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# Energy Pricing and Air Pollution

## Econometric Evidence from Manufacturing in Chile and Indonesia

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Energy pricing is a powerful indirect tool for reducing emissions. Whether it is attractive as one instrument among others depends on the costs of monitoring and enforcement associated with more direct instruments, such as emission taxes.

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## Summary findings

Sound public policy addresses externalities directly, when possible. Air pollution is best alleviated by policy instruments that internalize the social cost of pollution, making it attractive to reduce emissions.

One such instrument might be a tax levied on individual emissions, if they are measurable and if there is an accepted relationship between emissions and the damages to society. But such first-best solutions may not be feasible for many reasons, among them the cost of implementation. When first-best instruments are unavailable, indirect instruments, such as presumptive taxing of polluting inputs, may be a powerful alternative. Energy pricing is, for air pollution, one such indirect instrument.

Energy pricing policies affect emissions through fuel substitution and energy conservation. Eskeland, Jimenez, and Liu provide an empirical framework for measuring the magnitude of this impact and apply it to two cases: manufacturing in Chile and Indonesia. They find that:

- The responsiveness of emissions makes energy prices a powerful indirect tool for reducing emissions.
- There is room for substitution toward cleaner input combinations — both toward cleaner fuels and away from energy, toward labor, capital, and materials.
- Substitution toward cleaner fuels can also be induced without increasing energy prices generally, by increasing the price of the dirtier fuels, thereby reducing the relative price of the cleaner ones. But noncompensated price increases for the dirtier fuels, plus increases for all fuels, will be more powerful since they will also induce firms to reduce their overall energy use.

In exploiting interfuel substitution, it is important to assess the relative damage caused by different pollutants. In Indonesia, increases in coal prices could deliver reductions in particulate emissions, but in Chile they would not, because of a small own-price elasticity and a positive cross-price effect (though small) to electricity, a heavily-used source of energy that also produces particulate emissions.

Higher prices for pollution-laden fuels will generally reduce demand, as expected, but the net effect on emissions will depend on:

- Whether other fuels laden with the same pollutants are spared such price increases.
- Whether their cross-price elasticities are positive.
- Which fuel shares are high.

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# 1. INTRODUCTION

A fundamental principle of sound public policy is, if possible, to address an externality directly. Thus, an amount of air pollution in excess of socially optimal levels can best be alleviated by policy instruments which internalize, for the polluter, its full social cost. One such instrument might be a tax levied on individual emissions, if these are measurable and there is an accepted relationship between emissions and the damage caused to society. Such a tax would be set equal to the marginal social damages, to stimulate optimal control efforts from polluters.[1]

However, for a variety of reasons, such first-best solutions may not be feasible. One reason is the cost of implementation. It may be very costly to monitor the flow of emissions from each and every polluter if there are many of them, as in the case of motor vehicles and manufacturing firms. There have been practical ways developed to minimize the heavy monitoring and enforcement activities associated with taxes levied directly on emissions, such as setting standards for emission *rates* by type of equipment or activity (Opschoor and Voos, 1989).[2] However, studies show that these policies should be complemented by taxes on the throughput in the polluting activities (Eskeland 1993).

Thus, when first-best instruments are unavailable, indirect instruments, such as presumptive taxation of polluting inputs, may be attractive and powerful alternatives (Eskeland and Jimenez, 1991). Energy pricing is, for air pollution control, one such indirect instrument. It is potentially attractive to

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[1]In a framework of Coasean negotiation, an efficient outcome (with different distributional implications) could also result if the polluter were subsidized by its "pollutees" to cut its emissions.

[2]For vehicular emissions, there may be millions of polluters, and the costs of monitoring individual *flows* of emissions would have been insurmountable. However, the pollution-causing equipment to be modified is produced by a few, identifiable producers, and the automobiles can, in polluted cities, be compelled to show up for periodic inspections at a manageable number of sites. Thus, *regulations concerning machinery*, in combination with *fuel taxes*, can give a reasonably efficient control program without continuous monitoring of emissions at the source (see Eskeland, 1993). For industrial sources, it is generally possible to measure emission rates, which can be multiplied by utilization rates to form the basis for emission taxes or emission permits. For major stack sources, such as power plants, continuous emission monitoring is now feasible for some pollutants. In most jurisdictions, however, pollution control agencies are limited to making measurements of emission rates, usually with infrequent preannounced visits (See Russell, 1990).

the policymaker because the use of each energy carrier, or fuel[3], provides a good proxy for the rate of use of polluting equipment (sometimes also its "dirtiness") most of which is combustion equipment. Thus, if individuals and firms are induced to economize with fuel use, or to switch to cleaner fuels, then their emissions will be reduced. A good illustration of this is the Environmental Protection Agency's standard reference on emission modelling, AP-42, which projects emissions by multiplying a constant, an emission factor, by the amount of fuel used (U.S. EPA, 1986).

Fuel substitution and energy conservation are the two main transmission mechanisms by which changes in energy pricing policies affect emissions. The main objective of this paper is to provide an empirical framework for measuring the magnitude of this impact (section 2) and to apply it to two cases for which fuel pricing could be attractive policy instruments: manufacturing in Chile and Indonesia (sections 3 and 4). The analytical approach is to combine estimates of how fuel demand responds to prices, through econometric analysis, with engineering estimates of the technical link between input use and emissions. (The property described in the preceding paragraph is used to assign emissions to input use.) The main finding is that the responsiveness of emissions makes energy prices a powerful tool in the kit of indirect policy instruments available to the policy maker.

The relevance of our findings for control costs and strategy analysis is, however, not limited to the case in which fuel prices are used as policy instruments. Since analysis with first best instruments for manufacturing would be prospective (such instruments have not be used), one would need to analyze control costs using models of what polluters *could do* to reduce emissions. Analysis of substitutability in input demand, as well as technical control options, would be the main components in such prospective

[3] Our use of the word *energy* is conventional: From the user's perspective, energy is an aggregate of electricity and inputs used in combustion processes, such as fossil fuels and biomass. We shall use the term "energy conservation" when aggregate energy use per unit of output is reduced. Unconventionally, we shall include electricity when we use the word "fuels". This way, the term "interfuel substitution" includes choices between purchased electricity and conventional fuels. If conventional fuels are used by the firm to produce electricity, then this is accounted for as conventional fuel consumption only.

analysis (see Kopp 1992, for a general analytical framework, proposing eclectic use of knowledge from technical studies as well as econometric models).

The final section (5) discusses briefly the conditions under which it would also be economically efficient to use fuel pricing in emission control programs. The rest of this introduction elaborates on how this paper straddles two (mostly distinct) bodies of literature -- those of energy demand and pollution control.

Relationship to the literature. One of the paper's contribution is to add to the body of quantitative evidence on the price responsiveness of energy demand in developing countries. Since the first oil price shock in 1973, there has been a substantial literature on the price sensitivity of demand in OECD countries.[4] The evidence from aggregate data is that there is substantial scope for energy conservation and interfuel substitution. In OECD, manufacturing output increased by 62 percent between 1971 and 1988, while energy use remained unchanged, implying a 38 percent reduction in energy intensity (Bacon 1992). Using annual observations across Canadian provinces, Fuss (1977) found relatively large own price elasticities for fuels, in the range of -.7 to -2.9. His estimate was -.5 for aggregate energy. Using cross-country data, Pindyck (1979), found corresponding estimates of -.7 to -2.2 (fuels), and -.8 (aggregate energy).

Studies from developing countries are less numerous, but growing. Pindyck (1979) explains the high elasticities he found for Spain, Greece, Turkey, Brazil and Mexico as "consistent with the expectation that energy demand in the industrial sector should be more price elastic in developing countries due to a greater ability to substitute low-priced labor." (p. 255). There have also been demand

[4]Bacon (1992) examines evidence from aggregate data series, discusses evidence from econometric as well as engineering approaches to assessment of inter-fuel substitutability and energy conservation, and also reviews empirical findings. The empirical literature in the seventies generated methodological advances, as well as empirical estimates. Important landmarks, both critical to the method applied here, are flexible functional forms, such as the trans-log function (Christensen, Jorgenson and Lau, 1971), and the use of separability and homotheticity in the energy aggregate (Hudson and Jorgenson, 1974, Fuss, 1977), allowing the estimation of systems with more inputs. Fuss (1977) summarizes these, and demonstrates the methodology applied in the present study.

studies for the two case study countries in the present paper. Pitt (1985) used pooled cross section data from Indonesian manufacturing industries. With only three years of data (1976-78) and two aggregate inputs (energy and labor) he finds own price elasticities for aggregate energy between -.07 and -.8, with the higher for the more energy intensive sectors.[5] Moss and Tybout (1992), using plant-level data from Chile, finds substantial variability in fuel use per unit of output between firms and over time, even within subsectors. In another study, Guo and Tybout (1993) estimate inter-fuel substitution possibilities for four subsectors, using plant observations. They find significant substitutability for some sectors, little in others.

Although there have been previous demand studies of the case-study countries, this paper adds to the literature by using more recently available time-series data for a much longer period (in Indonesia, 1975-89), and by providing results for the manufacturing sector as a whole. It also focuses on cross-price elasticities for a disaggregated set of fuels. Thus, it provides results that are directly relevant for the responsiveness of emissions from manufacturing.

The other, and perhaps more innovative, contribution of this paper is that it combines information on the flexibility in fuel choice with its consequences for air pollution, thus making the link between prices and emissions explicit. To our knowledge, this has been done before only for one "pollutant", carbon dioxide, and even then, without empirical estimates of inter-fuel substitutability[6].

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[5]He used plants as observations (and a tobit type estimator to solve the problem of corner observations in the energy submodel, since some plants used zero of some types of fuels), and estimated models for seven two-digit ISIC sectors (with dummy variables for each region and each three-digit ISIC code).

[6]The most interesting modelling is found in Wilcoxen and Jorgenson (1991), where emissions of carbon dioxide are linked to energy use in an estimated computable general equilibrium model with investment. As in most CGE models, energy is not disaggregated into individual fuels, however; thus the models cannot easily be expanded to analyze whether the choice of fuel allows a choice between pollutants, or even a general pollution reduction. Moreover, many of the studies in the huge literature on the effect of carbon taxes use calibrated rather than estimated parameters. Our results should provide useful building blocks for such general equilibrium models in the future. Other studies are Whalley and Wigle, 1991, Shah and Larsen, 1992, and Glomsrod, Johnsen and Vennemo, 1992.

Studies linking emissions to fuel use are very rare -- in fact, they are available only for a few developed countries, such as the U.S., based on sample tests and engineer's estimates. The key result from these studies is that emissions can be modelled as proportional to fuel use, with emission factors for each fuel[7]. It is precisely this property that we exploit in the developing country case studies.

## 2. EMPIRICAL FRAMEWORK AND DATA

This section outlines the cost-function approach used in the analysis and briefly describes the data bases.

Framework. The general production function summarizes the relationship between inputs used in production and the resulting outputs:

$$y = f(x_1, x_2, \ldots, x_n), \tag{1}$$

where $y$ is the quantity of output and $x_i$ is the quantity used of input $i$, for n input types[8]. Pollution, or

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[7]A fuel may have different emission factors for different types of users. In the short-run, when equipment is assumed to be unresponsive to fuel price changes, a fuel's emission factor for a population of users will be the individual factors weighted by their share in the total fuel demand change. Assuming uniform demand elasticities across users for a given fuel, the factors will be weighted by their shares in total consumption. It is probably conservative, if anything, to assume that emission reductions will be proportional to fuel demand: Fuel costs will likely be a greater share of costs for users with older, "dirtier" equipment, so there may be a systematic tendency that users with older equipment reduce their demand more in response to fuel price increases. To our knowledge, studies allowing comparison of demand elasticities across individual users of a fuel do not exist, so the assumption that aggregate demand elasticities apply to individual users seem reasonable.

[8]Equation (1) reflects not merely technical relationships, but also the institutions, such as regulations, reward systems, etc., in which economic entities operate. Thus, while we make the customary behavioral assumptions, such as cost-minimizing, competitive producers, in order to write input demands and output supplies as functions of input prices and output, we also recognize that if major institutional changes occur, for instance in regulation, in the way managers are supervised, or in the way owners are taxed, the relationship between input use and outputs (1) may change. This is consistent with Hayek's warning (Hayek, 1952) against taking the view of an engineer or a natural scientist when studying economic systems. The warning becomes particularly relevant when we imagine explicit pollution control policies, since these aim to change, inter alia, the relationships between input use and emissions through institutional reform.

more specifically, emissions of air pollutants, can also be described as determined by the firm's use of inputs. If we let $e$ be a measure of the emissions from the producer, we can write[9]:

$$e = e(x_1, x_2, \ldots, x_n), \tag{2}$$

Under certain conventional assumptions about the function $f$, an assumption of cost minimization allows us to deduce, from (1), input demands as functions of input prices and output. This implies that from (2), we can also describe emissions as a function of input prices and output.

In order to derive the estimating equations, it is necessary to put more structure on the general framework described above. Following the work of Fuss (1977) and Pindyck (1979), we assume weak separability between the aggregate inputs: energy *(E)*, capital *(K)*, labor *(L)* and material *(M)* (details in Appendix 1). This means that, for the subset of inputs designated as the $m$ types of fuels, $x_1,\ldots,x_m$, the effect of fuel use on output can be summarized by its effect on the value of an aggregate energy function $E=E(x_1,\ldots,x_m)$. Thus, the marginal rates of substitution between fuels depend on only on the use of fuels, and the marginal rates of substitution between aggregate inputs depend on E but not on the use of individual fuels. We assume that the aggregate energy function is homothetic with respect to its respective components and that the cost function associated with the energy submodel is linearly homogenous in aggregate E.

Given these assumptions, the production function (1) above, can be written as:

$$Y = f(K, L, M, E(x_1, x_2, \ldots, x_m)), \tag{3}$$

where $K,L,M$ and $E$ denotes the aggregates capital, labor, material and energy, respectively. The corresponding short term cost function (which assumes that the amount of capital employed, $K$, is fixed)

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[9] e can measure emissions of one pollutant, say tons of sulphur dioxide or dust, or be a vector or an aggregate, such as a damage-weighted sum of emissions of various pollutants.

is:

$$c = c(Y, K, P_L, P_M, P_E(P_1, P_2, \ldots, P_m)), \tag{4}$$

where $P$'s with capital subscripts are prices corresponding to the aggregate inputs, and $P$'s with numerical subscripts are fuel prices.

Given the framework explained above, the demand for fuel $j$ can be expressed as:

$$x_i = x_i(E(Y, K, P_L, P_M, P_E(P_1, \ldots, P_m), P_1, P_2, \ldots, P_m) = \frac{\partial c}{\partial p_i} \tag{5}$$

where the latter equality is given by Shephard's lemma.

With input demand functions (5) derived from a cost function like (4), there will be two associated concepts of demand elasticities with respect to individual fuel prices $P_j$. One describes the substitutability of one fuel for another, while aggregate energy is held constant. The other describes the substitutability between inputs (and, among them, between individual fuels) when output is held constant, but the use of aggregate energy and the other aggregate inputs adjust. The relationships between the two demand elasticities are as follows:

$$\varepsilon_{ij} = \varepsilon_{EE} \cdot S_j + \varepsilon_{ij}|_{E\ constant}. \tag{6}$$

where $\epsilon_{ij(E\ const.)}$ reflects the price elasticity under the assumption that aggregate energy use, $E$, remains constant, and $\epsilon_{EE}$ is the elasticity of aggregate energy with respect to $P_E$.

We shall use both of these elasticity concepts in analyzing the effect of price changes on emissions. Equation (6) allows us to focus on inter-fuel substitution in isolation. For example, in a policy experiment, one could allow compensatory price changes for the energy aggregate, so that $P_E$ is held constant while the relative prices between fuels are changing -- then the firm could be held to the same level of aggregate energy use. In fact, since no other aggregate inputs would change, the firm's output level would also remain unchanged.

Assuming that emissions depend only on the amounts of fuels used (see footnote 2) and substituting fuel demand equations into (2), we can differentiate partially to see that the effect on emissions of a change in the price of fuel j is the sum of the partial derivatives of fuel demands weighted by the emission factors. Substituting $\epsilon_{ij} \cdot x_i/P_j$ for $\partial x_i/\partial P_j$, we have an expression for the elasticity of emissions with respect to $P_j$ under the assumption that aggregate energy use is held constant:

$$\frac{\partial e}{\partial P_j} \cdot \frac{P_j}{e} \Big|_{E\ constant} = \frac{1}{e} \sum e_i x_i \varepsilon_{ij} \Big|_{E\ constant}, \tag{7}$$

where $e_i$ is the partial derivative of emissions with respect to $x_i$

Similarly, allowing for adjustment in the price of aggregate energy, $P_E$, and thereby adjustment in overall energy use, we have the elasticity of emissions holding (only) output constant:

$$\frac{\partial e}{\partial P_j} \cdot \frac{P_j}{e} = \frac{1}{e} \sum e_i x_i \varepsilon_{ij} = \frac{1}{e} \sum \left( e_i x_i \cdot \left( \varepsilon_{EE} S_j + \varepsilon_{ij} \big|_{E\ constant} \right) \right) \tag{8}$$

Since own price elasticities are generally less than or equal to zero, price elasticities for individual fuels will generally be smaller in real value (i.e shifted farther below zero, if they are negative) when aggregate energy is allowed to adjust than under the restriction that aggregate energy is held constant.

The effect of a price change on emissions depends, as shown above, on the sum of demand elasticities weighted by each fuel's role in emissions, $e_i x_i/e$. When we allow aggregate energy to adjust, cross price elasticities as well as own price elasticities will be shifted downwards in real value. Thus, it is more likely that emissions will be reduced by a fuel price increase when aggregate energy is allowed to adjust than when aggregate energy use is held constant. Also, since the energy aggregate is homothetic, the own price elasticity for aggregate energy is also the price elasticity of emissions with respect to a proportional increase in all fuel prices.

Estimating technique and data. For econometric estimation (details in Annex 1), we use translog cost functions as local approximations to the energy aggregate and the cost functions. This procedure follows that of Fuss (1977) and Pindyck (1979). In each of the case study countries, we also follow these authors in estimating functions for the entire manufacturing sector. The aggregation over plants and subsectors is largely motivated by economy-- it provides directly a model of the responsiveness of the sector as a whole, which is relevant for the policy question at hand. Since differences in technology may lead to aggregation bias, building aggregate models on more disaggregated results would be an important area for future research.[10]

Each data set is a census of manufacturing firms and contains detailed plant level cost data, covering all plants with more than 10 workers (Chile) and 20 workers (Indonesia)[11]. The Indonesian data cover the period of 1975-1989 and the Chilean data cover 1979-1986. The data used in the pooled cross-sectional time-series analysis are aggregated at the regional level. The numbers of observations were 240 for Indonesia (16 regions times 15 years) and 78 for Chile (13 regions times 6). The geographical delineation enables us to retain the important geographical variability in input prices, in addition to the variability over time (no fixed or random effects are used)[12].

[10] For models of select sub-sectors, see Moss and Tybout, 1994, and Guo and Tybout, 1994, (Chile, initiated under the same research project) and Pitt, 1985, and Lee and Pitt, 1987 (Indonesia).

[11] Indonesia: Biro Pusat Statistik, Census of Medium and Large Scale Enterprises. Chile: Instituto Nacional de Estadestica, Manufacturing Census.

[12] Random effects could allow more efficient estimates, but only if regional effects were orthogonal to regional prices. With fixed effects, most of the important cross-sectional variation would be eliminated, driving down the signal-to-noise ratio in the case of measurement error.

Fuel consumption data is reported in detail in both data sets, with both quantity and expenditure figures, allowing construction of fuel-specific price series (unit values) and thus facilitating estimation of the inter-fuel substitution in the energy sub-model[13].

In addition to fuel data, the estimation of the aggregate cost share equations needs real output, real capital stocks, and unit values and cost shares for labor and materials. For Indonesia, due to lack of data, only the share equations of different fuels within the energy aggregate were estimated. For Chile, it was possible to construct the quantity and price measures necessary to estimate the aggregate model as well (a short term model, with capital given, allowing for substitutability between labor, material and the energy aggregate).

There are six fuel categories, as shown in Table 1.

Table 1: **Fuel Categories**

| CHILE | INDONESIA |
|---|---|
| **Electricity** | **Electricity** |
| **Fuel Oil** | **Others** (Fuel Oil, Kerosene, Wood, etc.) |
| **Coal** (two types) | **Coal** (Coal and Coke) |
| **Diesel** (Diesel and Destillate Oil) | **Diesel** |
| **Grouped Fuels** (Firewood, Kerosene, Gasoline, Coke) | **Grouped Fuels** (Gasoline and High Speed Diesel Oil(HSDO) |
| **Gas** (Natural and Liquid) | **Gas** (Natural) |

[13] There are nine types of fuel (including electricity) for Indonesia and twelve types for Chile. Both data bases have an entry named "Others" for which expenditures but no quantity is reported. Prices for these were constructed as a weighted average of other fuel prices. For a complete description of Chilean data preparation, see Liu (1990). The Indonesian fuel data preparation is available upon request.

## 3. Estimation Results: Chile

This section examines impacts of price changes on emission in the Chilean manufacturing sector. We first describe some basic parameters regarding fuel prices and emissions. Then, we present emission elasticities under the assumptions that overall energy use does not and then does adjust.

Table 2 presents fuel consumption data for the Chilean manufacturing sector. Electricity and fuel oil are the two most important fuels in expenditure terms, whereas fuel oil and coal are the two most important in energy terms (expressed in TOE, or ton oil equivalents, which is a measure of heating value, or calories; this calculation is in terms of heating value to the purchaser). This is because electricity is a relatively expensive fuel, in terms of heating value, while coal is relatively cheap. It is also worth noticing that the industry's expenditure on energy is 3.7 percent of its output value. Thus, the consequences for total costs of, say, a doubling of all energy prices, could not possibly exceed 3.7 percent (since, with such a budget increase, the industry could buy the old input combination at the new prices). A more disaggregate perspective would show that incidence is selective by subsector. Moss and Tybout (1994) report 8 out of 28 subsectors with an energy cost share exceeding five percent, with two exceeding 10 (cement and ceramics).

Table 2: **Chilean Manufacturing: Fuel Consumption Data (1985)**

| | Percent of Energy Cost | Percent of Output Value | Energy Share (%, TOE) | TOE/bn$ Output | Price: $/TOE |
|---|---|---|---|---|---|
| Electricity | 35.55 | 1.3 | 15.7 | 21655 | 579 |
| Fuel Oil | 34.33 | 1.2 | 39.6 | 54778 | 221 |
| Coal | 10.36 | .4 | 25.4 | 35182 | 104 |
| Diesel | 9.55 | .3 | 7.0 | 9703 | 347 |
| Grouped Fuels | 7.72 | .3 | 10.0 | 13835 | 197 |
| Natural Gas | 2.49 | .1 | 1.9 | 3212 | 332 |
| Total | 100 | 3.7 | 100 | 138354 | 256 |

Since different fuels are bought at different prices per unit of heat value, they cannot be perfect substitutes for the user. Fuel oil and coal are relatively cheap energy carriers, but may require more of other inputs to deliver a unit of output than is required by, say, electricity. Electricity, on the other hand, is usually *produced* by a process which wastes much of the heat value and is therefore relatively expensive. This heterogeneity is the reason why the econometric estimation is needed to draw inference about how substitutable these inputs are.

The top number of each cell in Table 3 shows estimated emission coefficients by fuel, in terms of kilograms per TOE. The pollutant measures are total suspended particles, or dust (TSP), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC) and carbon monoxide (CO). The calculations are based on standard models for predictions of emissions, given information about the fuels (US EPA, 1986). The fuel groups that contain several fuels are calculated as TOE-weighted averages of the coefficients for individual fuels. For example, electricity is the most polluting fuel, on a TOE basis, for both particulates and sulphur oxides. This is because electricity is assumed to be produced, at the margin, 50 percent through coal-fired power plants, and 50 percent by clean technologies (say, hydro).[14] Electricity is thus more polluting than coal, on a TOE basis, since about two-thirds of the heat value is lost in the conversion to electricity (the pollution coefficients for electricity are, thus, 3/2 times those for coal).

[14]In a given year in Chile, hydro accounts for 60-80 percent, but thermal power tends to play a greater role when demand drives marginal output changes.

Table 3: **Chilean Manufacturing: Emission Factors (kg/TOE) and each Fuel's Role in Emissions**[15]

| Emission Factor (Role, %) | Electricity | Fuel Oil | Coal | Diesel | Grouped Fuels | Natural Gas | Weighted Average | Total Tons/bn $ Output |
|---|---|---|---|---|---|---|---|---|
| Particulates, TSP | 34.8 (42%) | .9 (3%) | 23.2 (46%) | .3 (0%) | 10.4 (8%) | .0 (0%) | 12.8 (100%) | 1765 |
| Sox | 65.4 (29) | 31.6 (36%) | 43.6 (32%) | 12.8 (3%) | 4.9 (1%) | .0 (0%) | 35.4 (100%) | 4873 |
| NOx | 3.6 (13) | 6.6 (60%) | 2.6 (14%) | 2.4 (4%) | 3.6 (8%) | .3 (1%) | 4.4 (100%) | 600 |
| VOC | .3 (7%) | .3 (19%) | .2 (8%) | .0 (0%) | 4.2 (66%) | .0 (0%) | .6 (100%) | 88 |
| CO | 9.6 (9%) | .3 (1%) | 6.4 (10%) | .6 (0%) | 137.4 (81%) | .2 (0%) | 17.1 (100%) | 2337 |

The bottom numbers in each cell in Table 3 (in parenthesis) show the role of each fuel in the generation of emissions. They are calculated by multiplying intensities of use, from Table 2, by the emission coefficients described in the preceding paragraph. Electricity and coal, with 16 and 25 percent of energy consumption respectively, are each responsible for more than 40 percent of the emissions of particulates and for around 30 percent of sulphur oxides. Fuel oil in contrast, with 39 percent of energy consumption, is less important in generating particulates, but is the most important fuel in generating sulphur oxides.

Elasticities: aggregate energy use constant. We will first evaluate emission elasticities using the estimated energy submodel, which describes the extent to which fuels can be substituted for each other while holding aggregate energy use constant. Since the own price elasticity of energy by assumption is non-positive, this gives a conservative estimate of the extent to which emissions will fall with an increase in each fuel price (see equation 8).

[15]Assessed to be in agreement with AP-42 (U.S. EPA, 1986, see Weaver and Reale, 1994).

Table 4: **Chilean Manufacturing: Price Elasticities: Aggregate Energy Held Constant**[16]

| | Electricity Price | Fuel Oil Price | Coal Price | Diesel Price | Grouped Fuel Price | Natural Gas Price |
|---|---|---|---|---|---|---|
| Electricity | -.98<br>**(.09) | .45<br>**(.07) | .11<br>(.09) | .22<br>**(.07) | .21<br>**(.05) | -.00<br>(.03) |
| Fuel Oil | .55<br>**(.08) | -.96<br>**(.16) | .15<br>(.10) | .11<br>(.09) | .15<br>**(.07) | -0.1<br>**(.03) |
| Coal | .44<br>(.34) | .5<br>(.33) | -.00<br>(.56) | -.2<br>(.39) | -1.05<br>**(.24) | .31<br>*(.18) |
| Diesel | .56<br>**(.18) | .23<br>(.19) | -.12<br>(.24) | -.82<br>**(.31) | .75<br>**(.15) | .4<br>**(.13) |
| Grouped Fuels | .67<br>**(.15) | .39<br>**(.18) | -.81<br>**(.19) | .91<br>**(.19) | -1.38<br>**(.15) | .25<br>**(.09) |
| Natural Gas | -.03<br>(.47) | .09<br>(.43) | 1.07<br>*(.63) | 2.18<br>**(.71) | 1.14<br>**(O.39) | -4.27<br>**(.63) |

Table 4 shows the estimated price elasticities of demand when aggregate energy is held constant. With the exception of coal, own price elasticities are generally large in absolute value, ranging from -.94 for fuel oil to -4.27 for natural gas. Twenty-two out of thirty-six elasticities are statistically significant at a five percent level, and an additional two at a ten percent level. Pindyck (1979) also found own price elasticities large in absolute value, apart from for electricity, which he explains by the fact that since "electricity is a much more expensive fuel on a thermal basis, it should be used only where there is no possibility of using an alternative fuel" (p. 172). Such an explanation may not be valid among Chilean firms (or those in other developing countries), however, where self-generation of electricity is more

[16]Elasticities reported at means, standard errors on parenthesis. * denotes a coefficient significant at 10 % level, ** at 5 % level. For standard errors, approximate estimates are (Pindyck, 1979): $var\ \hat{\varepsilon}_{ij} = var\ (\hat{\delta}_{ij}) / \hat{S}_i^2$.

common. Many individual firms in developing countries have substantial primary, or at least, back-up capacity in order to compensate for unreliability of supply and lack of access to networks (see Lee et. al., 1992). This gives them more flexibility in responding to changes in prices of network-provided electricity, which is what we have measured in the tables shown in this paper.

Cross price elasticities take both signs, but most of them are positive and thus reflect substitutability between fuels. Among the most-used fuels -- diesel, electricity and fuel oil -- the cross price elasticities are positive, though not all of them are significantly different from zero, even at a 10 percent level.

These data can be used to calculate the elasticities of emissions with respect to each fuel price in the energy sub-model, i.e. holding aggregate energy use constant (equation 7). In Table 5, we have shown in some detail, for TSP (dust), how these parameters result from a combination of price and cross price effects, weighted by emissions (as shown by equation 7). In the table, the effects of a price change are shown in the columns (the effect of changing the electricity price, say, is found in the first column); the changes in emissions due to the change in the use of different fuels are shown along the rows. The number in the first diagonal element can be interpreted as follows: an own price elasticity of -.98, an emission factor of 34.8 and electricity use of 22720 TOE per one billion dollars of industrial output (TOE/bn$) yields an emission reduction of 7748 kg/bn$'s worth of industrial output. The total emission reduction due to a one percent increase in the electricity price, however, is only 2671 kg/bn$. Most of the difference is due to a high positive cross price elasticity with coal. A negative elasticity of TSP emissions with respect to the electricity price of -.14 indicates that a ten percent price increase would result in a reduction in TSP-emissions of 1.4 percent. For the fuel oil price, a 10 percent reduction would lead to a *reduction* in TSP emission of 4.3 percent, due to the cross price effects with electricity and coal, which are both heavy in TSP emission. Thus, following a price increase there will generally be emission increases due to cross-price effects that partly or fully compensate for the emission reductions due to negative own-price elasticities. The overall result of changing a price can be seen in the bottom row, where we have calculated the elasticity of TSP emissions with respect to the various prices, under the assumption that aggregate energy use is held constant.

Table 5: **TSP Emissions' Response to Price Changes of One Percent: Kilograms per Bn$ Output Aggregate energy held constant**

| Due to changes in: | Electricity Price | Fuel Oil Price | Coal Price | Diesel Price | Grouped Fuel Price | Natural Gas Price |
|---|---|---|---|---|---|---|
| Electricity Use | -7748 | 3558 | 870 | 1739 | 1660 | 0 |
| Fuel Oil Use | 284 | -497 | 78 | 57 | 78 | -5 |
| Coal Use | 3768 | 4282 | 0 | -1713 | -8991 | 2655 |
| Diesel Use | 17 | 7 | -4 | -25 | 23 | 12 |
| Grouped Fuels | 1008 | 587 | -1218 | 1369 | -2075 | 376 |
| Natural Gas | 0 | 0 | 0 | 0 | 0 | -0 |
| Total Change in TSP (kg/bn$) | -2671 | 7937 | -274 | 1427 | -9306 | 3037 |
| Percent of total TSP emissions | -.14 | .43 | -.01 | .08 | -.5 | .16 |

With such calculations for each of the pollutants, Table 6 shows the elasticities of emissions to price changes, holding aggregate energy use constant. We can see that one could increase the price of grouped fuels to reduce sulphur emission, reduce the electricity price or diesel price or increase the grouped fuel price to reduce VOC, and increase the coal or grouped fuel price to reduce CO.

Table 6: **Chilean Manufacturing: Emission Elasticities, Energy Constant**

| | Electricity Price | Fuel Oil Price | Coal Price | Diesel Price | Price of Grouped Fuels | Natural Gas Price |
|---|---|---|---|---|---|---|
| Particulates (TSP) | -.14 | .43 | -.02 | .08 | -.5 | .16 |
| $SO_x$ | .07 | -.04 | .07 | .03 | -.22 | .11 |
| $NO_x$ | .35 | -.41 | .03 | .11 | -.11 | .07 |
| VOC | .51 | .15 | -.5 | .62 | -.95 | .19 |
| CO | .49 | .4 | -.64 | .73 | -1.19 | .23 |

Elasticities: aggregate energy adjusting. In the energy submodel, above, where aggregate energy is held constant, the "tradeoff" among pollutants is accentuated, since the use of one fuel can only be reduced if the use of other(s) are increased. This is not so in the full model, where aggregate energy use can be reduced in response to a price rise. In fact, in that model, a proportional reduction in all pollutants can be achieved by a proportional increase in all fuel prices.

Table 7 shows price elasticities for the aggregate inputs: energy, labor and materials in a short term, cost function model, i.e. the use of capital is assumed to be given, and output is held constant. Own price elasticities are negative (and all are significant at a five percent significance level). Of particular interest is the own price elasticity of aggregate energy, -.63. Note, also, that labor demand is relatively elastic, and labor is substitutable with energy as well as material. Thus, while labor demand may be enhanced by policies which keep labor costs to employers down, it is not generally favored by policies making material and energy less expensive, since the substitutability with other inputs is quite strong.

Table 7: **Chilean Manufacturing: Elasticities For Aggregate Inputs**

| With respect to | Aggregate Energy Price | Wage | Material Input Price |
|---|---|---|---|
| Energy Demand | **-.63<br>(.36) | **1.57<br>(.49) | ** .95<br>(.31) |
| Labor Demand | **.52<br>(.16) | **-1.89<br>(.34) | **1.37<br>(.30) |
| Material Demand | **-.07<br>(.02) | **.32<br>(.07) | **-.25<br>(.08) |

Table 8 shows the price elasticities of individual fuels in the aggregate model, i.e. allowing aggregate energy to adjust, as shown in equation (6). Allowing demand for aggregate energy to adjust (equation 6), we would expect the absolute values of both own and cross price elasticities of fuels with respect to individual fuel prices to be greater. As we can see by comparing the elasticities with those in Table 4, this is indeed the case. Own-price elasticities are "more negative" and positive cross price elasticities have shifted downwards, though only one of them has changed sign from positive to negative.

Table 8: **Chilean Manufacturing: Price Elasticities: Aggregate Energy Adjusting**

| | Electricity Price | Fuel Oil Price | Coal Price | Diesel Price | Grouped Fuel Price | Natural Gas Price |
|---|---|---|---|---|---|---|
| Electricity Demand | -1.20 | .27 | .05 | .13 | .13 | -.02 |
| Fuel Oil Demand | .33 | -1.14 | .10 | .03 | .08 | -.02 |
| Coal Demand | .22 | .32 | -.06 | -.28 | -1.12 | .29 |
| Diesel Demand | .34 | .05 | -.18 | -1.91 | .67 | .39 |
| Grouped Fuels | .82 | .21 | -.86 | .82 | -1.45 | .24 |
| Natural Gas Demand | -.25 | -.27 | 1.02 | 2.10 | 1.07 | -4.27 |

**Table 9: Chilean Manufacturing: Emission Elasticities, Aggregate Energy Adjusting**

| | Electricity Price | Fuel Oil Price | Coal Price | Diesel Price | Price of Grouped Fuels | Natural Gas Price | TOE Price |
|---|---|---|---|---|---|---|---|
| Particulates (TSP) | -.37 | .25 | .07 | -.01 | -.58 | .15 | .63 |
| $SO_x$ | -.15 | -.22 | .01 | -.08 | -.29 | .09 | -.63 |
| $NO_x$ | .12 | -.59 | -.02 | -.01 | -.18 | .06 | -.63 |
| VOC | .26 | .03 | -.55 | .53 | -1.02 | .18 | -.63 |
| CO | .25 | .22 | -.69 | .64 | 1.26 | .22 | -.63 |

Allowing aggregate energy to adjust, we can also calculate the elasticities of emissions with respect to each fuel price. These are given in Table 9, where the figures reflect a stronger tendency that price increases will lead to emission reductions, as compared to Table 6. For instance, there are 17 emission elasticities with respect to individual fuel prices that are negative, as opposed to 11 in the model with aggregate energy constant. As an example that negative and positive elasticities are both lower, the elasticity of TSP emission to the electricity price is -.37, as opposed to -.14 when aggregate energy is constant. Also the elasticity of TSP emissions to the fuel oil price is .25, as opposed to .43 when aggregate energy is held constant. Thus, as price increases have become more potent instruments for the emission elasticities that were negative in the restricted model, price reductions have become less potent in the case of positive emission elasticities.

The extreme right column of Table 9 shows that a proportional increase in all energy prices will reduce all emissions with the own price elasticity of aggregate energy -- this follows from the assumption that the energy aggregate is homethetic, since fuel shares in the energy aggregate will not change unless relative prices between fuels change.

## 4. Estimation Results: Indonesia

Fuels are categorized and grouped somewhat differently in Indonesia (Table 10), thus complicating strict comparisons with the Chilean case. The most important difference is that fuel oil is included in a group called "others", and the category called "grouped fuels" contains only gasoline and high speed diesel, and not firewood and coke, as it did in the Chilean case. Coincidentally, energy expenditures are 3.7 percent of the value of manufacturing output in both countries (1985 for Chile, 1989 for Indonesia). A lower average price of energy in Indonesia (145$/TOE, as opposed to Chile's 256) is exactly compensated by a higher energy intensity (256,000, as opposed to 138,000 TOE/bn$ output) indicating an arc elasticity of -1, if we were to make inference on the basis of country comparisons.

Table 10: **Indonesia Manufacturing: Fuel Consumption Data (1989)**

| | Percent of Energy Cost | Percent of Output Value | Energy Share (%, TOE) | TOE/Bn.$ Output | $/TOE |
|---|---|---|---|---|---|
| Electricity | 32.0 | 1.19 | 6.6 | 16930 | 706 |
| Others (incl.f.oil) | 15.35 | .57 | 26.4 | 54778 | 85 |
| Coal | 5.80 | .22 | 15.4 | 39485 | 55 |
| Diesel | 16.36 | .61 | 18.2 | 46518 | 131 |
| Grouped Fuels | 25.46 | .95 | 26.5 | 67925 | 140 |
| Natural Gas | 5.03 | .19 | 6.9 | 17563 | 107 |
| Total | 1 | 3.73 | 1 | 256096 | 145 |

Relative prices between fuels differ also, however; fossil fuels are cheaper in Indonesia, but electricity is more expensive. Electricity has about a third of energy costs in both Chile and Indonesia, but only 6.6 percent in energy terms in Indonesia, as opposed to 15.7 percent in Chile. This could reflect the fact that other fuels have a lower relative price in Indonesia than they do in Chile (last column). Other differences are also marked. The "Others" category, which includes fuel oil, accounts for only 26.4 percent in energy terms in Indonesia, as opposed to 39.6 percent in Chile for fuel oil alone. Diesel, gasoline and natural gas are more important fuels in Indonesia than in Chile.

Emission factors (top number of each cell in Table 11) are almost identical to those for Chile, apart from for grouped fuels, which is lower in particulates and higher in sulphur because it consists of different component fuels. "Others" is assumed to consist mostly of fuel oil and would be higher in particulates, for instance, if wood plays an important role. The average emission factor, per TOE, is lower for Indonesia, due to the lower use of electricity, coal and fuel oil. These three, relatively dirty, fuels, constitute 81 percent of energy use in Chile, but only 48 percent in Indonesia. Comparing total emissions per billion dollar worth of output, emissions are higher in Indonesia for some pollutants, lower for others. The reason is that the relatively cleaner fuel composition in Indonesia is compensated for by the higher overall energy intensity in Indonesian manufacturing.

Table 11: Indonesia Manufacturing: Emission Factors (kg/TOE) and each Fuel's Role in Emissions[17]

| Emission factor Role, (%) | Electricity | Others (incl. f.oil) | Coal | Diesel | Grouped Fuels | Natural Gas | Weighted Average | TOE/ BN$ Output |
|---|---|---|---|---|---|---|---|---|
| Particulates (TSP) | 34.8 (37%) | .8 (4%) | 23.2 (57%) | .3 (1%) | .2 (1%) | 0 (0%) | 6.2 (100%) | 1598 |
| $SO_x$ | 65.4 (16%) | 36.3 (37%) | 43.6 (26%) | 12.8 (9%) | 12.8 (12%) | 0 (0%) | 26.2 (100%) | 6711 |
| $NO_x$ | 3.6 (6%) | 6.2 (46%) | 2.4 (10%) | 2.6 (13%) | 2.6 (23%) | .05 (0%) | 3.6 (100%) | 9910 |
| VOC | .3 (6%) | .0 (2%) | .2 (10%) | .0 (1%) | .9 (80%) | 0 (0%) | .3 (100)% | 80 |
| CO | 9.6 (7%) | .7 (2%) | 6.4 (12%) | .6 (1%) | 25.1 (77%) | .05 (0%) | 8.6 (100%) | 2201 |

The bottom number of each cell in Table 11 shows the roles of different fuels in generating emissions. Since emission factors are about the same, the differences from the Chilean case are mostly due to differences in fuel use. As in Chile, electricity and coal are responsible for most dust emissions. Coal is less important in energy use in Indonesia than in Chile, but has a higher share in TSP emissions, because electricity is less important in Indonesia. Fuel oil and co are the two important fuels for sulphur emissions in Indonesia, as in Chile, while electricity is less important in Indonesia.

Elasticities: overall energy constant. Table 12 shows the estimated price elasticities of demand when aggregate energy is held constant. As in Chile, own price elasticities are generally large in absolute value, ranging from -.83 for grouped fuels to -1.51 for coal. Eighteen out of thirty-six elasticities are statistically significant at a five percent level, and an additional six at a ten percent level. As in Chile, we find an own price elasticity for electricity close to one, which is higher than those of Pindyck (USA) and Fuss (Canada). The prevalence of self-generation in Indonesia could explain (also as in Chile) the higher elasticity, since these computed elasticities are for network provided (or purchased) electricity.

[17] Assessed in agreement with US EPA: AP-42.

Cross price elasticities take both signs, but most of them are positive and thus reflect substitutability between fuels, as expected.

Table 12: Indonesia Manufacturing: Price Elasticities: Aggregate Energy Held Constant[18]

| | Electricity Price | Others' | Coal Price | Diesel Price | Grouped Fuel Price | Natural Gas Price |
|---|---|---|---|---|---|---|
| Electricity Demand | -1.02<br>**(.11) | .17<br>*(.09) | .09<br>**(.04) | .04<br>(.03) | .80<br>**(.15) | -.08<br>**(.02) |
| Fuel Oil Demand | .23<br>*(.12) | -1.26<br>**(.29) | .04<br>(.06) | -.16<br>*(.09) | 1.1<br>**(.31) | .14<br>**(.05) |
| Coal Demand | .27<br>**(.12) | -.09<br>(.33) | -1.51<br>**(.12) | -.20<br>*(.12) | -1.06<br>**(.24) | .06<br>(.04) |
| Diesel Demand | .06<br>(.04) | .23<br>(.18) | .09<br>*(.05) | -1.37<br>**(.10) | 1.40<br>**(.18) | -.00<br>(.11) |
| Grouped Fuels' | .22<br>**(.04) | .39<br>**(.18) | -.09<br>**(.02) | .28<br>**(.04) | -.83<br>**(.10) | .01<br>(.01) |
| Natural Gas Demand | -1.11<br>**(.26) | -.09<br>(.43) | .27<br>(.17) | -.02<br>(1.04) | .59<br>(.69) | -1.21<br>*(.86) |

Emission Elasticities: overall energy constant. We now have the necessary data to calculate the elasticities of emissions with respect to each fuel price, in the energy sub-model, i.e. holding aggregate energy use constant (equation 7). In Table 13 is a full set of emission elasticities.

As for Chile, it is not difficult to find instruments for emission control even holding aggregate energy constant, although they are not exactly the same. For TSP control, in Indonesia, price increases for electricity and coal would help, as they would in Chile. Price reductions to grouped fuels (diesel and gasoline) would also help in Indonesia, whereas reductions for fuel oil would help in Chile. For $SO_x$ control, price increases for fuel oil and coal or reductions for gasoline and diesel would help in Indonesia, while there is no obvious instrument if aggregate energy is to be held constant in Chile.

[18] Standard deviation in parenthesis. * denotes a coefficient significant at 10 % level, ** at 5 % level.

Table 13: **Indonesia Manufacturing: Emission Elasticities, Energy Constant**

| With respect to: | Electricity Price | Others' (incl. f. oil) | Coal Price | Diesel Price | Price of Grouped Fuels | Natural Gas Price |
|---|---|---|---|---|---|---|
| Particulates (TSP) | -.21 | -.03 | -.83 | .12 | .94 | .01 |
| $SO_x$ | .02 | -.44 | -.37 | -.09 | .83 | .05 |
| $NO_x$ | .12 | -.55 | -.14 | -.17 | .67 | .07 |
| VOC | .14 | .15 | -.07 | .23 | -.47 | .01 |
| CO | .13 | .15 | -.09 | .22 | -.42 | .01 |

Emission elasticities: overall energy adjusting. In Table 14, we have calculated emission elasticities with aggregate energy adjusting, assuming an own price elasticity of -.63, as estimated in the Chilean case. While these are calculations for illustrative purposes only (data to estimate the full model for Indonesia were unavailable), they are further indicators of the greater flexibility, and greater tendency for negative responses of emissions, to price increases when energy is adjusting.

Table 14: **Indonesia Manufacturing: Emission Elasticities, Aggregate Energy Adjusting *Assuming* Own Price Elasticity for Aggregate Energy = -.63, as in Chile**

| With respect to: | Electricity Price | Others' (incl. f. oil) | Coal Price | Diesel Price | Price of Grouped Fuels | Natural Gas Price | TOE Price |
|---|---|---|---|---|---|---|---|
| Particulates (TSP) | -.41 | -.13 | -.87 | .01 | .78 | -.02 | -.63 |
| $SO_x$ | -.18 | -.54 | -.40 | -.19 | .67 | .02 | -.63 |
| $NO_x$ | -.08 | -.65 | -.17 | -.27 | .51 | -.04 | -.63 |
| VOC | -.06 | .05 | -.11 | .12 | -.63 | -.02 | -.63 |
| CO | -.07 | .05 | -.13 | .12 | -.58 | -.02 | -.63 |

Is there any indication that the aggregate energy elasticity for Chile is applicable in Indonesia? While data availability precludes a rigorous test, the elasticity is in the middle of the range (-.37 to -.82) found by Pitt (1985) for Indonesia. While his results are from a model with only two aggregate inputs, energy and labor, and for a select set of subsectors, we may note that adopting an elasticity from his models would yield similar results. As a conservative alternative, Table 13 holds if an aggregate energy elasticity of 0 is applied.

## 5. Summary and conclusions

Emission reductions can be stimulated by changes in fuel prices, because of the effects that inter-fuel and input substitution have on the various pollutants. The a priori observations are that emission elasticities depend on how flexible firms are in their input use, how different fuels are in terms of carrying the critical pollutants, and whether present fuel shares leave much room for substitution towards cleaner fuels.

Using data from Chile and Indonesia, this paper has provided some empirical evidence on the qualitative aspect and the quantitative magnitude of this effect in developing countries. The findings are that there is room for substitution towards cleaner input combinations, both towards cleaner fuels and away from energy, towards labor, capital and materials. Also, substitution towards cleaner fuels can be induced without increasing energy prices in general, by increasing the price of the dirtier fuels to reduce the prices of the cleaner ones. However, non-compensated price increases for the dirtier fuels, as well as increases for all fuels, will to a greater extent lead to reductions in *all* pollutants, since firms will reduce their overall energy use.

When only inter-fuel substitution is exploited, one must be careful to assess the relative damage caused by different pollutants. For both case study countries, if we assume priority for reduced particulates emissions (dust) because of associated acute health effects (Ostro, 1994 for Indonesia, and

Eskeland, Ostro and Sanchez 1994, for Chile) increased prices of electricity, as well as general energy price increases could deliver such reductions. One needs to be aware of cross price effects, however. In Indonesia, coal price increases could deliver reductions in particulates' emissions, but in Chile they would not, because of a small own price elasticity and positive cross price effect (though small) to electricity, which is a heavily used source of energy that also carries particulates. Thus, while increased prices for pollution-laden fuels will generally lead to demand reductions, as expected, the net effect on emissions will depend on: whether other fuels laden with the same pollutants are spared such price increases, their cross price elasticities are positive, and which fuel shares are high.

The attractiveness of these policy instruments depends ultimately on the other costs of selective or general energy price increases. Also, it will depend on governments' ability to implement alternative instruments (such as emission taxes backed by emission monitoring) and on the effectiveness that technical emission control devices (which reduce emission factors) would have. Since there is no historical material of data on firms exposed *mainly* to first best instruments such as pollution taxes, studies of what firms can do to reduce emissions will be synthetic, building on studies of the various avenues that firms could pursue to reduce emissions. This paper has shown that inter-fuel substitution and energy conservation are two such avenues.

Analysis of control costs can only be one input in making concrete policy recommendations, however. One also needs information on the priority given to each pollutant, and implications in other areas such as government tax revenues, administrative feasibility and industrial competitiveness. Analysis in Chile and Indonesia, focusing on health, indicates that reductions in particulates emissions (dust) should be of priority. Price increases for electricity and grouped fuels, and also general energy price increases would contribute towards this goal. Whether energy pricing is attractive as one instrument among others would also depend on the costs of monitoring and enforcement associated with more direct instruments, such as emission taxes.

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## Annex 1: Econometric Model for Estimation

The procedure and modelling framework applied here was pioneered by Jorgenson, Christensen and Lau (1971), Berndt and Christensen (1973), Hudson and Jorgenson (1974) and Fuss (1977). Multicollinearity and computational problems associated with the estimation of demand systems with many inputs are solved by imposing a priori constraints of weak separability and homotheticity in input aggregates[19].

First, we shall assume that the production function is weakly separable in aggregates of energy (E), labor (L), capital (K), and materials (M). This assumption allows the use of aggregate price indices for K, L, M, E in a model of demand for these aggregate inputs. Second, the aggregate inputs K, L, E, M, are assumed to be homothetic in their respective components. As shown by Fuss (1977), these assumptions provide a necessary and sufficient condition for a two-stage optimization process for the producers: optimize the mix of components within each aggregate (taking detailed prices into account), and then optimize the mix of aggregates K, L, E and M (taking only the price indices for the aggregates into account).

The separability of energy from other factor inputs implies that the marginal rates of substitution between any two components of the energy aggregate is independent of the usage of L, M, K. In addition, the energy aggregate is homothetic in its components, so the marginal rate of substitution between fuels is independent of E as well. The two-stage process can thus be described as producers minimizing the unit cost of energy use by choosing the appropriate fuel mix in the energy submodel

[19]The model is based on Fuss (1977), where also a detailed theoretical justification for weak separability can be found.

before choosing optimal inputs of K, L, E and M. For purposes of econometric estimation, the estimated aggregate energy price (or the unit cost of the energy aggregate) will be used as an instrumental variable in the second stage of the cost function estimation.[20]

These assumptions can be conveniently expressed by the following production function:

$$Y = f(K, L, M, E\ (x_1, x_2, \dots, x_m)) \tag{10}$$

where E is a homothetic function of the vector fuel components $x_i$, $i = 1, \dots, n$. Given exogenously determined factor prices and output (Y), and capital which is fixed in the short-term, duality implies the following short run cost function.[21]

$$C = C\ [P_L, P_M, P_E(P_1 P_2, \dots, P_m), K, y] \tag{2}$$

Separability allows us to use the function $P_E$, a price index for aggregate energy, E, which depends only on the prices of inputs in the energy aggregate (which we will denote fuels although one of them is electricity).

The aggregate cost function, above, can be represented by the translog second order approximation:

$$\ln C = \alpha_o + \sum_i \alpha_i \ln P_i + \sum_k \alpha_k \ln Q_k + \frac{1}{2} \sum_i \sum_j \gamma_{ij} \ln P_i \ln P_j + \frac{1}{2} \sum_k \sum_m \gamma_{km} \ln Q_k \ln Q_m$$

$$+ \sum_k \sum_i \gamma_{ki} \ln Q_k \ln P_i \tag{3}$$

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[20] In theory, one can also estimate the optimal mix of K, L, M, respectively in the first stage to get aggregate price indices, but the lack of disaggregate price data on the components of K, L, M prevents such attempt. In fact, the first stage optimization is usually limited to fuel mix.

[21] The long run cost function, in contrast, would reflect that the capital stock is at its equilibrium level.

where i, j = E, L, M, and k, m = y, K. By Shephard's lemma, the i'th input demand function, expressed in terms of input cost share, is:

$$\frac{\partial lnC}{\partial lnP_i} = \frac{P_i X_i}{C} = S_i = \alpha_i + \sum_i \gamma_{ij}\, lnP_j + \sum_k \gamma_{ki} lnF_k \tag{4}$$

Since the shares must add up to one and the cost function must satisfy the properties of a well-behaved production function, the parameters must satisfy the following constraints:

$$\sum_i \alpha_i = 1 \qquad i = E,L,M \tag{5}$$

$$\sum_j \gamma_{ij} = \sum_i \gamma_{ij} = 0 \qquad i,j = E,L,M$$

$$\sum_i \gamma_{ik} = 0 \qquad i = E,L,M;\ k = Y,K$$

$$\gamma_{ij} = \gamma_{ji} \qquad i \neq j \qquad i,j = E,L,M$$

Two measures given by these parameters interest us: the Allen-Uzawa partial elasticities of substitution ( $\theta_{ij}$ ) and the price elasticities of demand ( $\varepsilon_{ij}$ ). These measures can be calculated as (Bernt and Wood, 1975):

The unit cost function of energy is assumed linearly homogenous in E. Given optimization behavior, the share of each fuel in energy costs is:

$$S_{Ei} = \beta_i + \sum_{j \epsilon E} \beta_{ij} \ln P_j \qquad i,j = 1,...n \tag{11}$$

where the following parameters constraints apply:

$$\sum_i \beta_i = 1$$

$$\sum_j \beta_{ij} = \sum_i \beta_{ij} = 0 \tag{12}$$

$$\beta_{ij} = \beta_{ji} \qquad i \neq j$$

The derivations of the Allen-Uzawa partial elasticities of substitution and energy submodel price elasticities of demand are similar to equations (6)-(9).

Second Stage Estimation: The Aggregate Model. One result of the first stage estimation, above, is a function, $P_E = P_E(P_1, \ldots P_M)$, which can be used in the estimation of the aggregate cost function (2), to be estimated in stage 2. Combining the parameters estimated in the two stages, we will find total price elasticities of fuel demand, allowing the quantity of aggregate energy to adjust while output is still held constant as:

$$\varepsilon_{ii} = \varepsilon_{ii}\big|_{E\ const.} + \varepsilon_{EE} S_{Ei} \tag{13}$$

$$\varepsilon_{ij} = \varepsilon_{ij}\big|_{E\ const.} + \varepsilon_{EE} S_{Ej}$$

where $\varepsilon_{EE}$ is the own price elasticity for aggregate energy, and $S_{Ei}$ = ith fuel's share of fuel costs.

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