Heterogeneity in Costs and Second-Best Policies for Environmental Protection

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Resources for the Future

July 14, 1999

Abstract:

This paper investigates heterogeneity in the cost of pollution abatement using a simple computable general equilibrium framework. When underlying costs are heterogeneous, aggregation to a sector-level abatement cost function yields qualitatively different findings from a disaggregated representation of costs. Tradable permits that do not raise revenue (grandfathered permits) out-perform command and control approaches over a wide range of emission reductions, reversing a finding in the recent literature. In addition, we identify an opportunity for cost savings by applying incentive-based approaches in a limited way, mixed with traditional approaches applied in other sectors or industries. This finding contradicts standard economic prescriptions that incentive-based instruments perform better if applied broadly. The finding also resembles actual regulatory practice, and perhaps enhances the political acceptability of incentive-based regulations. We find the results to be sensitive in a predictable way to the characterization of heterogeneity in the underlying data, providing guidance about the requisite level of detail for similar modeling efforts.

Key Words: cost-effectiveness analysis, general equilibrium, environmental policy, instrument choice, second-best regulation

JEL Classification Nos.: D58, H21, L51

[Ψ] This paper was prepared for the "Workshop on Market-Based Approaches to Environmental Protection," at the John F. Kennedy School of Government, July 18-20, 1999. The authors are indebted to Larry Goulder, Ian Parry and Rob Williams for collaboration on related aspects of this project, and to David Evans for assistance. Funding was received from the Environmental Protection Agency and the National Science Foundation. Address correspondence to: Resources for the Future, 1616 P Street NW, Washington DC 20036 (Burtraw@rff.org; Cannon@rff.org).

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1. Introduction

Several types of efficiency are discussed in the economics literature. One type is “technical efficiency,” or “static cost-effectiveness,” where the focus is on minimizing out-of-pocket compliance costs within a setting with fixed factor prices and consumer demand. Partial equilibrium analysis is the usual tool for looking at technical efficiency because it allows for detailed industry and firm specific data.

A second type is “allocational efficiency,” where the focus is on the allocation of resources that is achieved, and the extent that prices equal social opportunity costs. Increasing use of general equilibrium analysis has made this focus more practical. The study of efficiency has also broadened to incorporate so-called “second-best” analysis that takes into account pre-existing distortions away from economic efficiency when evaluating environmental policy alternatives. These broader perspectives have yielded new findings about the efficacy of alternative policy instruments.

Although general equilibrium models are sophisticated in their internal consistency, they often appear naïve with respect to technological characteristics of the economy that are present in partial equilibrium models. An important question for the use of economic analysis is the appropriate level of detail in modeling.

This paper investigates the value of detailed information about abatement cost in general equilibrium economic models of environmental policy. We create a computable general equilibrium model and apply parameter values in the model representing the cost of reductions in NO_X to replicate previous findings. Then we explore alternative formulations of the model to account for underlying heterogeneity in abatement costs data for NO_X, and we compare these versions with respect to recent findings of the burgeoning literature on environmental policy in a second-best context.

Several recent papers have compared the social costs of alternative instruments such as various types of command and control regulation, emission permits, emission taxes and other instruments. A common conclusion of these papers is that the extension of a modeling framework to incorporate pre-existing distortions away from economic efficiency such as taxes on labor or capital income is significant to understanding the cost of environmental policy.

Under standard assumptions (Parry, 1998), the existing literature offers two central findings. One is that the cost of a new regulation typically is estimated to be greater in a model that includes pre-existing distortions than in a model that ignores these distortions.[1] The second is that the relative cost-effectiveness of various policy instruments for environmental regulation can change substantially when pre-existing distortions are taken into account.

One issue that has not received scrutiny previously is the characterization of heterogeneity in abatement costs. Our exploration of this dimension of the problem indicates that the first of the central findings - that the costs of regulation appear to be greater when pre-existing distortions are taken into account - is robust to the characterization of heterogeneity, when other standard assumptions are held constant. The magnitude of the difference between the estimate of regulatory costs in a partial and a general equilibrium framework is affected, but the qualitative direction of the difference is unaffected.

However, the second finding - regarding the relative cost-effectiveness of various instruments - is sensitive to this modeling issue. The ordering of instruments in terms of cost-effectiveness is affected when heterogeneity is taken into account. Previous studies (Goulder et al. 1999; Fullerton and Metcalf, 1997) identify command and control policies (technology standards and/or performance standards) as more cost-effective than grandfathered tradable permits that do not raise revenues. We verify this finding when costs are aggregated to a homogenous case, in particular when replicating the results of Goulder et al. for NO_X reductions. However, in the heterogeneous case when costs are disaggregated the cost-effectiveness ranking of instruments is altered over a significant range of emission reductions. Hence, the level of aggregation in constructing the model appears to have an important effect on the policy recommendations that are achieved.

The previous literature has consistently abstracted away from heterogeneity in abatement costs or not modeled abatement cost explicitly at all.[2] Most often, the context for investigating environmental policy in a second-best setting (with pre-existing distortions away from economic efficiency) has been the analysis of policies to reduce carbon dioxide emissions.[3] For this problem abatement technologies are of little relevance and most emission reductions are achieved through input substitution.

Few studies have included abatement costs explicitly. Goulder et al. (1997) examine the sulfur dioxide trading program and compare the performance of (grandfathered) tradable permits with a revenue-raising tax. Only Goulder et al. (1999) and Fullerton and Metcalf (1997) have considered a broader set of policy instruments including some form of command and control regulation. Both studies employed an

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[1] Williams (1998) investigates an analogous proposition that benefits of environmental policies may be underestimated in a model that excludes pre-existing distortions.

[2] For example, see Bovenberg and de Mooij (1994), Bovenberg and Goulder (1996).

[3] For example, see Carraro and Gallo (1996), various authors in Carraro and Siniscalco (1996), and Parry, Williams and Goulder (1998). A recent review is contained in de Mooij (1999).

aggregate abatement cost function for the polluting sector to yield results that differ from those in this paper.

A second result that emerges from this analysis addresses what one may characterize a "folk theorem" in environmental economics, which is that regulatory programs, and especially tradable permit programs, should cast their net of coverage as broadly as possible. The general idea is that by casting the net broadly, the program can take advantage of differences in marginal costs and achieve greater cost-effectiveness. However, Parry and Williams (1997) discovered a case in which the social cost of regulation under a tradable permit program appeared to decline for modest emission reductions in a CGE model when one industry was excluded from the regulation.

We construct a hybrid case in which the regulator excludes the industry with relatively higher marginal abatement cost from a tradable permit regime and instead imposes a command and control regulation on that sector. The hybrid dominates tradable permits and command and control when costs are heterogeneous. The reason is that sectors that have relatively high cost for pollution reduction contribute little to emission reductions in a tradable permit scheme. Nonetheless, their inclusion allows them to capture rents on their tradable emission allowances. The change in product prices contributes to the interaction of the program with pre-existing taxes, raising social costs without contributing to cost-effectiveness. This finding suggests the undoing of a folk theorem, providing a justification for discriminating among industries in designing tradable permit schemes, as is current practice in NO_X and SO_2 policies.

The organization of this paper is the following. The next section provides further motivation for the analysis by illustrating the bias that is embedded in aggregation of data for economic modeling. Section 3 provides some evidence of the magnitude of heterogeneity in the case of NO_X abatement costs, a topic of relevance to current regulatory efforts of the EPA and various state governments, and the focus of our numerical simulations. Section 4 describes our model and data. Section 5 presents our findings, Section 6 offers observations and sensitivity analysis, and Section 7 concludes.

2. Motivation

Economic modeling inherently depends on a simplified representation of the economy. Characteristics of individual facilities or industries are lost when we construct an aggregate representation of abatement costs. The motivation for this paper is to identify the degree to which aggregation of cost data has an effect on the policy prescriptions that obtain, and in fact whether those prescriptions may be subject to bias.

The way that heterogeneity in abatement costs may matter to evaluating the cost of alternative policies can be illustrated easily. Consider a sector with two constituent industries, one with low and one with high marginal abatement cost curves, as illustrated in Figure 1. Aggregation at some level is always required in economic modeling. How should one go about constructing an aggregation of the industries in this case?

One way to construct a sector aggregate of abatement costs would be to calculate a vertical sum of the abatement costs at each level of emission reduction for the constituent industries. The change in aggregate abatement costs at each increment of emission reduction would map out an aggregate marginal abatement cost schedule for the sector. In general, when the percent reduction in emissions is constrained to be equal in the constituent industries (facilities) within the sector, the aggregate marginal abatement cost schedule is equivalent to the emission weighted vertical mean of the marginal abatement cost schedules for the constituent industries (facilities). This is illustrated by the heavy line in Figure 1. One can attribute the aggregate marginal abatement cost curve to one or several homogenous constituent firms to characterize a sector.

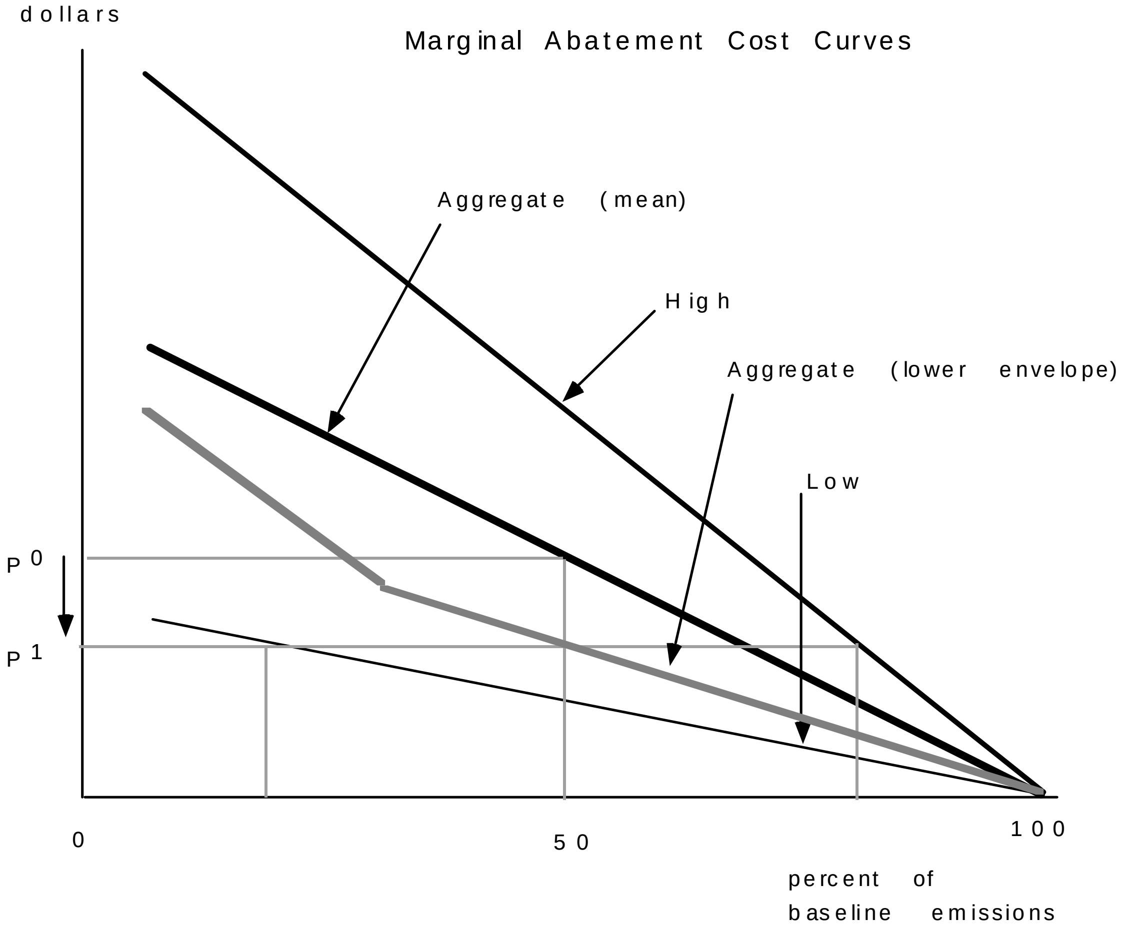

Figure 1: Two ways to aggregate marginal abatement cost.

By construction, the mean (aggregate) marginal abatement cost schedule in Figure 1 is accurate for evaluation of an equal percent reduction in emissions, as sometimes describes a performance standard. However, if an alternative such as tradable emission permits is contemplated, the schedule will not provide an accurate indication of costs. The permit instrument allows firms to reduce total costs by equating marginal costs of emission reduction. In Figure 1, a 50% emission reduction can be achieved at a marginal cost of P^0 under a performance standard, but a marginal cost of P^1 would result under emissions trading, since the constituent industries could exchange obligations to reduce emissions.[4] A systematic bias emerges when comparing instruments using mean marginal abatement costs as an aggregate representation of constituent marginal costs. Of course, if the industry aggregates are themselves mean representations of marginal abatement costs for their constituent firms, and firms are aggregates of plants, and plants are aggregates of generating units, the cost of a trading program would be further still from the prediction of costs using an aggregate representation for the sector.

The bias in the comparison of instruments is increased when the change in product price is accounted for in a general equilibrium framework. Given that the relevant emission constraint is satisfied, under a performance standard the cost of a change in emissions is just the abatement cost. For tradable permits, there is an additional positive opportunity cost evident in the price of the permit, presumably equal to the marginal cost of abatement. If the marginal cost is overestimated in the model, then the compliance cost and the opportunity cost of the policy are biased high, compounding the bias in the predicted change in product price and exacerbating the bias in comparing instruments.

And, the bias is compounded further when comparing instruments in a model that accounts for pre-existing distortions away from economic efficiency in factor markets, such as a tax on labor income. The interaction of an environmental regulation with a pre-existing labor tax stems from the effect of the regulation on product price, the effect this has on the real wage of workers, and in turn, on the supply of labor. If the representation of marginal abatement cost for a sector is systematically biased in evaluating alternative policies, this bias will be passed all the way through to the calculation of social welfare.

The remedy to this problem might be to use a different approach in constructing an aggregation of abatement costs. Imagine that instead of using the (emission weighted) mean of constituent marginal abatement costs, one used the *lower envelope* of marginal costs among constituent industries in the sector. This would inherently account for the flexibility implicit in a permit or tax approach to the problem by reflecting the most cost-effective way of achieving those reductions. One could apply this schedule to one or several homogenous constituent industries to characterize a sector.

This approach would accurately reflect the compliance cost of a permit or tax policy. However, in evaluating policies such as a performance standard that required equal percentage reductions at each constituent industry, or in evaluating a technology standard that required specific investments at various plants, again there would be a surprise! This time the aggregate marginal abatement cost schedule would be in error by underestimating costs. This error would be passed through the model in the calculation of

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[4] If marginal abatement costs are linear, the more heterogeneous are the marginal costs of the constituent firms, the lower will be the marginal costs of a trading program at every level of emission reduction (Ben-David *et al.*, 1998).

product prices and social welfare, again imposing a bias in the comparison of instruments.

A uniform approach to constructing aggregate marginal cost schedules is inherently problematic when using these schedules to compare alternative policy instruments. However, general equilibrium models inherently depend on aggregate representation of detail in the economy. The question before us is whether the bias that is contained in the aggregate cost data is significant enough to affect the conclusions of an economic analysis.

3. Evidence and magnitude of heterogeneity in abatement costs

Among the sources of abatement cost differences at various facilities are the vintage of capital and the transport of inputs and outputs. These differences are often omitted from a general model with the justification that capital and location are malleable in the long-run, and constant returns to scale are assumed to obtain.

Often, the comparison of policy instruments is not a long-run question. Policy makers are interested in the cost of environmental improvements in the near-term, with capital and other firm-specific factors of production fixed or costly to adjust. In this case differences between sectors or industries may be important for a model to accurately reflect the relative cost-effectiveness of various instruments.

	Baseline Emissions (million tons)	**Percent of Total**	**Percent reduction under CAAA**	**Average Cost** ($/ton)
Utilities	7.5	33	49	438
Nonutility point sources	3.4	15	13	1289
Mobile	7.3	32	10	2919
Other	4.8	21	N/A	N/A

Table 1: Illustration of NO_X abatement costs for compliance with 1990 Clean Air Act, by sector (Pechan, 1996).

Table 1 presents a range of estimates of NO_X abatement costs estimated by Pechan (1996) for compliance with the 1990 Clean Air Act Amendments. The four rows represent the aggregation of emitters into four sectors. The first column reports baseline emissions expected for 2003, and the second column indicates the relative percent of emissions for each sector. The third column reports the percent reduction required under the legislation, and the fourth column reports the average cost of reduction for each sector. The differences in average cost per ton aggregated at the sector level vary nearly seven fold.

Incremental cost ($/ton)	**Percent of observations**
0-100	19
100-200	38
200-400	22
400-600	9
600-1200	9
1200-2000+	3

Table 2: Distribution of *incremental cost* for approximate 50% NOX reduction at utility sources in sample of thirteen eastern states (N=646), Pechan (1996).

Table 2 presents a distribution of cost within one of the sectors – the utility sector – reported in the previous table. The estimates are for a 50% reduction in NO_X emissions in the northeast. One source of variability is the lumpy nature of abatement capital. The distribution is asymmetric, with the median less than the mean, and the tenth and ninetieth percentiles vary by an order of magnitude.

The examples in Tables 1 and 2 indicate significant heterogeneity in costs, between and within sectors. We choose a 25% level of reduction for the analysis because it more closely represents the emissions reductions to be achieved under the 1990 Clean Air Act (about 21% across all sectors), as indicated in Table 1. In the next section we describe a general equilibrium model that incorporates a relatively modest measure of heterogeneity in abatement costs, and subsequently we use this model to calculate the bias in estimates of regulatory cost using different instruments.

4. Model

We have adapted the numerical model used by Goulder et al. (1999) by making adjustments to account for heterogeneity in the cost of pollution abatement. The model is a static general equilibrium model using constant elasticity of substitution (CES) forms in the production and utility functions. Labor (L) and emissions (E) are the primary inputs to production. The representative household receives an endowment of time that it allocates to labor or leisure, with income from labor (less government taxes), transfers from government, and economic rents (manifest under the tradable permit policy) available to pay for consumption. The government levies a tax on labor income that it returns as a lump-sum distribution to the representative household. The labor tax rate is set endogenously so as to keep government revenue constant.[5]

Production is comprised of clean and dirty intermediate good sectors (D, N) and final consumption goods (C_D, C_N). Two additional intermediate sectors (B1, B2) produce emission abatement services. The polluting (dirty) intermediate sector (D) is disaggregated into two smaller sectors that we refer to as "industries" (D_J), with potentially different costs of abatement. Appendix A provides a graphical illustration of the structure of the industries while Appendix B outlines the mathematical form of the CES functions.

The aggregate of abatement (B_J) and emissions (E_J) can be thought of as potential pollution of $NO_{X.}$ The polluting industries take potential NO_X (the B-E aggregate) as an input to production. If abatement is zero, emissions equal potential pollution of NO_X. When the allowable amount of emissions is reduced, the B-E aggregate exhibits increasing convex costs, and the industries exhibits declining returns to scale with respect to the B-E input to production.

The two dirty industries are modeled as having identical production technologies, except potentially for the B-E aggregate, which is maintained to isolate the effect of heterogeneous abatement costs. The partial equilibrium cost of abatement is determined by the elasticity of substitution between the emissions (E_J) and abatement (B_J) inputs used in the production of the dirty industries (D_J), as well as the level of abatement in place in the benchmark. When the dirty industries have identical elasticities between E and B (i.e. the Homogenous Case and Lower Envelope Case), the results are the same as if they were modeled as a single industry at the sector level. In contrast, the Heterogeneous Case describes industries with different abatement costs. When regulation reduces the allowable emissions, differences in the cost of abatement emerge causing a shift in production among the industries. Both industries remain active despite an asymmetric cost advantage because their outputs are not perfect substitutes. This example is most plausible in describing differences between energy or emission intensive industries such as electricity, industrial production and transportation. Alternative formulations with perfect substitutes are explored in sensitivity analysis, with comparable results to those described for the basic model.

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[5] Under the emissions tax policy, the labor tax is endogenously set so that the sum of revenue from the labor tax and emissions tax equals benchmark government revenue.

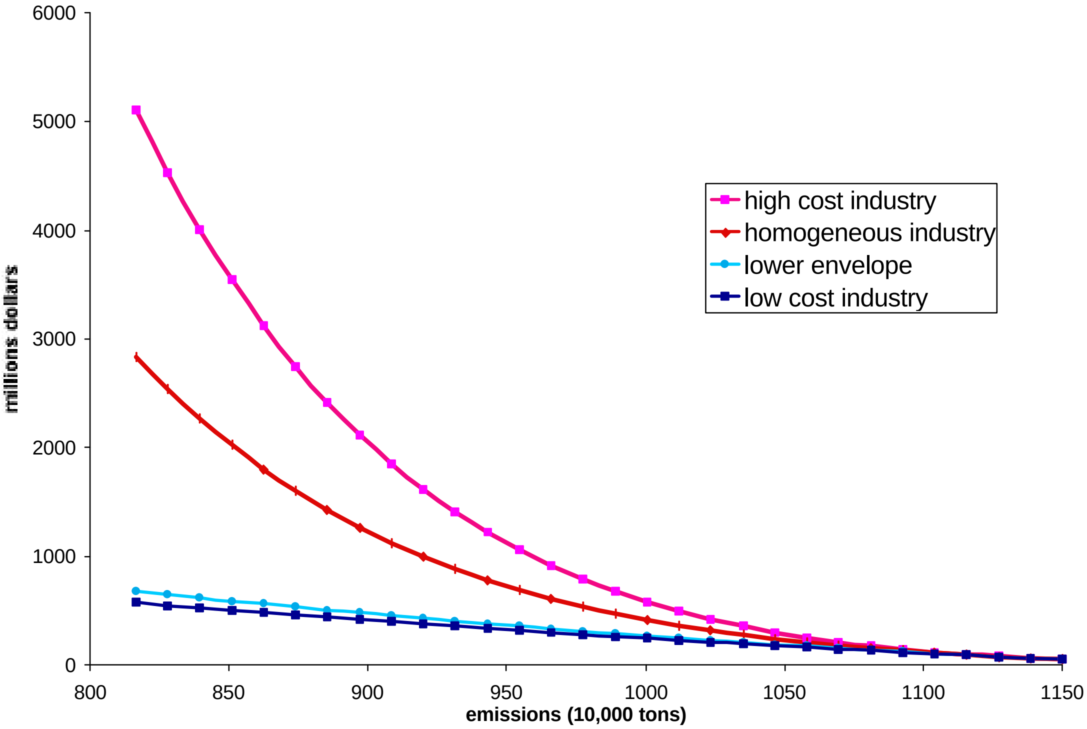

Figure 2: Total abatement cost functions used in the model.

The Heterogeneous Case has one high and one low cost industry; the Homogeneous Case is characterized by two identical industries. The elasticity of substitution and other parameters in the abatement cost functions are derived so that the total (partial equilibrium) cost of abatement for equal increments of emission reduction at the constituent industries is equal in the Homogeneous Case and the Heterogeneous Case.[6] This is illustrated in Figure 2, which plots the partial equilibrium abatement cost functions that are used in the model. The strategy in constructing the model was to characterize heterogeneity as a mean-preserving spread in abatement costs around the Homogeneous Case, which approximates the abatement cost curve used by Goulder et al. (1990), drawn from Pechan (1996). The variability in the cost functions in the Heterogeneous Case roughly approximates that described in Pechan. In this analysis we consider the functions in the Heterogeneous Case to illustrate underlying data. The function in the Homogeneous Case illustrates an aggregation of the data.

The fourth curve in Figure 2 is labeled Lower Envelope, and this case is also characterized by two identical industries. This illustrates an alternative aggregation of the

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[6] The elasticity of substitution for the two industries in the Heterogeneous Case are constant. The equalization of total costs is achieved by calculating a different elasticity of substitution at each level of emission reduction for the Homogeneous Case.

data that maps out the cost-effective schedule for emission reductions, given the variability of the underlying data in the Heterogeneous Case.

The values of the abatement cost functions at the common benchmark and at a 25% reduction in emissions are reported in Table 3. The Homogeneous Case and Heterogeneous Case have equal total costs. The total cost for the Lower Envelope reflects cost effective implementation by design.

	Benchmark		**25% reduction**	
Cases	MAC ($/ton)	Abatement Cost (million $)	MAC ($/ton)	Abatement Cost (million $)
Homogeneous (2 Industries)	100	50	1472	1801
Total		100		3602
Heterogeneous – Low Cost Industry	100	50	189	481
Heterogeneous – High Cost Industry	100	50	3438	3121
Total		100		3602
Lower Envelope (2 Industries)	100	50	284	561
Total		100		1122

Table 3: Characterization of NO_X abatement costs.

An important feature of the model is that abatement costs are positive in the Benchmark. This reflects the fact that there are various types of control in place for NO_X even before implementation of the 1990 Clean Air Act Amendments, so the marginal cost for the first increment of reduction is greater than zero.[7] Finally, economic rents accrue from the endowments of emissions (E), and the rents change as the endowment of emissions is reduced. The rents are treated in a variety of ways as a means to implement alternative policies.

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[7] In sensitivity analysis we find that variation in the absolute or relative level of abatement in the benchmark has an affect on the relative performance of policy instruments. McKitrick (1999) discusses nondifferentiability of the abatement cost function that can result from similar characteristics of the problem.

Characterization of policies

The benchmark includes an initial marginal cost of emission reductions equal to \$100 per ton of NO_X, with emissions at 23 million tons annually. We explore the relative performance of policies for up to a 30% reduction in emissions below the benchmark, with particular focus on a 25% reduction.

Performance Standard

The performance standard is modeled as an equal percentage reduction in emissions by all industries (D_J) in the polluting sector. This is implemented by reducing the endowment of allowable emissions. Rents from the endowment of emissions (E) are offset directly with an output subsidy so that prices are unaffected by the rents.

Emission Tax

The emission tax is set endogenously to achieve a specified level of emission reduction below the benchmark levels. This is achieved by endowing emissions to the government, which sells them to the polluting industries. Revenues are used by the government to reduce the tax on labor income, subject to the constraint that the absolute level of government spending remains constant. The emissions tax would be equivalent to an emission permit approach were permits distributed by the government through a revenue-raising auction.

Emission Permits

In modeling emission permits, the specified level of emissions are endowed to the representative household. The income accruing to the household is analogous to changes in corporate earnings and shareholder wealth were assets accounted for at the industry (firm) level and, in turn, returning the change in earnings to the household as the owner of firms. Hence, no revenue is raised for the government.[8]

Technology mandate

The modeling of a technology mandate is similar to that for a performance standard, except that there is no opportunity for input substitution to achieve the emission reductions. Managers are precluded from changing the intensity of the B-E aggregate relative to other input factors to achieve requisite reductions.

The mandated technology requires equivalent reductions in the two industries, but at different costs. Here, the regulator has managed to identify a technology mandate that lies on the efficient schedule of options for each of the heterogeneous industries. This formulation could be interpreted as a favorable characterization of the regulatory process, analogous to the informed regulator in Goudler et al. (1999), because the regulator has

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[8] In principal there could exist revenues flowing to the government if the government taxes corporate earnings on rents from emission permits. In this version, we set that tax rate equal to zero.

solved the asymmetric information problem that is often associated with environmental regulation and identified a specialized mandate for each industry. Were the regulator less than omniscient, analogous to the uninformed regulator in Goulder et al. (1999), the mandated technologies could lie off the cost-effective schedule for one or both industries. The one-size-fits-all criticism that one often hears of technology mandates is probably a characteristization of the latter situation, and hence our model may be a generous portrayal of this instrument.

Hybrid

The hybrid policy is a combination of instruments. The low cost industry is regulated with tradable permits and the high cost industry is regulated with a performance standard. The allocation of emission reductions between these industries is achieved in a cost-effective manner.

Welfare

Policy instruments are evaluated according to an equivalent variation measure of welfare that is determined by the levels of final-goods consumption and leisure in the household utility function. The change in welfare associated with each instrument is measured against a benchmark of using an emissions tax to achieve the same level of emissions as in the benchmark. We ignore the environmental benefits of a policy and focus exclusively on its cost. We define the *relative welfare loss* of a policy as:

$$\frac{\left(welfare_{benchmarktax} - welfare_{currentpolicy}\right)}{\left(welfare_{benchmarktax} - welfare_{currenttax}\right)}$$

We normalize the welfare measure around the most cost-effective instrument (the emissions tax) at benchmark levels of emissions, so that positive costs are measured for all instruments at all levels of emission reduction.[9]

CGE framework with MPSGE

The model is solved using GAMS/MPSGE software (Rutherford, 1995), which generates a set of inequalities involving constant returns to scale, constant elasticity of substitution (CES) functions based on user-specified parameters. A solution is comprised of a set of final goods, intermediate goods and primary factor prices, production sector activity levels and household income levels such that the following set of inequalities are satisfied:

- Zero profit for each production sector: The user cost of inputs used in production is greater than or equal to the value of output.

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[9] Also note that we consistently replicate the finding that all instruments are more costly in a second-best setting than in a first best world absent pre-existing taxes. However, all welfare measures are relative to the emissions tax in a second-best setting.

- Market clearance for goods and primary factors: Production output and initial endowment is greater than or equal to intermediate and final demand.

- Income balance for households: Expenditure equals income from factor ownership and redistribution of tax revenue.

The series of inequalities are solved as a mixed complementarity problem: activity levels are complementary with zero profit conditions, prices are complementary with market clearance, and income is complementary with income balance. When endogenous taxes are included in the model, the endogenous tax is complementary with the equation determining the tax rate.

Data

Data for the social accounting matrix that balances inputs and outputs in the economy is drawn from Goulder, et al. (1998). To create the abatement sector activity in the benchmark, we shift 100 million dollars in inputs from the N sector. Since B is used in producing D, this increased D by 100. Finally, relative to the values in Goulder, 100 million dollars less of N and that much more of D were used to produce the C_D.

The elasticities used in the model are listed in Appendix A. To calibrate elasticity of substitution in the D sector, we depart from values in Goulder in order to accommodate a different structure to our model involving an increased number of inputs in that sector. We sought to replicate the relative role of abatement in the production of D, relative to other means of reducing emissions.

Emission reductions occur through three types of changes in production, referred to as “three channels” for abatement by Goulder et al. (1999). Technological abatement includes the out-of-pocket compliance costs incurred by industry, and is the usual measure included in partial equilibrium models. A second channel is input substitution, which occurs when the firm alters the relative intensity of factors of production. The third channel is output substitution, which results when the demand for production changes in response to changes in product prices. One of the main distinctions among the policies is the degree to which they employ these channels in achieving emission reductions. The least cost approach would employ each channel such that the marginal cost of reductions through each channel is equated.

In the Goulder model, for a 50% reduction under an emissions tax (with homogenous abatement costs), 79% of the reduction is achieved through the abatement effect, 18.5% through input-substitution, and 2.5% through output substitution. To replicate this in our model, we chose value for the elasticity of substitution in D that achieve a relatively conservative contribution from abatement, so as not to exaggerate the role of differences in abatement cost that we seek to investigate. For a 25% reduction under an emissions tax in the Homogeneous Case, we obtain 52% of the reduction coming through the abatement effect, 31% through input substitution, and 17% through output substitution.

5. Findings

Our primary interest is in the relative cost-effectiveness of alternative instruments under three representations of abatement cost: the Homogeneous (aggregate) Case, the Heterogeneous Case, and the Lower Envelope (aggregate) Case. We first report results for the Homogeneous Case. Figure 3 illustrates that the emission tax has the least social cost at every level of emission reduction. The costs of other policies are illustrated as ratios compared to the cost of the tax. The performance standard is slightly less expensive than the technology mandate, because it offers the additional opportunity for reducing costs of input substitution, which the technology standard does not offer. The most expensive policy over the range of emission reductions illustrated is tradable permits. As identified previously, this stems from the rents associated with the asset value of the permits, and the influence this has on product prices and ultimately on labor supply.

The relative welfare loss of tradable permits is about 1.9 times that of emission taxes at a 25% level of reduction. The picture illustrated in Figure 3 is qualitatively similar to that reported in Goulder et al. (1999) for a similar experiment.

Results for the Heterogeneous Case are illustrated in Figure 4. Again, the emissions tax is the most cost-effective. However, an important qualitative difference distinguishes this from the Homogeneous Case. Over a large range of emission reductions, tradable permits dominate the command and control type policies, beginning at a 15% reduction for a technology mandate and a 23% reduction for a performance standard.

The costs for tradable permits and for the emissions tax are both reduced relative to the homogeneous representation of abatement, but they are reduced by proportionately more for tradable permits. Both permits and emissions tax account for the cost heterogeneity of the polluting sector. In addition, the efficiency loss associated with rents is reduced under the tradable permit scenario. As a result, the relative welfare loss of tradable permits relative to taxes is about 1.6 for a 25% reduction in emissions, while it was 1.9 in the Homogeneous Case.

The costs of the command and control policies are virtually unchanged in absolute terms when comparing the Homogeneous and Heterogeneous Cases, but the costs relative to taxes are affected because the costs of emission taxes falls in absolute terms. Hence, there is an upward shift of the command and control relative loss curves in Figure 4.

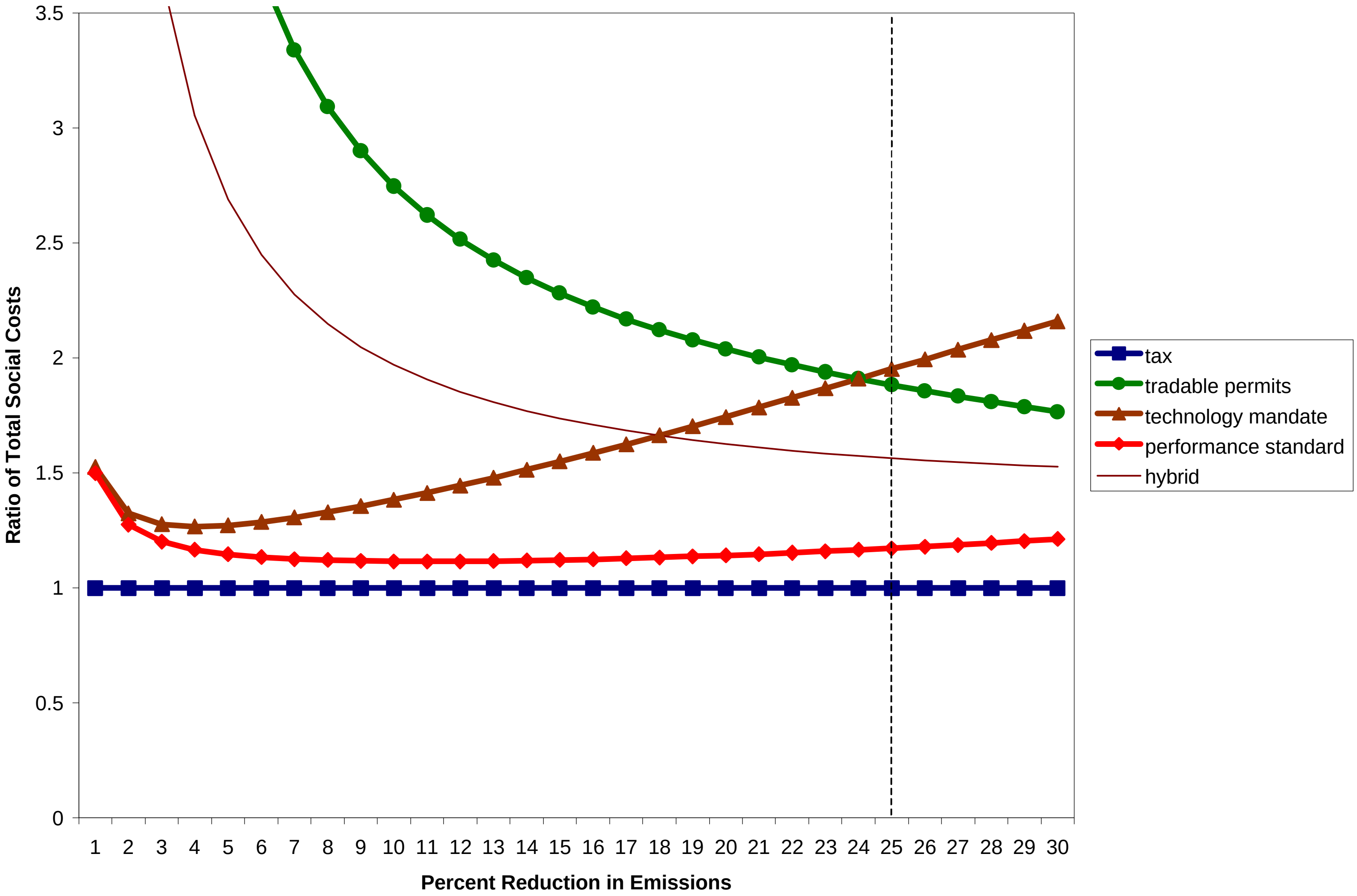

Figure 3: Ratio of Total Social Cost of Various Policies to Total Social Cost of Tax in the Homogeneous Case.

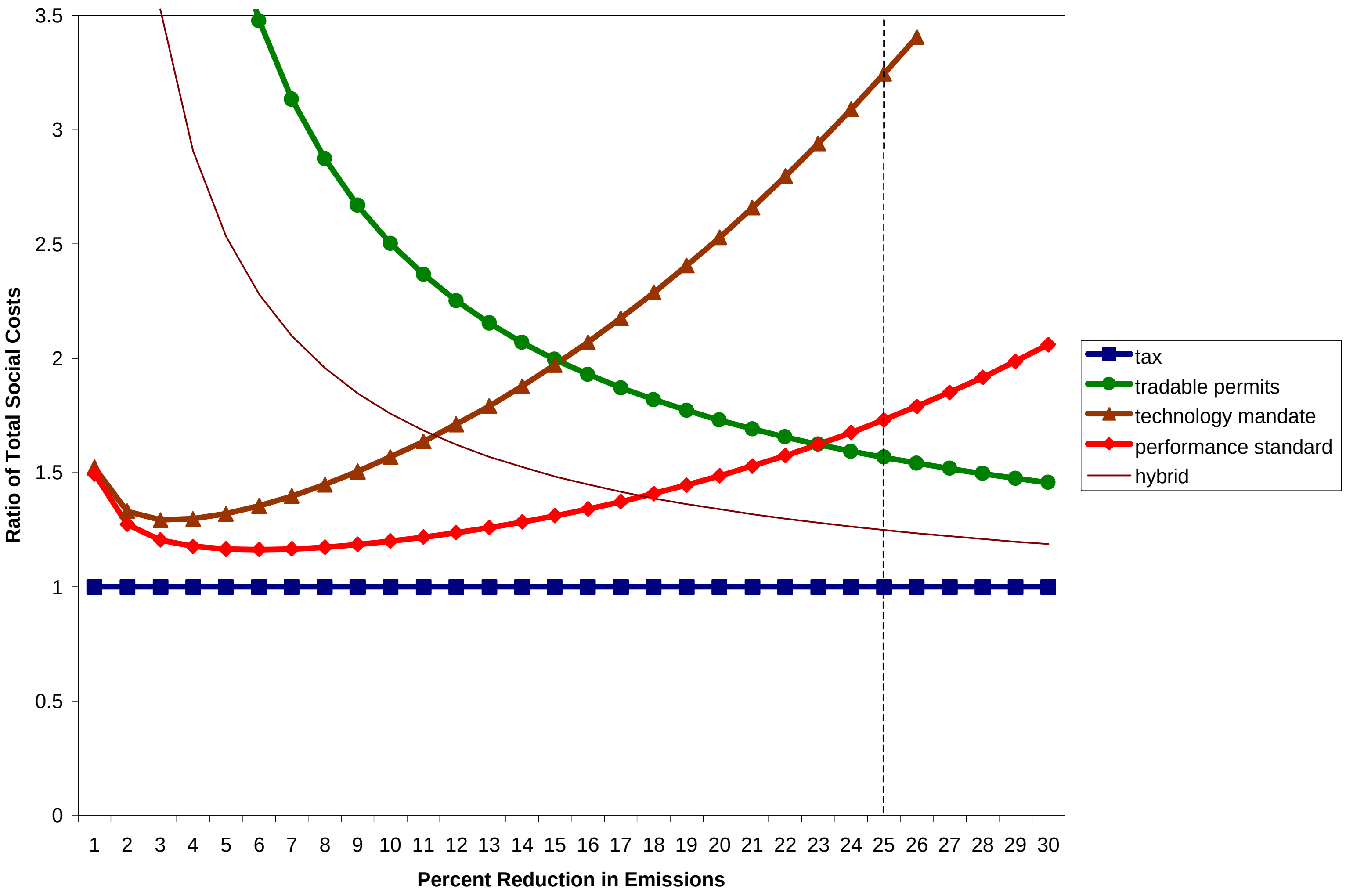

Figure 4: Ratio of Total Social Cost of Various Policies to Total Social Cost of Tax in the Heterogeneous Case.

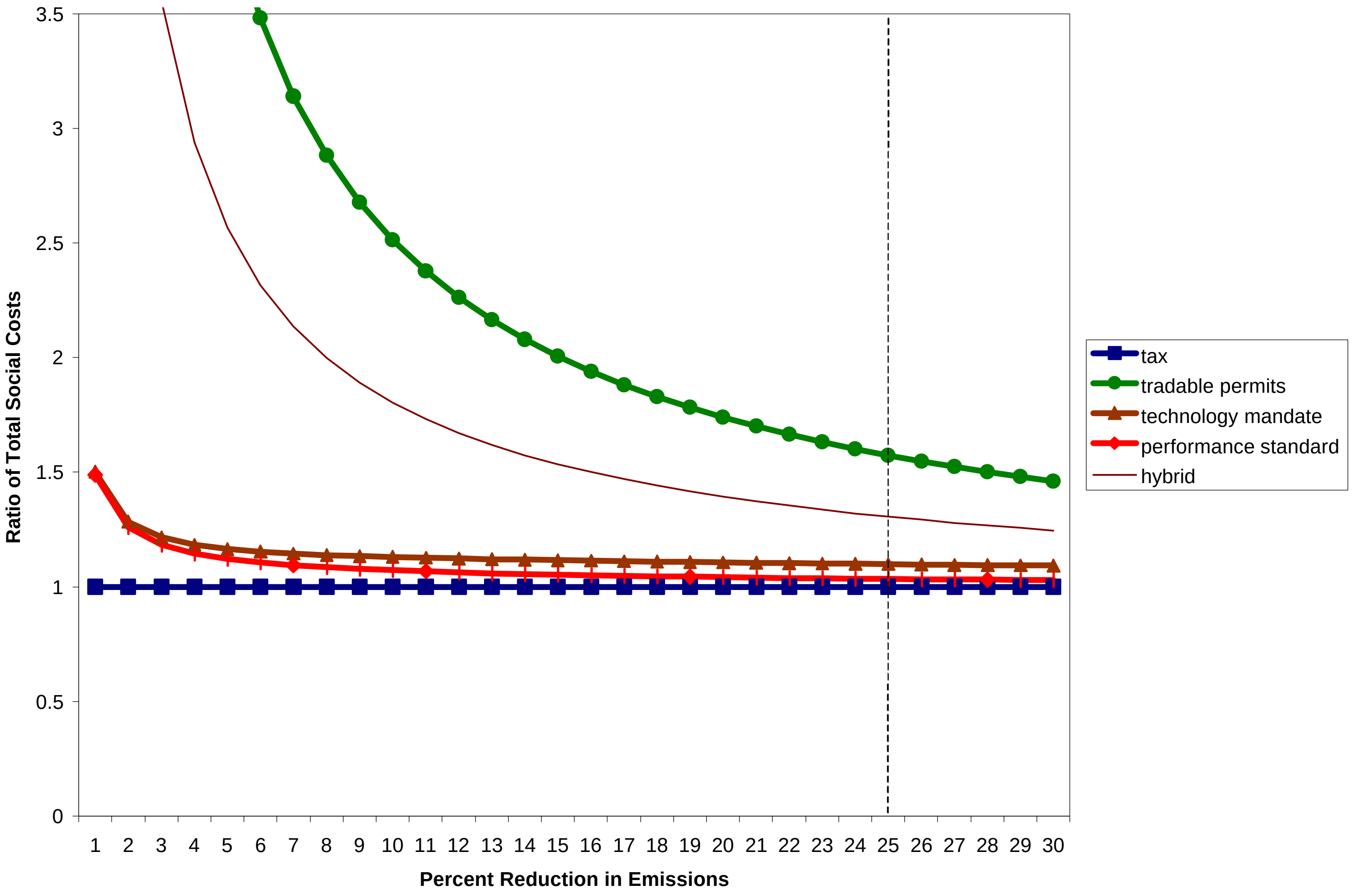

Figure 5: Ratio of Total Social Cost of Various Policies to Total Social Cost of Tax in the Cost Effective (Lower Envelope) Case.

Results for the Lower Envelope Case in Figure 5 illustrate the converse to Figure 4. In the Lower Envelope Case, the abatement cost curve is an aggregate constructed around a cost-effective schedule for abatement. Hence, there is no reduction in compliance costs in using tradable permits when heterogeneity is considered. However, in this case the command and control policies are significantly inaccurate, and heterogeneity causes them to be much more expensive than represented in Figure 5.

The measures of welfare cost (total social cost), marginal social cost and marginal (technical) abatement cost for a 25% reduction for all cases are reported in Table 4. The welfare cost under a tax in the Heterogeneous Case is estimated to be $732 million less than that estimated in the Homogeneous Case. However, the welfare cost under tradable permits is reduced by $1670. There is only a slight reduction in the welfare cost of a performance standard and technology mandate in moving from a Homogeneous to a Heterogeneous Case.

	Technology Mandate	Performance Standard	Tradable Permits	Tax	Hybrid
Welfare Cost (Millions $)					
Heterogeneous	2998	1599	1447	924	1154
Homogeneous	3232	1941	3117	1656	2590
Lower Envelope	1013	954	1451	922	1204
Marginal Social Cost ($/ton)					
Heterogeneous	1302	589	239	219	216
Homogeneous	1501	781	1002	627	916
Lower Envelope	236	222	240	220	231
Marginal Abatement Cost ($/ton)					
Heterogeneous	1288	408	196	197	204
Homogeneous	1493	543	329	334	416
Lower Envelope	237	205	197	197	201

Table 4: Cost measures for 25% reduction in emissions under various policies in the Heterogeneous, Homogeneous, and Lower Envelope Cases.

An indication of how these cost savings are achieved is evident in Table 5, which presents the percent of emission reductions that result from each of the three possible channels of reduction. The role of technological abatement is increased in comparing the Homogeneous Case to the Heterogeneous Case, especially for the incentive-based policies that are most able to capture cost savings associated with heterogeneity. For both permits and taxes, the role of technical abatement increases from approximately 50% to 80%. At the same time the role of input and output substitution for these policies is decreased.

(percent)	Technology Mandate	Performance Standard	Tradable Permits	Tax	Hybrid
Output					
Heterogeneous	4	2	7	7	3
Homogeneous	4	2	18	17	11
Lower Envelope	1	1	7	7	4
Input					
Heterogeneous	0	26	14	14	14
Homogeneous	0	36	31	31	33
Lower Envelope	0	15	14	14	14
Abatement					
Heterogeneous	96	72	79	79	83
Homogeneous	96	62	51	52	56
Lower Envelope	99	84	79	79	82

Table 5: Percent of emission reduction through alternative channels for 25% reduction in emissions in the Heterogeneous, Homogeneous and Lower Envelope Cases.

The hybrid policy illustrated in these results combines the tradable permit and performance standard approaches. In Figure 4, the hybrid policy dominates tradable permits over a large range of emission reductions. In a tradable permit scenario, the industry having higher abatement costs has little emission reductions relative to the low cost industry, but gains rents from the ownership of the permits. Welfare is increased by excluding the high cost industry from the permit trading scenario, and eliminating the associated rents.

6. Observations and Sensitivity Analysis

Within the model we employ, the most sensitive feature is the elasticity of substitution in the dirty industries. This elasticity determines the ability of the industry to substitute away from abatement (the B-E aggregate) toward other inputs as a way to meet its emissions reduction requirements. The results reported above depend on a parameter that yields a low level of abatement, relative to input and output substitution, compared to that displayed in Goulder et al. (1999). Nonetheless, with this conservative bias we still find the rankings of instruments to be affected by heterogeneity. Were we to use a parameter that placed abatement in a greater role, the results would be stronger still. However, in cases where abatement has little or no role, such as in reducing carbon dioxide emissions, the issue of heterogeneity in abatement of course is irrelevant. Heterogeneity in other features of the model, for example in the ability to use input substitution to reduce emissions, may be of continuing importance.

The second and more abstract sensitivity has to do with the structure of production within the model. We assume imperfect substitutes in the intermediate goods produced by the dirty industries. This ensures that a slight advantage in abatement costs for one industry does not cause the other industry to shut down.

We also explored in detail other formulations of production. When output by the dirty industries are perfect substitutes, we identify two ways to model production such that both industries remain in operation with only a slight shift in production from the higher to the lower cost industry, as one would expect to result from a moderate policy. One way is to assume a fixed factor of production, which could be thought of as resources (R_J), that is special to industry J.

The second and more flexible way to model perfect substitutes is to assume that both industries use both additional factors (R_1 and R_2), but in different proportions in the benchmark. As the ratio of the use of these factors approaches infinity, so that each firm has a unique fixed factor, this formulation converges to the case of a fixed factor in production. As the ratio approached 50:50, the industries become identical, and one industry shuts down when emission reductions impart a cost advantage to the other industry. For ratios in the benchmark slightly different than 50:50, both industries remained in business and meaningful results were obtained.

In both cases, with industry-specific fixed factors or with industry-specific factor intensities in the benchmark, we were able to replicate the main results of this paper in convincing fashion. These alternative approaches describe alternative industrial structures and regulatory situations. The main result of interest is that the qualitative finding regarding the sensitivity to the ordering of instruments appears robust in these various scenarios, suggesting the importance of modeling a regulated sector in sufficient level of detail to capture inherent cost heterogeneity.

7. Conclusion

Two primary insights have emerged from the burgeoning literature on the cost-effectiveness of alternative environmental policies when considered in a second-best setting. One is the absolute importance of pre-existing taxes in determining the full social cost of regulation. A significant cost advantage accrues to policies that raise revenues that can be used to reduce pre-existing distortionary taxes. A second insight is that the relative performance of tradable permits is so penalized when permits are allocated without cost (and therefore raise no revenue) that they can be dominated by command and control approaches.

This paper reaffirms the first of these insights, but casts doubt on the generality of the second. We find that when heterogeneity of abatement costs is accounted for in a fairly simple way, the relative performance of tradable permits improves significantly and this policy appears to dominate command and control policies within our model. The reason is that heterogeneity in abatement costs lowers the relative cost of technological abatement using tradable permits (and taxes), compared to estimated costs of command and control approaches. This in turn lowers other costs that fuel the interaction with pre-existing taxes.

Our findings provide a justification for more detail in economic modeling. However, more detail comes at greater cost to the investigator. We suggest that investigators can be reasonably confident that this issue is not undermining model results if technological abatement cost functions estimated outside of a general equilibrium model, in a detailed sector model, vary little for each type of instrument being considered. If differences in cost are significant (for example, because heterogeneity is significant), then this must be accounted for in the general equilibrium framework. It may be adequate to apply different abatement cost functions when considering different instruments, but this runs the risk of covering-up subsidiary issues. This is a question we plan to explore further.

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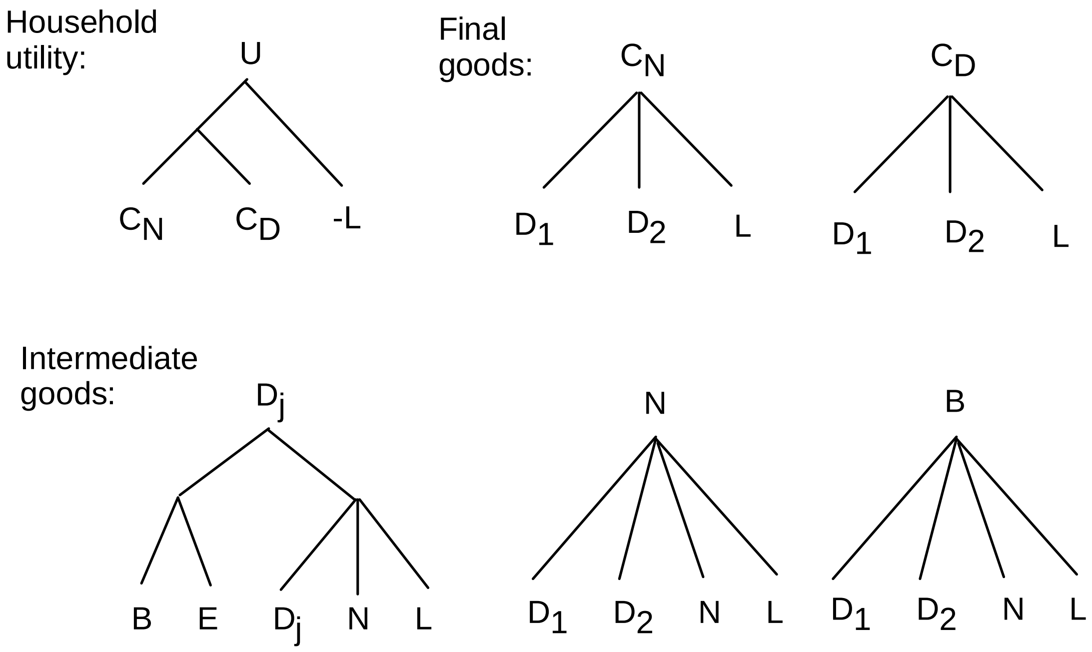
Appendix A: The nesting structure for the model.



Primary factors: E, L

Utility	
Upper nest	**.96**
Consumption subnest	**.85**
Final Goods	**.9**
Intermediate Dirty Goods	
Upper nest	**.05***
Abatement-Emissions Aggregate	
Heterogeneous – Low Cost Industry	**4**
Heterogeneous – High Cost Industry	**1.25**
Homogeneous Case	**1.38 – 2**
Lower Envelope	**2.5 - 3**
Productive Aggregate	**.8**
Other Intermediate Goods	**.8**

Table A1: Elasticity of substitution parameter values.

* The value for the intermediate dirty good upper nest was .05 for all policies except the Technology Mandate, where elasticity was 0.

Appendix B: Functional forms for the model.

I. Parameters:

Share parameters in utility and production functions:

$$\mathrm{q}_u,\mathrm{q}_c,\mathrm{q}_{1cn},\mathrm{q}_{2cn},\mathrm{q}_{1cd},\mathrm{q}_{2cd},\mathrm{q}_{x_{i1}},\mathrm{q}_{x_{i2}},\mathrm{q}_{x_{i3}}\left(x_i=\{B_1,B_2,N\}\right),$$
$$\mathrm{q}_{D_j},\mathrm{q}_{D_{ja1}},\mathrm{q}_{D_{ja2}},\mathrm{q}_{D_{jb}}\left(j=\{1,2\}\right)$$

Substitution parameters in utility and production functions:

$$\mathrm{r}_c,\mathrm{r}_u,\mathrm{r}_{cn},\mathrm{r}_{cd},\mathrm{r}_{x_i}\left(x_i=\{B_1,B_2,N\}\right),$$
$$\mathrm{r}_{D_j},\mathrm{r}_{D_{ja}},\mathrm{r}_{D_{jb}}\left(j=\{1,2\}\right)$$

Other parameters:

L = time

TR = revenue transfer from government

E = quantity of permits

II. Endogenous variables:

l_d = demand for leisure

cn_d = demand for clean final good

cd_d = demand for dirty final good

p_l = wage rate

p_{cn} = price of clean final good

p_{cd} =price of dirty final good

p_e = permit price

cn_s = supply of clean final good

N_{cn} = clean intermediate good used in clean final good production

D_{1cn} =first dirty intermediate good used in clean final good production

D_{2cn} =second dirty intermediate good used in clean final good production

cn_s = supply of dirty final good

N_{cd} = clean intermediate good used in dirty final good production

D_{1cd} = first dirty intermediate good used in dirty final good production

D_{2cd} = second dirty intermediate good used in dirty final good production

x_{is} = supply of x_i, $x_i = \{B_1, B_2, N\}$

N_{x_i} = clean intermediate good used in production of x_i, $x_i = \{B_1, B_2, N\}$

D_{1x_i} = first dirty intermediate good used in production of x_i, $x_i = \{B_1, B_2, N\}$

D_{2x_i} = second dirty intermediate good used in production of x_i, $x_i = \{B_1, B_2, N\}$

l_{x_i} = labor used in production of x_i, $x_i = \{B_1, B_2, N\}$

D_{js} = supply of dirty intermediate good , $j = \{1,2\}$

N_{d_j} = clean intermediate good used in production of dirty intermediate good, $j = \{1,2\}$

D_{D_j} = dirty intermediate good used in production of dirty intermediate good, $j = \{1,2\}$

l_{D_j} = labor used in production of dirty intermediate good, $j = \{1,2\}$

B_{D_j} = abatement used in production of dirty intermediate good, $j = \{1,2\}$

E_{D_j} = emissions from production of dirty intermediate good, $j = \{1,2\}$

t_l =labor tax

Note: $r_i = \frac{(s_i - 1)}{s_i}$, where s_i is the elasticity of substitution.

III. Utility and Production Functions :

Household utility is represented through a nested CES utility function having the form:

$$U = \left[\theta_u (l_d)^{\rho_u} + (1-\theta_u)\left(\theta_c (cn_d)^{\rho_c} + (1-\theta_c)(cd_d)^{\rho_c}\right)^{\frac{\rho_u}{\rho_c}}\right]^{\frac{1}{\rho_u}}$$

The household chooses l_d, cn_d, cd_d to maximize utility subject to the household budget constraint. When emssions are controlled through an emissions tax, technology mandate or performance standard, the household budget constraint is represented by:

$$p_l l_d + p_{cn} cn_d + p_{cd} cd_d = p_l L + TR$$

When emissions are controlled through tradable permits, households also receive rents from the ownership of these permits. In the tradable permits scenario, the household budget constraint is:

$$p_l l_d + p_{cn} cn_d + p_{cd} cd_d = p_l L + TR + p_e E$$

Final good production is represented through CES production functions having the form:

$$cn_s = \left[\theta_{1cn}(N_{cn})^{\rho_{cn}} + \theta_{2cn}(D_{1cn})^{\rho_{cn}} + (1-\theta_{1cn}-\theta_{2cn})(D_{2cn})^{\rho_{cn}}\right]^{\frac{1}{\rho_{cn}}}$$

$$cd_s = \left[\theta_{1cd}(N_{cd})^{\rho_{cd}} + \theta_{2cd}(D_{1cd})^{\rho_{cd}} + (1-\theta_{1cd}-\theta_{2cd})(D_{2cd})^{\rho_{cd}}\right]^{\frac{1}{\rho_{cd}}}$$

Production of abatement and the clean intermediate good uses labor in addition to the clean and dirty intermediate goods as inputs:

$$x_{is} = \left[\theta_{x_{i1}}\left(N_{x_i}\right)^{\rho_{xi}} + \theta_{x_{i2}}\left(D_{1x_i}\right)^{\rho_{xi}} + \theta_{x_{i3}}\left(D_{2x_i}\right)^{\rho_{xi}} + \left(1-\theta_{x_{i1}}-\theta_{x_{i2}}-\theta_{x_{i3}}\right)\left(l_{x_i}\right)^{\rho_{xi}}\right]^{\frac{1}{\rho_{xi}}} ,$$

$$x_i = \{B_1, B_2, N\}$$

The two dirty intermediate goods have nested CES production functions of the form:

$$D_{js} = \left[\begin{array}{l} \theta_{Dj}\left[\theta_{Dja1}\left(N_{Dj}\right)^{\rho_{Dja}} + \theta_{Dja2}\left(l_{Dj}\right)^{\rho_{Dja}} + \left(1-\theta_{Dja1}-\theta_{Dja2}\right)\left(D_{Dj}\right)^{\rho_{Dja}}\right]^{\frac{\rho_{Dj}}{\rho_{Dja}}} + \\ \left(1-\theta_{Dj}\right)\left[\theta_{Djb}\left(B_{Dj}\right)^{\rho_{Djb}} + \left(1-\theta_{Djb}\right)\left(E_{Dj}\right)^{\rho_{Djb}}\right]^{\frac{\rho_{Dj}}{\rho_{Djb}}} \end{array}\right]^{\frac{1}{\rho_{Dj}}}$$

$$j = \{1,2\}$$

IV. Government revenue constraint :

The tax on labor is set endogenously such that government revenue is held constant at a benchmark level. Under the technology mandate, performance standard and tradable permit policy scenarios, the tax on labor is the sole source of government revenue. Under the emissions tax scenario, government revenue is raised both from the tax on labor and emissions.

$$TR = t_l \, p_l \left(L - l\right)$$

$$TR = t_l \, p_l \left(L - l\right) + p_e E$$