2-0.5551x+11.775$
68	0	115	$Y=4.2109e^{0.0428x}$
69	0.6	1.4	$Y=0.5708e^{2.6627x}$
70	15	35	$Y=0.3228e^{0.1323x}$
71	0	280	$Y=0.0093X^2-0.5135X+9.9007$
72	0	900	$Y=0.003X^2-0.1509X$
73	0	57	$Y=0.0578X^2-0.0402X$
74	0	200	$Y=0.0086X^2+1.1576X$

These functions estimate the total annualized cost in 10^6 1995 US$ for emission reductions in 10^3 short tons per year
(y is the annualized cost, x is the emission reduction).

Table 2 Summary of Regional Cost Functions[3]

Emission Region	Range of Emission Reduction		Equation
	Minimum	**Maximum**	
10	0	150	$Y=0.0532X^2$
11	0	2.8	$Y=4.3192X^2 + 0.7381X$
12	5	10.5	$Y=0.1867X^2 + 1.817X$
13	0	9.5	$Y= 0.1316e^{0.4982x}$
14	0	600	$Y=0.9E\text{-}08X^2 +0.0501X2$
15	0	270	$Y=0.0038X^2 - 0.0048X +3.2777$
16	5	11.5	$Y=0.0084e^{0.7306x}$
17	0.05	31	$Y=0.4401e^{0.1251x}$
	31	80	$Y=0.0376X^2 - 1.3116X + 19.82$
	80	105	$Y=6.1361e^{0.0407x}$
18	0	165	$Y=0.0243e^{0.0402x}$
19	0	51	$Y=0.0298e^{0.1086x}$
20	0	150	$Y= 0.0048X^2 + 0.5292X -0.361$
	150	175	$Y=11.123e^{0.0297x}$
21	0	130	$Y=0.0054X^2 +0.0514X+1.3734$
	130	170	$Y= 2.2553e^{0.0297x}$
22	0	20	$Y= 0.03X^2 +0.164X + 0.3884$
	20	43	$Y=0.008X^2 + 5.8647X -10.4.59$
23	20	200	$Y=0.0007X^2 + 0.0122X + 2.6587$
	200	385	$Y=8x10^{-8}X^{3.7677}$
24	3	23	$Y=0.3591e^{0.2196x}$

Strategy for the Utilization of SO2 Cost Functions

Canada has already met its commitment for 2010 with respect to reduction of SO2 while US has not. Given that the cost functions are developed based on the 1990 emissions, the following procedure is proposed on how to make use of the aggregate cost functions. The main point of discussion is to present proposed ways of using the cost curves based on 1990 data for analysis of the post 2010 situation.

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[3] These functions estimate the total annualized cost in 10^6 1995 US\$ for emission reductions in 10^3 short tons per year (y is the annualized cost, x is the emission reduction).

Strategy I

Assuming that each region has reduced certain percentage of their total emission between 1980 and 1990, determine by how much emission has been reduced between 1990 and 1994, and then calculate by how much more each region has to reduce emissions to comply with the commitment. From the cost functions, determine emission removed between 1990 and 1994, and the corresponding cost for each emission region. This point on the curve will indicate where Canada will be in 2010.

That is, for source i, actual emission e and targeted reduction E,

$$\sum e_{it} = E_{target,i} - \sum e_{i,t-1} \qquad \text{.................................. (9)}$$

The amount of emission a source region i has to reduce equals the target less what has been reduced to date (1980 to 1994). Identify this level of removal on the cost curve, such that we will have:

$$C_{it} = f(E^*_i) \qquad \text{... (10)}$$

where $E^*_i = e_{it}$, and that

$$C_i = f(E_i) \leq C_{it} = f(E^*_i) \qquad \text{.................................. (11)}$$

(Insert Equation # 11 here)

Equation (11) ensures that the curve representing reductions after accounting for past performance should be higher than the initial curve.

The next step is to incorporate the revised cost function into the IAM. To do so, there must be i) a restriction that will indicate that additional removal from Canadian sources would be exercised only after total emission removed from the US totals the remaining reduction requirement (total commitment less removal between 1980 and 1994), ii) allow the restriction to explore minimum cost reduction strategies once the US achieved its committed reduction, iii) by the time both countries attained their commitments, impose a constraint into the IAM that will force the optimization program to allow unrestricted North American reduction subject to a set of environmental goals starting in the year 2010 level as zero reduction. The tricky part is that the US reductions cannot be confidently tied to particular emission regions because of trading. The alternative is to take the state level reduction projections from EPA study to establish the region-specific reductions. Then, the remaining portion of the curves can be used for further reductions.

Strategy II

An alternative to strategy I is to assume that all plants or regions have attained the required emission reduction. What would happen if we assume that the same cost functions would apply to situations in the year 2010 and beyond? Obviously, this approach may also overestimate future control costs because of the declining cost of control technologies and cost per ton of SO2 removed. Since the starting point is not high on the cost curve, this procedure may result in less overestimation of future costs compared to the first approach.

In summary, there are two points of concern with respect to the fact that costs may be overstated. One is the declining cost of controls as competition and market growth contribute to improved efficiency in control implementation. The other is the observation that higher removals in later years put emission region further up on the curve. The latter point is as it should be, that is, marginal costs are increasing. The former point should just give us confidence that future costs will not be underestimated.

Approaches to Incorporation of SO2 Cost Functions into the Integrated Assessment Model (IAM)

The aggregate cost functions will be incorporated into the IAM via an optimization scheme. There are several optimization models. Deposition minimizing models are preferred in examining feasible emission abatement strategies. Most of these models use single-objective optimization technique. However, deposition-minimization models, with inviolate or relaxed deposition targets, are criticized for being single-objective (see Ellis, et al., 1994; Gough, et al., 1994). That is, their objective function is either minimization of cost or deposition. Realistic assessment of pollution abatement strategies cannot be accomplished using a framework based on a single criteria or objective. Multiobjective optimization models promote appropriate roles for participants in planning and decision-making processes, enable identification of a wide range of alternatives and provide a more realistic perception of the problem

because of inclusion of many objectives (see Cohon, 1978). Therefore, a simple yet realistic multiobjective optimization model will be used in this study (see Ellis, 1988; Ellis, et al., 1994).

The mathematical formulation is a least-cost deposition-relaxed model is given as:

$$\text{Minimize } (z_1 + z_2 + z_{3)} = Z = \sum_{i=1}^{n} C_i R_i + \sum_{i=1}^{n} LC_i \lambda_i + \sum_{j=1}^{m} (W_j^u U_j + W_j^v V_j) \quad \text{...... (12)}$$

Subject to:

$$\sum_{i=1}^{n} (EC_i - R_i) T_{ij} + \sum_{k=1}^{o} EU_k T_{kj} + BD_j - V_j + U_j \leq (1 + \mu_j) CL_j \quad \text{.................. (13)}$$

$$R_m = \triangle (EC_m + EU_m) \quad \text{.................. (14)}$$

$$0 \leq \lambda_I \leq 1 \quad \text{............. (15)}$$

$$\sum_{i=1}^{n} R_i = EA \quad \text{.................. (16)}$$

$$R_i \geq 0 \quad \text{.................. (17)}$$

$$0 \leq V_j \leq \mu_j CL_j \quad \text{.................. (18)}$$

$$0 \leq \mu_j \leq 1 \quad \text{.................. (19)}$$

$$U_j \geq 0, \ \forall j \quad \text{.................. (20)}$$

where W_j's are user-specified objective function weights for receptor j (j=1...m), C_i is the marginal cost of emission removal at controlled point source(EC) i (i=1... n), R_i is the amount of emission removed from controlled source i (decision variable), EC_i is existing emission rate at controllable source i, T_{ij} is the unit transfer coefficient that relates the rate of deposition at receptor j and the rate of emission from controllable source i , EU_k is existing emission rate at non-controllable source k (k=1...o), T_{kj} is transfer coefficient that links receptor j and uncontrollable source k, BD_j background wet deposition rate at receptor j, AD_j is maximum allowable deposition rate at receptor j; CL_J is critical deposition loadings at receptor j; U_j is the magnitude of over achievement (deposition less than the target) at receptor j, V_j is the magnitude of violation (deposition exceeding target) at receptor j , EA is predetermined aggregate emission reduction level, LC_i is employment at point source I, λ_i is the proportion of losses in employment as a result of the chosen control option at source i and μ_j is the proportion of violation of critical deposition loadings at receptor j. Equation 14 states that the amount of pollutant removed from source m should be a certain percentage or fraction ($\triangle$) of total unabated emission from source m. The reason for inclusion of this constraint is that some regions or sources of emission may have already implemented control strategies to satisfy the regional emission quota while others may have not. This constraint, therefore, avoids an unnecessary burden to those sources of emission that have made progress toward cleaner environment. The above formulation can be modified to include constraints specific to each receptor or sources of emission. Equation 18 sets an upper limit to the violation of deposition. Equations 12 to 20 could be be simplified by dropping the underachievement variable (U) and others as may be necessitated by the availability of the data set.

This equation will be incorporated into the IAM platform so that the selected feasible emission reduction strategy will satisfy socioeconomic and environmental criteria that are included in the optimization scheme as constraints. Since the cost functions as well as the optimization scheme could be linear or nonlinear, the IAM platform is being developed to run nonlinear models. With the completion of this development, the IAM can be run to select strategies in a multi-pollutant/multi-effect platform.

Conclusions

Canada and the USA have made substantial progress toward reducing one of the precursors of acidic depositions, that is emissions of SO2. However, the Canada-US SO2 emission reduction plans were intended to protect moderately acid sensitive ecosystems. Consequently, there are several ecosystems are still being acidified. Without further emission reductions it is unlikely that many ecosystems will return to their natural state. As a result, the government of Canada, despite attaining a 14% more reduction beyond what was agreed for the year 2000, is searching for further feasible reduction strategies.

Given capacity and technological constraint of industrial establishments, future measures to reduce emissions have to explicitly examine cost-effective and environmentally benign strategies. Identification of these kind of strategies requires, among other things, a holistic approach to strike a balance between economic growth and environmental sustainability. This in turn necessitates the development of cost functions to explore ways of reducing emission from both Canadian and US sources. This is because SO2 is a transboundary pollutant that impacts ecosystems in both countries. In fact, the Canadian acidifying emissions task group will recommend further SO2 emission reductions in 1997. However, new US emission reduction strategy may not be in place before 2010. Therefore, immediate action with respect to emission reduction is required to prevent further environmental degradation.

Past approaches to management plans, that is the use of a single-point estimate of costs to identify feasible abatement strategies should be modified. Multi-pollutant/multi-effect approach should be adopted to provide an optimal holistic solution. This approach should be able to identify a strategy that is not only cost effective but also results in reduced human health risk and damages to aquatic and terrestrial ecosystems. Control measures for sources of emissions, their costs, expected benefits, etc., can only be modeled in a holistic manner if Canada's Integrated Assessment Model is utilized. Without such model, the resulting strategies would be less than optimal or would maximize economic and environmental benefits. That is, they would not bring the maximum environmental benefit from any measure that relies on a single pollutant management plan.

The results presented here are expected to provide a reasonable first estimate for SO2 emission reduction cost curves. However, it is important to review and perhaps improve these results with 1) verification and updating of the baseline emissions inventories, 2) enhancement of cost estimates and validation with recent installations, 3) expansion of the control options with additional technologies, 4) detailed analysis

of major industrial sources and 5) expansion of the policy options to include date of compliance alternatives and phase-in of control technologies, thus allowing for a dynamic analysis.

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